FLORIDA POWER CORPORATION

CRYSTAL RIVER UNIT 3

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ATTACHMENT A

CR-3 LOCA SUMMARY REPORT –
EPU/ROTSG/MARK-B-HTP,
REVISION 4

AREVA

CALCULATION SUMMARY SHEET (CSS)

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Title CR-3 LOCA Summary Report – EPU/ROTSG/Mark-B-HTP

PURPOSE AND SUMMARY OF RESULTS:

Progress Energy is pursuing an extended power uprate (EPU) at Crystal River Unit 3 (CR-3), raising nominal power level from 2609 MWt to 3014 MWt. The full set of loss-of-coolant accident (LOCA) analyses at this EPU have been completed with the B&W Canada-designed replacement once-through steam generators (ROTSGs) with up to 5 percent tube plugging in each steam generator.

The limiting results of the large break LOCA (LBLOCA) and three small break LOCA (SBLOCA) analyses are outlined in Section 2. That section also provides details of compliance to the 10 CFR 50.46 criteria. An outline of the methods used in the analyses is presented in Section 3. Section 4 provides the plant parameters, and inputs used in the LOCA calculations. A detailed discussion of the LBLOCA analyses and sensitivity studies is given in Section 5. Three sets of SBLOCA analyses are described in Section 6. Two of the SBLOCA spectra evaluate results at the full EPU power level with 1) one HPI pump and credit for steam generator (SG) cooldown and 2) two HPI pumps with no SG cooldown. The third SBLOCA spectrum evaluates the results at a reduced core power level with one HPI pump and no SG cooldown. These three SBLOCA spectra support the proposed emergency operating procedures and confirm which set of boundary conditions provide the most limiting 50.46 results. Finally, Section 7 identifies evaluation model (EM) safety evaluation report (SER) restrictions that have been met or must be monitored for the LOCA analyses.

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CR-3 LOCA Summary Report – EPU/ROTSG/Mark-B-HTP

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Record of Revision

Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
000	September 2008	All	Initial Release
001	September 2009	Refer to description of changes.	Throughout: Update to increase revision level for summary report. Throughout: Updated for grammatical, editorial, increase in template revision and readability purposes. Throughout: Note that page numbering for any given Section, Table or Figure has changed from revision 0 due to adding and deleting various items. Cover Page: Updated to reflect customer comments and revised content of this document and completion of SBLOCA and LBLOCA analyses. List of Common Acronyms: updated per customer comments and for addition/deletion of acronyms. Section 1.0: Updated to reflect customer comments, the addition of EOL LBLOCA results, HLI Line break results, CFLB results, partial-power LBLOCA results, and SBLOCA mixture level plots. Section 2.0: Updated to reflect customer comments, addition of EOL LBLOCA results, SBLOCA reanalysis results, partial-power LBLOCA analyses results, and enhancement of coolable geometry discussion. Section 3.0: Update SBLOCA methods to delete discussion of Gadolinia since it was not necessary to model Gadolinia fuel pins for SBLOCA analyses. Section 4.0: Updated to reflect customer comments, reference acceptance letter for AIS, decision of only having the RCP trip at one minute, addition of EOL Gad transient EDF calculation reference, SBLOCA EFIC sensitivity study, SBLOCA EFW wetting percentage, HPI flows for CFTLB, and added LPI flow for CFT and CLPD SBLOCA analyses. Section 5.0: Updated to reflect customer comments, addition of HLI sensitivity study, EOL LBLOCA analyses results, LBLOCA partial-power analyses results and discussion of PSC 2-98. Section 6.0: Updated to reflect customer comments, complete SBLOCA spectrum reanalysis with updated EFW wetting and LPI flows, additional HLI and EFIC sensitivity studies, decision of only having the RCP trip at one minute, SBLOCA collage plots for reanalyses and HLI line break results.

Record of Revision
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Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
			Section 7.0: Updated to reflect confirmation of SBLOCA transition break size, LBLOCA partial-power results and confirmation that the SBLOCA local peak has been determined. Section 8.0: Updated to add, delete or update references.
002	October 2009	Refer to description of changes. Changes marked with change bar.	Throughout: Note that page numbering for any given Section, Table or Figure has changed from revision 0 due to adding and deleting various items. These changes will not be marked. Record of Revision: Updated to delete Proprietary from the header and to describe the changes made in Revision 3. List of Common Acronyms: Updated per customer comments and deleted DHR acronym. Sections 2, 5 and 6 and Figure 4-1: Updated per customer comments. Section 6 was also updated to enhance readability. Section 8: Updated references to current revision levels and added notification of proprietary document to reference 28.
003	May 2010	All.	Complete reissue. Updated based on revised SBLOCA analyses that credit Fast Cooldown System via both ADVs at 10 minutes after LSCM and modulated at 350 psig. Updated references to reflect most recent revisions and added the necessary references to support this revision. Other corrections and updates per customer comments.
004	December 2011	Refer to description of changes.	Complete Reissue. This revision principally supports the Engineering Change for adjusting the HPI throttle valves, and updates the discussions for the areas listed below. 1) Include discussion of automatic plant features to be installed at CR3: automatic RCP trip, and inadequate core cooling mitigation system ICCMS. 2) Include increased HPI flow rate from unthrottling HPI valves. 3) Include discussion of full power SBLOCA HPI line break with unthrottled HPI valves at full power.

Record of Revision
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Revision No.	Date	Pages/Sections/ Paragraphs Changed	Brief Description / Change Authorization
			4) Include discussion of EFW sensitivity study without FCS. 5) Include discussion of EPU reduced power (2619.4 MWt) SBLOCA without FCS. 6) Include discussion of full power SBLOCA analyses with 2 HPI pumps and no FCS. 7) Include discussion of post-LOCA boron precipitation approach. 8) Include discussion of FOGG logic interaction with FCS. 9) Included discussion of separate document for long-term core cooling analysis of various ECCS alignments.

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List of Common Acronyms

AC	– Average Channel
Appendix K	– 10 CFR 50 Appendix K
ADV	– Atmospheric Dump Valve (Secondary Side)
ANS	– American Nuclear Society
APF	– Axial Peaking Factor
AREVA	– AREVA NP Inc.
BAST	– Boric Acid Storage Tank
BCC	– Boiler Condenser Cooling
BCM	– Boiler Condenser Mode
BOC	– Beginning of Cycle
BOCR	– Bottom of Core Recovery
BOL	– Beginning of Life
BWNT	– Babcock & Wilcox Nuclear Technologies
BWOG	– B&W Owners Group
BWST	– Borated Water Storage Tank
C_D	– Break Discharge Coefficient
CFLB	– Core Flood Line Break
CFR	– Code of Federal Regulations
CFT	– Core Flood Tank
CHF	– Critical Heat Flux
CL	– Cold Leg
CLPD	– Cold Leg Pump Discharge
CLPS	– Cold Leg Pump Suction
CV	– Control Volume
DE	– Double-Ended
CR-3	– Crystal River 3
DEG	– Double-Ended Guillotine
DH	– Decay Heat
DHDL	– Decay Heat Drop Line
DNB	– Departure from Nucleate Boiling
ECCS	– Emergency Core Cooling System
EDF	– Energy Deposition Factor
EFIC	– Emergency Feedwater Isolation & Control
EFW	– Emergency Feedwater
EM	– Evaluation Model
EOAH	– End of Adiabatic Heatup
EOB	– End of Blowdown
EOC	– End of Cycle
EOL	– End of Life
EOPs	– Emergency Operating Procedures
EOT	– End of Transient
EPU	– Extended Power Uprate
ES	– Engineered Safeguards
ESAS	– Engineered Safeguards Actuation System
FA	– Fuel Assembly
FCS	– Fast Cooldown System
FOGG	– Feed Only Good Generator
GSI	– Generic Safety Issue
HA	– Hot Assembly
HC	– Hot Channel
HFP	– Hot Full Power

List of Common Acronyms, Continued

HL	– Hot Leg
HLI	– Hot Leg Injection
HP	– Hot Pin
HPI	– High Pressure Injection
HS	– Heat Structure
ICCMS	– Inadequate Core Cooling Mitigation System
ISCM	– Inadequate Subcooling Margin, may be used interchangeably with LSCM (below)
LASP	– Licensing Above System Pressure
LBB	– Leak Before Break
LBLOCA	– Large Break Loss of Coolant Accident
LHR	– Linear Heat Rate
LL	– Lowered Loop
LOCA	– Loss of Coolant Accident
LOOP	– Loss of Offsite Power
LPI	– Low Pressure Injection
LSCM	– Loss of Subcooling Margin, may be used interchangeably with ISCM (above)
LTC	– Long-Term Cooling
MFW	– Main Feedwater
MOL	– Middle of Life
MSIV	– Main Steam Isolation Valve
MSSV	– Main Steam Safety Valve
MTC	– Moderator Temperature Coefficient
NRC	– Nuclear Regulatory Commission
OTSG	– Once Through Steam Generator
PCT	– Peak Cladding Temperature
PE	– Progress Energy
PORV	– Power-Operated Relief Valve
PSC	– Preliminary Safety Concern
PSV	– Pressurizer Safety Valve
PWR	– Pressurized Water Reactor
PZR	– Pressurizer
RB	– Reactor Building
RC	– Reactor Coolant
RCP	– Reactor Coolant Pump
RCS	– Reactor Coolant System
RL	– Raised Loop
ROTSG	– Replacement Once Through Steam Generator
RPS	– Reactor Protection System
RV	– Reactor Vessel
RVVV	– Reactor Vessel Vent Valve
SBLOCA	– Small Break Loss of Coolant Accident
SCM	– Subcooling Margin
SER	– Safety Evaluation Report
SG	– Steam Generator
SS	– Stainless Steel
T_{ave}	– Average RCS Fluid Temperature
TER	– Technical Evaluation Report
TIL	– Time in Life
TSP	– Tube Support Plate
UFLT	– Upper Face of the Lower Tubesheet
UPTF	– Upper Plenum Test Facility
w/o	– weight percent

1.0 INTRODUCTION AND BACKGROUND

Progress Energy is pursuing an extended power uprate (EPU) at Crystal River Unit 3 (CR-3), raising nominal power level from 2609 MWt to 3014 MWt. The full set of loss-of-coolant accident (LOCA) analyses at this EPU have been completed with the B&W Canada-designed replacement once-through steam generators (ROTSGs) with up to 5 percent tube plugging in each steam generator. The limiting cold leg pump discharge (CLPD) large break LOCA (LBLOCA) break size was used in the linear heat rate (LHR) analyses. These LBLOCA analyses included the variety of plant modifications to support the EPU, to demonstrate compliance with the 10 CFR 50.46 criteria and define the allowed LHR limits for use in reload licensing analyses.

The LOCA analyses were performed explicitly for the Mark-B-HTP fuel assemblies containing both UO_2 and Gadolinia fuel rods with M5® cladding. These assemblies include HTP spacer grids, HMP spacer grids, and FUELGUARD™ inlet debris filters. Large and small break loss-of-coolant accident input models that represent the CR-3 unit with Mark-B-HTP fuel were prepared in accordance with the methods prescribed in the BWNT LOCA Evaluation Model (EM) described in BAW-10192P-A [1]. Generic noding and convergence sensitivity studies documented in BAW-10192P-A [1] were reviewed and the evaluations documented in Sections 5 and 6 concluded that they are applicable to these models. In addition, AREVA NP (AREVA) reviewed previous plant-specific sensitivity studies to confirm that the most limiting set of plant boundary conditions were established and applied to the licensing analyses for both large and small LOCAs.

The bounding reactor coolant system (RCS) and EM model input parameters derived from the sensitivity studies were used in the eleven LBLOCA analyses completed to establish the nominal, full-power LOCA LHR limits for all core elevations and at three different core times in life (TIL). A new LBLOCA minimum containment pressure response was established for use in the new EPU LBLOCA analyses. Various partial-power cases with three and four reactor coolant pumps (RCPs) in operation were analyzed to provide the LHR limit inputs for the partial-power core power distribution analyses. In addition, an end-of-cycle RCS average temperature reduction was performed to support this maneuver that supports longer fuel cycle operation. These EPU evaluations and analyses are consistent with the set of LBLOCA analyses that are performed on pages LA-92 and LA-93 of the EM Volume III, Licensing Addendum [1].

The CR-3 small break LOCA (SBLOCA) plant model was also constructed with bounding RCS and EM model input parameters derived from sensitivity studies. Three sets of SBLOCA analyses were performed to fully cover the EPU power level and the plant changes based on different equipment availability and the emergency operating procedure actions based on HPI flow. The full SBLOCA spectra included CLPD breaks, core flood line breaks (CFLBs) and high pressure injection (HPI) line breaks. These EPU evaluations and analyses are consistent with the set of SBLOCA analyses that are identified on pages LA-92 and LA-93 of the EM Volume III [1].

The large and small break LOCA EPU analyses credited modifications needed to support the power level increase. The key LOCA related changes that will be implemented by Progress Energy to support the EPU and ensure continued compliance with regulatory requirements are:

1. Two larger safety-related atmospheric dump valves (ADVs), one for each steam generator, and logic for the operator-initiated or automatic fast cooldown system (FCS) following loss-of-subcooling margin (LSCM) in response to a SBLOCA with insufficient HPI flow available.
2. A new system, the Inadequate Core Cooling Mitigation System (ICCMS), will ensure an automatic RCP trip based on LSCM rather than require manual operator actions to trip the RCPs within 1 minute.
3. ICCMS will also compare required and actual HPI flow to automatically determine if actuation of the FCS is required.
4. ICCMS will also perform an automatic reset of the SG level to the LSCM setpoint at 10 minutes after LSCM, which is earlier than the previous manual action credited at 20 minutes after LSCM.

5. A new continuously open low pressure injection (LPI) cross-tie line that can provide some LPI flow to each core flood nozzle even with a single failure of one of the two LPI trains during a CFLB.
6. A new hot leg injection (HLI) flow path that connects upstream of the decay heat drop line (DHDL) RCS isolation valves. This flow path has redundant safety related valves that the operators can open to manage the post-LOCA core boric acid concentrations for either a large or small LOCA event.
7. Changes in the HPI line throttle valve resistances (MUV-590, MUV-591, MUV-592, and MUV-593) that increase the flows for the limiting SBLOCA break locations.

The results from these three SBLOCA spectrum analyses are summarized in Section 2, along with the EPU LBLOCA analyses. Section 2 also provides details of compliance to the Code of Federal Regulations (CFR) criteria, specifically 10 CFR 50.46. An outline of the methods used in the analyses is presented in Section 3. Section 4 provides a summary of the plant parameters used in the LBLOCA and the three SBLOCA analyses, as well as a chronology of the LOCA analyses and key plant design changes. The large and small break LOCA analyses are described in Sections 5 and 6, respectively. Finally, Section 7 identifies EM safety evaluation report (SER) restrictions that have been met or must be monitored for the LOCA analyses.

2.0 SUMMARY OF RESULTS

10 CFR 50.46 specifies that the emergency core cooling system (ECCS) for a commercial nuclear power plant must meet five criteria:

1. The calculated peak cladding temperature shall not exceed 2200 F.
2. The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
3. 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 surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.
4. Calculated changes in the core geometry shall be such that the core remains amenable to cooling.
5. Long-term cooling shall be established and maintained after the LOCA.

Calculations to support compliance to the first three criteria were performed with the approved RELAP5/MOD2-B&W [13] code-based evaluation model [1] and associated approved changes and 50.46 changes as summarized in Section 3. The LBLOCA analyses are documented in [2]. The SBLOCA analyses are documented in [3], [65], [69], and [72]. These calculations demonstrate compliance with these first three acceptance criteria for breaks up to and including the double-ended severance of the largest primary coolant pipe.

These analyses also generate core peaking limits that are used for core power distribution analyses. These limits are valid for the replacement steam generator with a tube plugging of up to 5 percent in each SG. An initial core power level of 3026.1 MWt, representing 3014 MWt with an applied 0.4% power uncertainty, was analyzed with the FCS available. When FCS is not available, the maximum core power level including uncertainty is limited to 2619.4 MWt to support the SBLOCA mitigation. If adequate HPI flow has been determined by the new ICCMS, the actuation of the FCS is not required. A summary of the results is presented in the following sub-sections. These results are applicable for the inputs and boundary conditions described Section 4.

2.1 Adherence to 10 CFR 50.46 Criteria

The compliance of the LBLOCA and SBLOCA analysis results with the five 10 CFR 50.46 ECCS criteria is summarized on Table 2-1 and Table 2-2, respectively. The following subsections provide additional detail.

2.1.1 Peak Cladding Temperature

The first criterion of 10 CFR 50.46 requires that the calculated peak cladding temperature (PCT) remains below 2200 F. The peak cladding temperature results for the Mark-B-HTP fuel design at the EPU conditions with ROTSGs installed are summarized in Table 2-3 through Table 2-8. For all LOCA cases, the PCT was calculated to be less than 2200 F. The limiting LBLOCA PCT was calculated to be 1947.2 F at the 7.779-ft elevation at the middle of life (MOL) burnup [2]. The limiting SBLOCA PCT was calculated to be 1426.0 F for 0.13-ft^2 CLPD break [3 and 69] at full power with FCS.

2.1.2 Local Cladding Oxidation

The second criterion of 10 CFR 50.46 requires that the maximum local cladding oxidation not exceed 17 percent. Compliance with this criterion is demonstrated by evaluating the results of the calculation of the peak cladding temperature. In the calculation, local cladding oxidation is computed as long as the cladding temperature remains above 1000 F.

The hot channel local cladding oxidation values for all cases analyzed are summarized in [2, 3, 69, 65, and 72]. In all cases, the LBLOCA hot pin local cladding oxidation was less than 3 percent, which is significantly less than 17 percent. For SBLOCAs, the results confirmed that the amount of local cladding oxidation is less than 1 percent, which is also significantly less than 17 percent. The oxidation values were calculated using a conservative (minimum) initial oxide thickness to maximize the cladding temperature response and transient oxidation due to metal-water reaction.

Further, a set of supplemental checks allow for a check of the local oxidation limits with respect to realistic initial oxidation (or pre-accident oxidation) were developed in [4]. It has been demonstrated that the use of a realistic initial oxidation coupled with the transient induced additional oxidation does not result in exceeding the 17 percent local oxidation criterion for the Mark-B-HTP fuel assemblies [2, 3, 69, 65, and 72].

There is also new NRC rulemaking activity in progress on maintaining cladding ductility post-LOCA, described as 50.46(b). While the regulations are not finalized at this time, there are proposed criteria that make the local oxidation limit dependent on the cladding hydrogen content and time above 800 C (1472 F) to less than 5000 seconds primarily for SBLOCA transients [63]. The local oxidation criterion is highly dependent upon the cladding type and fuel pin burnup. M5® cladding is used for CR-3 and as such, the allowed local oxidation is 17 percent at beginning-of-life (BOL) conditions and it reduces to 15 percent at end-of-life (EOL) conditions. In all cases, there is significant margin to this criterion, with the limiting LOCA oxidation predicted for a LBLOCA case. Its two-sided oxidation (double the unruptured cladding oxidation) value was calculated to be less than 5 percent based on the Baker-Just metal-water reaction model, so there is ample margin to the currently proposed limit. In addition, since the SBLOCA PCT is less than 1472 F, there is also ample margin to the time at temperature limit in the proposed criteria.

2.1.3 Whole-Core Oxidation and Hydrogen Generation

The third criterion of 10 CFR 50.46 states that 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 reacted, excluding the cladding surrounding the plenum volume.

The whole-core hydrogen generation for the cases analyzed was determined in [2, 3, 69, 65, and 72] based on the method outlined in Section 6 of the evaluation model [1]. The maximum LBLOCA whole-core hydrogen generation was calculated to be less than 0.2 percent for all cases. For the SBLOCA analyses, the maximum whole-core hydrogen generation rate was calculated to be less than 0.1 percent.

The LOCA cases performed and documented in this report cover the entire range of possible power distributions and fuel burnup conditions for all times in life (TIL). The maximum possible oxidation increase that can occur during a LOCA has been enveloped with the analyzed cases and a significant margin has been demonstrated to the one percent limit contained in the third criterion of 10 CFR 50.46.

2.1.4 Coolable Core Geometry

The fourth acceptance criterion of 10 CFR 50.46 states that calculated changes in core geometry shall be such that the core remains amenable to cooling. AREVA has evaluated the effects of initial fuel assembly flow area considering fuel rod or fuel assembly bowing, mechanical deformation from LOCA plus seismic (safe shutdown earthquake) dynamic loads, and the swelling and rupture alterations of the fuel pins and assembly flow area from the thermal effects during a LOCA. These contributions are evaluated to ensure that gross flow blockage will not occur (i.e., reduction in fuel assembly flow area by more than 90 percent [64]) and that the changes in the geometry will not impair or prevent the insertion of the control rods.

The effects of fuel rod or fuel assembly bowing on assembly flow area and control rod guide tubes are considered in the fuel assembly and fuel rod designs, which minimize the potential for rod bow. The plants perform control rod drop tests based on their Technical Specifications to confirm that the control rods will fully insert into the fuel assemblies (Section 3.1.4 of [59]). The effects of rod bowing are also considered on pin peaking limits using methods described in [5]. The minor adjustments of fuel pin pitch due to rod bowing do not alter the fuel assembly flow area substantially, and the average subchannel flow area is preserved until the LOCA transient is initiated.

When the LOCA is initiated, the mechanical loads on the reactor vessel from the break opening results in short-term or dynamic loads that could cause permanent distortion of the core support structures, reactor vessel internals, and the fuel assemblies. The maximum assembly loading occurs before the fuel pin experiences any significant heat up. Therefore, the mechanical effects are evaluated separately from the LOCA 10 CFR 50.46 analyses. Stress analyses of these dynamic blowdown effects, in combination with the seismic loads from an earthquake, are used to evaluate the mechanical loads on these components. The leak-before-break (LBB) methodology in BAW-2292 [6] as approved in [7] is used to demonstrate that the spacer grid impact loads are below the spacer grid elastic load limit, and no permanent grid deformation is predicted. The assessment in [54] verified that the component loads remain in the elastic ranges resulting in no permanent deformation of the fuel bundle or core geometry from the faulted condition (Seismic and LOCA) loads.

The RELAP5/MOD2-B&W [13] and BEACH [15] code calculations directly assess the alterations in core geometry from the clad swelling and rupture during a LOCA. These calculations demonstrate that the fuel pin is cooled successfully during the short-term phase of the LOCA. For M5® cladding, clad swelling and flow blockage due to rupture are calculated based on the models presented in [8 and 16]. For the Mark-B-HTP fuel design, which uses M5® cladding, the hot assembly flow area reduction at rupture is less than 60 percent for all LBLOCA cases [2] and less than 73 percent for all SBLOCA cases [3, 69, 65, and 72]. Furthermore, the upper limit of possible channel blockage, based on [16], is 90 percent, because the rupture in a fuel assembly is distributed between the grid spans and does not become coplanar across the assembly. Therefore, the assembly retains a pin-coolant-channel arrangement that is capable of passing coolant along the pin to provide cooling for all regions of the assembly.

The maximum seismic and LBB mechanical loads are combined to confirm there is no initial deformation of the fuel assemblies. The consequences of both mechanical and thermal deformation of the fuel assemblies in the core have been assessed for the Mark-B-HTP fuel in [54] to confirm that there is no permanent deformation of the fuel bundle or core geometry. Without any initial fuel assembly grid deformation, the flow blockage from the LOCA thermal effects will not exceed 90 percent. Therefore, the coolable geometry requirements of 10 CFR 50.46 have been satisfied and the core has been shown to remain amenable to cooling.

2.1.5 Long-Term Core Cooling

The fifth acceptance criterion of 10 CFR 50.46 states that 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. Successful initial operation of the ECCS is shown by demonstrating that the fuel pins remain in compliance with the first three criteria of 50.46 and the core is quenched, and the cladding temperature is returned to near saturation temperature. Thereafter, long-term cooling (LTC) is achieved by preserving continuous flow from the pumped injection systems until normal decay heat removal is established. These systems are redundant and there are a variety of configurations that are able to provide a continuous flow of cooling water to the core fuel assemblies so long as the coolant channels in the core remain open. Moreover, operator actions directed by Emergency Operating Procedures (EOPs) assure LTC by actions such as swapping ECCS suction from the BWST to the reactor building sump, thus assuring the continued availability of pumped injection. The EOPs or the technical support center may direct actions to perform further cooldowns as appropriate based on the indicated conditions and equipment available to establish normal decay heat removal if possible. These LTC actions are not significantly altered for the EPU. An evaluation of the adequacy of ECCS alignments that support LTC is described in [76].

In addition to the above, two other areas are also evaluated to show compliance with the fifth criterion: Generic Safety Issue (GSI)-191 and post-LOCA boron precipitation. The concerns expressed about continuous long-term core cooling associated with debris, GSI-191, must be adequately addressed. GSI-191 concerns the ability of the ECCS to cool the core when debris from the containment could be potentially entrained into the ECCS flow. To address this concern, evaluations included characterizing the types and the quantity of debris generated by the LOCA, its transport and potential for obstruction of the sump screens, and the downstream effects of debris that passes through the sump screen to the ECCS pumps, RCS and finally the core. CR-3 has modified its sump to incorporate debris-intercepting structures. The sump is now more effectively partitioned in order to filter the recirculation flow such that debris are trapped or otherwise hindered from entering the ECCS flowpath. As a result of fibrous insulation reduction efforts, CR-3 has a relatively small quantity of fibrous material that could affect reactor building sump and ECCS performance. As noted in [71], the NRC has acknowledged CR-3 compliance with GSI-191, with one open item related to in-vessel downstream effects. Nevertheless, the ultimate resolution for GSI-191 will be applicable to EPU power levels.

Additional areas examined that relate to LTC include the potential for boric acid precipitation to block core coolant paths. Compliance with this criterion is not specifically demonstrated by the 10 CFR 50.46 analyses for the systems and components specific to the CR-3 plant. Compliance is implied as discussed in this section and augmented by a variety of supporting analyses. The initial phase of core cooling has been shown by the analysis to result in acceptable cladding and fuel temperatures.

A pumped-injection system capable of reactor building sump recirculation and heat removal is available and operated by plant personnel as directed by the emergency operating procedures (EOPs) to provide extended coolant injection. For a cold leg break or any other scenario for which core exit subcooling is not reestablished, the concentration of boric acid within the core might induce a crystalline precipitation, which could prevent the coolant flow from reaching certain portions of the core. The concentration of dissolved solids is shown to be limited to acceptable levels through the timely initiation of active boron concentration control methods, regardless of fuel design, through both passive and active means. The passive means include loop refill and restoration of liquid natural circulation, liquid recirculation through the reactor vessel vent valves, and the hot leg nozzle gaps. The loop refill may not be possible for certain break sizes and locations. The fit-up gap for the hot leg nozzles provides a passive liquid path so long as the reactor vessel shell and reactor vessel internals temperature difference supports an open flow path that is not plugged by debris accumulation.

As mentioned in the introduction, a plant modification that cross-connects the LPI pump discharge and the decay heat drop line (DHDL) is included to support the CR-3 EPU boric acid precipitation control strategy. This hot leg injection (HLI) path, which is normally closed, is designed with two parallel safety-related valves with independent power supplies to ensure it is available regardless of any single failure. By having the HLI valves closed during the short-term core cooling phase, the LPI flow to the core flood nozzles is maximized such that the PCT is unaffected [74]. Since the valves are normally closed, operator action to open the HLI line near the time of sump switchover is required.

These modifications were designed for the EPU via an initial feasibility study [60] that used the NRC reviewed methods described in [57]. These CR-3 calculations at the EPU power level established the minimum required HLI flows that could be used in the hydraulic design for the modified LPI/HLI system. A target dilution flow of at least 300 gpm at an RCS pressure of 14.7 psia during sump recirculation was selected to cover the potentially limiting range of conditions for LBLOCA boric acid dilution. Higher RCS pressure conditions coinciding with a SBLOCA event have also been considered and the required flow rates were established as 135 gpm at 60 psia [60]. These design requirements were used in the conceptual design for the LPI cross-tie and HLI line [58]. The calculated flow rates based on the as-designed HLI path exceeds the minimum flow requirements by more than one third [73].

Based on recent NRC reviews of other plant EPUs, the technical rigor used in the methods for post-LOCA boric acid concentration[1] calculations at 2568 MWt may not be acceptable for licensing CR-3 at the EPU power level. The higher HLI line flow rates, that have considerable margin to the targeted flow rates from [60], provide margin that can be used to support more conservative boric acid concentration calculations than those previously accepted. In fact, the 400 gpm plus HLI flow rate can match core decay heat near the time of the ECCS pump suction source swap from the BWST to the reactor building emergency sump. This HLI flow allows sufficient margin such that the EOPs can be structured to initiate HLI flows near the time of sump recirculation. The core

[1] These methods included; Recirculation (Dump-To-Sump - DTS) of RCS fluid from the hot leg to the Reactor Building (RB) sump using the decay heat drop line, and Hot leg injection via the Auxiliary Pressurizer Spray (APS), where injection is through a portion of LPI flow into the pressurizer through the auxiliary spray line.

boric acid concentration is well below the boric acid solubility limit at the time of sump switchover so the HLI flow will halt the concentration increase and dilute the boric acid concentrations prior to reaching the solubility limit for any large or small break LOCA scenario.

The CR-3 EPU post-LOCA boric acid concentration control analyses credit operator initiation of HLI flow near the time of the BWST-to-sump switchover. For LBLOCAs, the HLI flow exceeds the core boiloff shortly after its initiation. The excess HLI flow that is not boiled off by the core decay heat dilutes the core boric acid concentration via reverse core flow prior to the core reaching concentrations that could precipitate. For SBLOCAs, the RCS pressure could be above the LPI shutoff head or in the range where the HLI flow does not match core decay heat. However, at these elevated saturation temperatures coinciding with the higher RCS pressures, the solubility limit is above the maximum concentration that the core could achieve. The HLI flow will increase as the pressure decreases (either naturally or through operator cooldown) such that the flows match core decay heat and provide a boric acid dilution flow prior to reaching the solubility limit.

The EPU post-LOCA core boric acid concentration analyses use the Appendix K fission product decay heat with a multiplier of 1.2. The analyses include the effects of a spectrum of postulated cold leg break sizes for both large and small break LOCAs. The core mixing volume, which uses only the liquid mass in the core region, upper plenum, and outlet annulus region below the mixture level, considers the core mixing volume from [57] with adjustments to account for the EPU power level and reductions that address recent NRC concerns and questions on post-LOCA boric acid precipitation. The steam in this mixing region is excluded from the mixing volume. The analyses do not credit any lower plenum liquid volume and they subtract a 4 weight percent H_3BO_3 uncertainty from the solubility limit. No containment over-pressure is credited for LBLOCA, but the RCS pressure and saturation temperature is considered in the solubility limit for SBLOCAs. The core mixing volume liquid mass is determined based on pure water properties.

The core boric acid analyses consider flow from the concentrated boric acid storage tank (BAST) until the tanks are isolated by operator action, passive pressure differences between the BWST and makeup tank, or sump switchover. While the analyses do not explicitly consider GSI-191, opening of the HLI valve(s) at the time of sump switchover and the magnitude of the HLI flows do provide margin to address certain GSI-191 effects on the core mixing volume and uniformity of the core boric acid concentrations. Also, since it is recommended that HLI is initiated near the time of sump recirculation, when there is inadequate core exit subcooling, there is no requirement for the CR-3 EPU configuration to have the boronometer that was used to support the operator actions in the previous plant licensing [57] bases prior to installation of the new HLI path.

Finally, the steam generator tube-to-shell delta temperatures and their associated stresses following a hot leg U-bend LOCA have been evaluated by Progress Energy and B&W Canada. It was concluded that the SG tube integrity will be maintained for this scenario such that the accident-induced primary-to-secondary leakage is less than 1 gpm such that this scenario does not challenge acceptable LTC. References [44] and [46] comprise the proprietary evaluations and justifications used for confirming LTC is preserved.

2.2 Summary of LBLOCA Results

The beginning of life (BOL) and MOL LBLOCA LHR limit analyses, which are characteristically PCT limited, are developed by adjusting the LHR to achieve a PCT in the range of 1950 F to 2050 F. While there is a target PCT range for LBLOCA, the LHR limits may be reduced to support the maximum power limits imposed on the BEACH code reflooding power peaking or by SBLOCA upper elevation limits.

The LBLOCA analyses use an axial peaking factor of 1.7 at the midpoints for each of the five sets of fuel spacer grids between the 2 and 10 ft core elevations. These five core elevations are analyzed at both BOL and MOL to produce the PCT-limited LHR limits. At end of life (EOL), the TACO3 LOCA initialization is limited to a LHR that achieves a maximum initial pin pressure. The EOL LBLOCA LHR is generally not limited by the LOCA PCT. One representative LBLOCA analysis is performed to confirm that EOL is not PCT limited. This analysis is performed at the LHR that produces the maximum LOCA initialization pin pressure consistent with the licensing above system pressure limit of the approved steady-state fuel code (in this case TACO3 for UO_2 fuel and GDTACO for Gadolinia fuel). The LHR limits for the entire length of the core, for any TIL are derived from these eleven LBLOCA analyses.

The LBLOCA calculations at the EPU power level for all TIL with ROTSGs are documented in [2]. These LOCA analyses demonstrate compliance to the first three 50.46 criteria for a full core of Mark-B-HTP fuel assemblies with 3-, 4-, 6- and 8- weight percent (w/o) Gadolinia fuel rods. Table 2-3 and Figure 2-1 specify the UO_2 linear heat rate (LHR) limits that were determined for the entire length of the core at all TIL. The core inlet and outlet LHR limits were determined as discussed in Section 5.2.5. The Gadolinia fuel has lower fuel thermal conductivity and volumetric heat capacities than the UO_2 fuel. The allowed peaking or LHR limits for gadolinia is developed based on targeting PCTs similar to the UO_2 fuel. The derived Gadolinia LHR limits are given in Table 2-4 through Table 2-7 and Figure 2-2 through Figure 2-5 for 3-, 4-, 6- and 8-w/o enriched Gadolinia fuel rods. A detailed discussion of these results is presented in Section 5.2.3.

Steady-state and transient energy deposition factors (EDFs) specific to the allowed TIL LHR limit were used for the hot channel and hot pin. The EDFs considered in each analysis are summarized in the notes to Table 2-3 through Table 2-7.

Other considerations for application of the LOCA LHR limits are the moderator temperature coefficient (MTC) and radial and axial core peaking factors for PCT-limited BOL and MOL cases. These parameters preserve EM limitations and restrictions (Section 7.0) and ensure the calculated PCTs are not violated. In addition, the fuel pin bounding power history used in the steady-state fuel pin analyses is devised with margin that allows the results to be used for multiple fuel reload cycles, so long as the other input parameters remain applicable.

It is intended that the MTC for each fuel cycle must be equal to or below the MTC versus power level limit shown in Figure 2-6. This MTC ensures that the full power peak cladding temperatures remain bounding for lower power LOCA applications with positive MTCs. Verification that the core design remains below the MTC curve at the EPU power level is performed on a cycle specific basis for each fuel reload.

The MOL and EOL steady-state LOCA initializations are dependent upon the fuel assembly power history during its time at operation. Studies have shown that assemblies that are burned at radial power histories less than those used in the TACO3 or GDTACO LOCA initializations will have initial fuel temperatures and pin pressures that are less than the values used in the LOCA analyses [10]. Lower fuel temperatures produce calculated PCTs that are less limiting and ensure the reported PCTs are bounding.

LBLOCA sensitivity studies have shown that PCTs fluctuate with variations in radial and axial peaking changes that maintain the maximum LHR limit. A method was developed to apply a penalty to the LHR limit calculated with an axial peak of 1.7. This penalty is used in core power distribution analyses if the limiting margin between the LOCA LHR limit and the augmented maneuvering analysis peak was less than 5 percent. Under these conditions, the reduction in allowed LHR limit ensures that the variations in the radial and axial peaking for these scenarios preserves the calculated PCT from the 1.7 axial cases and it therefore complies with this specific EM limitation and restriction. Section 7 provides additional details on the required adjustments to meet this EM limitation on a cycle specific basis.

2.3 Summary of SBLOCA Results

For the Mark-B-HTP fuel assemblies, a LBLOCA LHR limit of 17.3 kW/ft with a transient EDF of 1.0 was modeled at 9.536 ft. A SBLOCA LHR limit of 17.3 kW/ft was used with a more upward skewed power peak. The 1.7 axial peak at 9.5 ft was skewed to ~11-ft to maximize the cladding temperature increase during periods of core uncovery. This produced a bounding SBLOCA PCT and bounded the exit power shapes at all times in life for the CR-3 EPU SBLOCA analyses. The same axial peaking was used for all SBLOCA analyses supporting the EPU.

The CR-3 plant uses several concentrations of Gadolinia doped fuel pins to control the assembly radial power peaks. Gadolinia fuel has lower fuel thermal conductivity and volumetric heat capacities than the UO_2 fuel. The allowed peaking or LHR limits for gadolinia are reduced to control the LBLOCA PCTs. The reduction in LHR limits for Gadolinia is larger than the volumetric heat differences between Gadolinia and UO_2. Since the LHR limit reduction for Gadolinia is lower than the volumetric heat capacity ratio, the PCTs for Gadolinia rods will be lower, so they are not explicitly included in the SBLOCA analyses.

There are several sets of SBLOCA calculations that support CR-3 at the EPU conditions with ROTSGs that are documented in [3, 65, 69, and 72]. These analyses demonstrate compliance with the first three 10 CFR 50.46 criteria for cores that include a full core of Mark-B-HTP fuel assemblies at EPU conditions for a spectrum of SBLOCAs. The SBLOCA spectra analyzed breaks in the reactor coolant pump discharge piping ranging in size from 0.005 ft^2 up to 0.50 ft^2. Some of the analyses included a spectrum of high pressure injection line breaks (0.02 to 0.02463 ft^2) and a spectrum of CFT line breaks ranging in size from 0.25 ft^2 up to 0.44 ft^2. The throttled HPI valves produce differing effects on HPI flows depending on the break location, the details of which can be seen in Table 4-2. In all SBLOCA analyses, the most limiting HPI core flows (HPI flow that reaches the core) were utilized. Thus, the HPI line breaks were evaluated with reduced HPI core flows that consider the effect of unthrottled HPI valves [69], and the CLPD breaks were analyzed with a slightly lower core flow based on throttled HPI valves. The HPI valves in the above case are unthrottled (Cv = 6.2) relative to the previous throttled position (Cv = 4.2) [77]. By unthrottling the HPI valves the desired flow rate that produced the most limiting HPI core flow was achieved, though the HPI valve was not necessarily fully open. Later references to throttled or unthrottled HPI valves reflect the respective flow coefficients. In addition, the PCT variations from different EFW flow rates and time to reset LSCM level were studied and the limiting PCTs were included in the results.

The three SBLOCA spectra or partial spectrum analyses were performed to support the EPU or partial power level with different equipment available or some out of service. These analyses were performed at different times (see Section 4.1) with changes that result in different equipment credited in the analyses. The SBLOCA spectra considered were:

1. A full spectrum of CLPD, CFLB, and HPI line SBLOCA break sizes initiated from the full EPU power level. The limiting single failure postulated in these analyses resulted in the loss of a full train of emergency core cooling system ECCS equipment (1 of 2 HPI pumps and 1 of 2 LPI pumps). With only one train available, the FCS is actuated and ADV cooldown is credited by either manual or automatic action within 10 minutes following LSCM.
2. A partial spectrum of potentially limiting CLPD and HPI line SBLOCA break sizes initiated from the full EPU power level to determine the acceptable HPI flow that would obviate the need for actuating the FCS. It was determined that when either one or two HPI pumps can deliver more than 1.3 times the minimum degraded flow from one HPI pump, FCS need not be actuated following LSCM. *No specific single failure was explicitly postulated as limiting for this partial spectrum. However, implicit in the study is a single failure such that full flow cannot be achieved when both trains of HPI*

are actuated. Additionally, a single failure of the Emergency Feedwater Initiation and Control (EFIC) to control as designed was also investigated for its effects.

3. A full spectrum of CLPD, CFL, and HPI line SBLOCA break sizes initiated from a reduced core power of 2619 MWt (including power level uncertainties) with the FCS out of service. The limiting single failure postulated in these analyses is a loss of a full train of ECCS equipment. Since FCS is not available, the allowed power level is reduced, and the ADV cooldown is not credited in these SBLOCA analyses.

The inputs used for all three SBLOCA spectra are described in Section 4 and the results detailed in Section 6. The limiting PCTs for each are summarized in this section as a function of break size in Table 2-8 and in Figure 2-7, Figure 2-8, and Figure 2-9. The full sequence of events and analytical results for the EPU SBLOCA cases analyzed with FCS are provided in Section 6.

Table 2-1: Summary of 10 CFR 50.46 Compliance for LBLOCA

Criteria	Acceptance Criteria	Mark-B-HTP
PCT	2200 F	1947.2 F (17.8 kW/ft)
Max Local Oxidation	17 %	< 3%
Whole Core H_2 Generation	1%	< 0.2%
Coolable Geometry	Core remains amenable to cooling	Section 2.1.4
Long Term Cooling	LTC shall be established and maintained	Section 2.1.5

Table 2-2: Summary of 10 CFR 50.46 Compliance for Mark-B-HTP SBLOCA

Criteria	Acceptance Criteria	Full Power One HPI With FCS	Full Power Two HPIs Reduced Without FCS	Reduced Power One HPI Without FCS
PCT	2200 F	1426.0 F (17.3 kW/ft)	1397.9 F (17.3 kW/ft)	1406.9 F (17.3 kW/ft)
Max Local Oxidation	17 %	< 1%	< 1%	< 1%
Whole Core H_2 Generation	1%	< 0.1%	< 0.1%	< 0.1%
Coolable Geometry	Core remains amenable to cooling	Section 2.1.4	Section 2.1.4	Section 2.1.4
Long Term Cooling	LTC shall be established and maintained	Section 2.1.5	Section 2.1.5	Section 2.1.5

Table 2-3: Summary of Mark-B-HTP UO_2 LHR Limits

(Table 8-1 from [2])

Elevation	LOCA LHR Limit, kW/ft (PCT, F) BOL	LOCA LHR Limit, kW/ft (PCT, F) MOL (40 GWd/mtU)	LOCA LHR Limit, kW/ft (PCT, F) EOL (62 GWd/mtU)
0.0 ft	*16.9 (<1883.9)*	*16.9 (<1942.3)*	*13.4 (<1672)*
2.506 ft	**17.8 (1883.9)**	**17.8 (1942.3)**	**13.4 (1602.4)**
4.264 ft	**17.8 (1879.7)**	**17.8 (1934.3)**	*13.4 (1602)*
6.021 ft	**17.8 (1850.6)**	**17.8 (1921.2)**	*13.4 (1602)*
7.779 ft	**17.8 (1883.0)**	**17.8 (1947.2)**	*13.4 (1612)*
9.536 ft	**17.3 (1863.0)**	**17.3 (1869.3)**	*13.4 (1662)*
12.0 ft	*16.4 (<1863.0)*	*16.4 (<1869.3)*	*13.4 (<1732)*

Notes:

1. The LHR limits presented above represent the power generated by the pin (i.e., all sources of useable energy caused by the fission process).
2. All analyzed LHR limits and PCTs are in bold text and all estimated LHR limits and PCTs are in italicized text.
3. Analyses at BOL and MOL used a steady-state EDF of 0.973 for initial core energy and a transient EDF of 1.0. Analysis at EOL used a steady-state EDF of 0.987 for initial core energy and a transient EDF of 1.062.
4. Linear interpolation for LHR limits is allowed between elevations and TIL.
5. The PCT-limited LHR limits below 2.506 feet are reduced linearly to $0.95*LHR_{2.506}$ at 0.0 feet at BOL and MOL. The PCT-limited LHR limits above 9.536 feet are reduced linearly to $0.95*LHR_{9.536}$ at 12.0 feet at BOL and MOL. At EOL, a PCT increase of 70 F was applied to the adjacent elevation PCT (2.506-ft or 9.536-ft) for the 0.0-ft and the 12.0-ft elevations since the LHR limits were not reduced.

Table 2-4: Summary of Mark-B-HTP 3-w/o Gadolinia LHR Limits

(Table 8-2 from [2])

Elevation	LOCA LHR Limit, kW/ft (PCT, F) BOL	LOCA LHR Limit, kW/ft (PCT, F) MOL (40 GWd/mtU)	LOCA LHR Limit, kW/ft (PCT, F) EOL (62 GWd/mtU)
0.0 ft	*15.7 (<1832.4)*	*15.4 (<1855.0)*	*12.1 (<1621)*
2.506 ft	**16.5 (1832.4)**	**16.2 (1855.0)**	**12.1 (1551.4)**
4.264 ft	*16.5 (1829)*	*16.2 (1847)*	*12.1 (1551)*
6.021 ft	*16.5 (1800)*	*16.2 (1834)*	*12.1 (1551)*
7.779 ft	*16.5 (1832)*	*16.2 (1860)*	*12.1 (1561)*
9.536 ft	*16.0 (1812)*	*15.7 (1782)*	*12.1 (1611)*
12.0 ft	*15.2 (<1812)*	*14.9 (<1782)*	*12.1 (<1681)*

Notes:

1. The LHR limits presented above represent the power generated by the pin (i.e., all sources of useable energy caused by the fission process).
2. All analyzed LHR limits and PCTs are in bold text and all estimated LHR limits and PCTs are in italicized text.
3. Analyses at BOL and MOL used a steady-state EDF of 0.973 for initial core energy and a transient EDF of 1.03. Analysis at EOL used a steady-state EDF of 0.984 for initial core energy and a transient EDF of 1.085.
4. Linear interpolation for LHR limits is allowed between elevations and TIL.
5. The PCT-limited LHR limits below 2.506 feet are reduced linearly to $0.95*LHR_{2.506}$ at 0.0 feet at BOL and MOL. The PCT-limited LHR limits above 9.536 feet are reduced linearly to $0.95*LHR_{9.536}$ at 12.0 feet at BOL and MOL. At EOL, a PCT increase of 70 F was applied to the adjacent elevation PCT (2.506-ft or 9.536-ft) for the 0.0-ft and the 12.0-ft elevations since the LHR limits were not reduced.
6. The estimated LHR limits are based on the analyzed Gd-to-UO_2 LHR ratio.

Table 2-5: Summary of Mark-B-HTP 4-w/o Gadolinia LHR Limits

(Table 8-3 from [2])

Elevation	LOCA LHR Limit, kW/ft (PCT, F) BOL	LOCA LHR Limit, kW/ft (PCT, F) MOL (40 GWd/mtU)	LOCA LHR Limit, kW/ft (PCT, F) EOL (62 GWd/mtU)
0.0 ft	*15.3 (<1836.6)*	*15.0 (<1841.9)*	*11.7 (<1611)*
2.506 ft	**16.1 (1836.6)**	**15.8 (1841.9)**	**11.7 (1541.1)**
4.264 ft	*16.1 (1833)*	*15.8 (1834)*	*11.7 (1541)*
6.021 ft	*16.1 (1804)*	*15.8 (1821)*	*11.7 (1541)*
7.779 ft	*16.1 (1836)*	*15.8 (1847)*	*11.7 (1551)*
9.536 ft	*15.7 (1816)*	*15.3 (1769)*	*11.7 (1601)*
12.0 ft	*14.9 (<1816)*	*14.5 (<1769)*	*11.7 (<1671)*

Notes:

1. The LHR limits presented above represent the power generated by the pin (i.e., all sources of useable energy caused by the fission process).
2. All analyzed LHR limits and PCTs are in bold text and all estimated LHR limits and PCTs are in italicized text.
3. Analyses at BOL used a steady-state EDF of 0.973 for initial core energy and a transient EDF of 1.03. Analyses at MOL used a steady-state EDF of 0.974 for initial core energy and a transient EDF of 1.04. Analysis at EOL used a steady-state EDF of 0.985 for initial core energy and a transient EDF of 1.100.
4. Linear interpolation for LHR limits is allowed between elevations and TIL.
5. The PCT-limited LHR limits below 2.506 feet are reduced linearly to $0.95*LHR_{2.506}$ at 0.0 feet at BOL and MOL. The PCT-limited LHR limits above 9.536 feet are reduced linearly to $0.95*LHR_{9.536}$ at 12.0 feet at BOL and MOL. At EOL, a PCT increase of 70 F was applied to the adjacent elevation PCT (2.506-ft or 9.536-ft) for the 0.0-ft and the 12.0-ft elevations since the LHR limits were not reduced.
6. The estimated LHR limits are based on the analyzed Gd-to-UO_2 LHR ratio

Table 2-6: Summary of Mark-B-HTP 6-w/o Gadolinia LHR Limits

(Table 8-4 from [2])

Elevation	LOCA LHR Limit, kW/ft (PCT, F) BOL	LOCA LHR Limit, kW/ft (PCT, F) MOL (40 GWd/mtU)	LOCA LHR Limit, kW/ft (PCT, F) EOL (62 GWd/mtU)
0.0 ft	*14.8 (<1844.3)*	*14.8 (<1852.1)*	*11.7 (<1607)*
2.506 ft	**15.6 (1844.3)**	**15.6 (1852.1)**	**11.7 (1536.9)**
4.264 ft	*15.6 (1841)*	*15.6 (1845)*	*11.7 (1537)*
6.021 ft	*15.6 (1811)*	*15.6 (1831)*	*11.7 (1537)*
7.779 ft	*15.6 (1844)*	*15.6 (1857)*	*11.7 (1547)*
9.536 ft	*15.2 (1824)*	*15.2 (1780)*	*11.7 (1597)*
12.0 ft	*14.4 (<1824)*	*14.4 (<1780)*	*11.7 (<1667)*

Notes:

1. The LHR limits presented above represent the power generated by the pin (i.e., all sources of useable energy caused by the fission process).
2. All analyzed LHR limits and PCTs are in bold text and all estimated LHR limits and PCTs are in italicized text.
3. Analyses at BOL and MOL used a steady-state EDF of 0.974 for initial core energy and a transient EDF of 1.05. Analysis at EOL used a steady-state EDF of 0.985 for initial core energy and a transient EDF of 1.100.
4. Linear interpolation for LHR limits is allowed between elevations and TIL.
5. The PCT-limited LHR limits below 2.506 feet are reduced linearly to $0.95*LHR_{2.506}$ at 0.0 feet at BOL and MOL. The PCT-limited LHR limits above 9.536 feet are reduced linearly to $0.95*LHR_{9.536}$ at 12.0 feet at BOL and MOL. At EOL, a PCT increase of 70 F was applied to the adjacent elevation PCT (2.506-ft or 9.536-ft) for the 0.0-ft and the 12.0-ft elevations since the LHR limits were not reduced.
6. The estimated LHR limits are based on the analyzed Gd-to-UO_2 LHR ratio.

Table 2-7: Summary of Mark-B-HTP 8-w/o Gadolinia LHR Limits

(Table 8-5 from [2])

Elevation	LOCA LHR Limit, kW/ft (PCT, F) BOL	LOCA LHR Limit, kW/ft (PCT, F) MOL (40 GWd/mtU)	LOCA LHR Limit, kW/ft (PCT, F) EOL (62 GWd/mtU)
0.0 ft	*14.3 (<1849.8)*	*14.3 (<1842.8)*	*11.3 (<1630)*
2.506 ft	**15.1 (1849.8)**	**15.1 (1842.8)**	**11.3 (1559.6)**
4.264 ft	*15.1 (1846)*	*15.1 (1835)*	*11.3 (1560)*
6.021 ft	*15.1 (1817)*	*15.1 (1822)*	*11.3 (1560)*
7.779 ft	*15.1 (1849)*	*15.1 (1848)*	*11.3 (1570)*
9.536 ft	*14.7 (1829)*	*14.7 (1770)*	*11.3 (1620)*
12.0 ft	*13.9 (<1829)*	*13.9 (<1770)*	*11.3 (<1690)*

Notes:

1. The LHR limits presented above represent the power generated by the pin (i.e., all sources of useable energy caused by the fission process).
2. All analyzed LHR limits and PCTs are in bold text and all estimated LHR limits and PCTs are in italicized text.
3. Analyses at BOL and MOL used a steady-state EDF of 0.975 for initial core energy and a transient EDF of 1.06. Analysis at EOL used a steady-state EDF of 0.987 for initial core energy and a transient EDF of 1.116.
4. Linear interpolation for LHR limits is allowed between elevations and TIL.
5. The PCT-limited LHR limits below 2.506 feet are reduced linearly to $0.95*LHR_{2.506}$ at 0.0 feet BOL and MOL. The PCT-limited LHR limits above 9.536 feet are reduced linearly to $0.95*LHR_{9.536}$ at 12.0 feet BOL and MOL. At EOL, a PCT increase of 70 F was applied to the adjacent elevation PCT (2.506-ft or 9.536-ft) for the 0.0-ft and the 12.0-ft elevations since the LHR limits were not reduced.
6. The estimated LHR limits are based on the analyzed Gd-to-UO_2 LHR ratio.

Table 2-8: SBLOCA PCT versus Break Size

Offsite Power Availability	Break Type and HPI Valve Condition	Break Size (ft^2)	Mark-B-HTP		
			PCT for 1 HPI, Full Power with FCS (F)	PCT for 2 HPI, Full Power without FCS (F)	PCT for 1 HPI, Partial Power without FCS (F)
			Table 6-7 & 6-8 from [3,] Table 6-1 from [69] [4]	*Table H-3 from [72]*	*Table 8-16 from [65]*
LOOP (Loss of Offsite Power)	HPI – Unthrottled Valves	0.02	712 [1]	—	921.8 [2]
		0.022	712 [1]	712 [3]	1110.5 [2]
		0.02463	712.0	855.7 [3]	1326.5 [3]
	CLPD – Throttled HPI Valves	0.005	712.0	712 [1]	—
		0.01	712.0	712 [1]	713 [4]
		0.03	712.0	712 [1]	713 [2]
		0.04	712.0	712 [2]	1290.2 [2]
		0.045	—	992.9 [2]	—
		0.05	—	1236.2 [2]	—
		0.055	—	1357.7 [3]	1374.1 [2]
		0.06	1328.1	**1397.9** [3]	1055.4 [2]
		0.065	—	1382.2 [3]	—
		0.07	1319.5	1323.4 [4]	1374.6 [4]
		0.08	1333.4	1354.3 [4]	**1406.9** [4]
		0.09	1381	1380.1 [4]	—
		0.1	1379.5	1394.9 [4]	1399.2 [4]
		0.11	1395.7	1349.4 [4]	—
		0.12	1410.4	1339.4 [4]	1295.2 [4]
		0.13	**1426.0**	1371.9 [4]	—
		0.14	1344.5	967.4 [4]	1240.2 [4]
		0.15	1209.5	727.4 [4]	—
		0.16	—	—	1361.8 [4]
		0.2	1364.7	1262.1 [4]	1295.0 [4]
		0.3	1223.7	1224 [1]	1150.9 [4]
		0.5	1070.2	1070 [1]	1065.4 [4]
	CFT – Throttled HPI Valves	0.25	712.0	712 [1]	713 [1]
		0.3	712.0	712 [1]	713 [1]
		0.35	712.0	712 [1]	713 [1]
		0.4	712.0	712 [1]	713 [1]
		0.44	712.0	712 [1]	713 [1]
Offsite Power Available 1-Min RCP Trip	CLPD – Throttled	0.3	848.4	848 [1]	780 [1]
		0.5	712.0	712 [1]	713 [1]
	CFT – Throttled HPI Valves	0.25	712.0	712 [1]	713 [1]
		0.3	712.0	712 [1]	713 [1]
		0.35	712.0	712 [1]	713 [1]
		0.4	712.0	712 [1]	713 [1]
		0.44	712.0	712 [1]	713 [1]

Note 1: Estimated case (712 F or 713 F indicates the initial steady-state cladding temperature).

Note 2: Maximum EFW flow rate – early LSCM level reset (within ~5 minutes – see Section 4.1).

Note 3: Maximum EFW flow rate – late LSCM level reset (10 minutes for two HPI train CLPDs and 20 minutes for others – see Section 4.1).

Note 4: EFIC level rate limited EFW flow rate with 20 minute LSCM level reset. (See Section 4.1)

Figure 2-1: CR-3 Mark-B-HTP UO_2 LOCA LHR Limits for EPU with Burnup

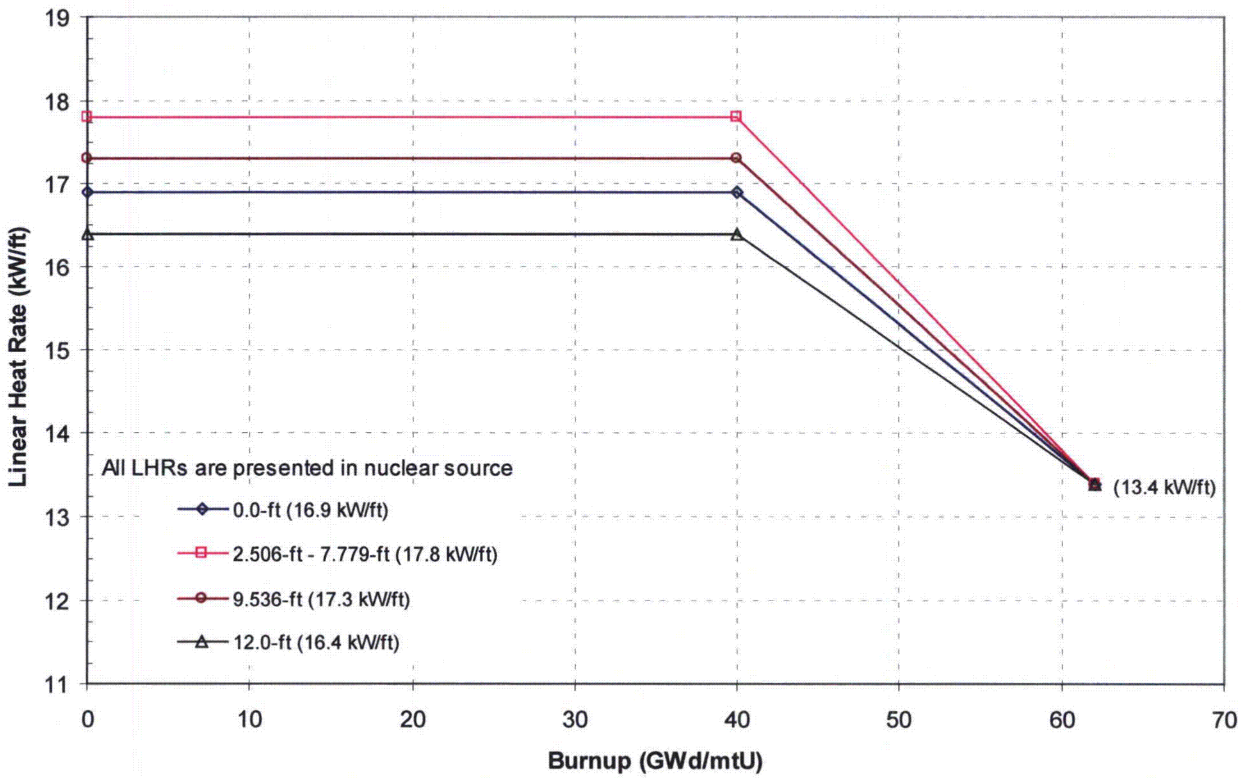


Figure 2-2: CR-3 Mark-B-HTP 3-w/o Gadolinia LOCA LHR Limits for EPU with Burnup

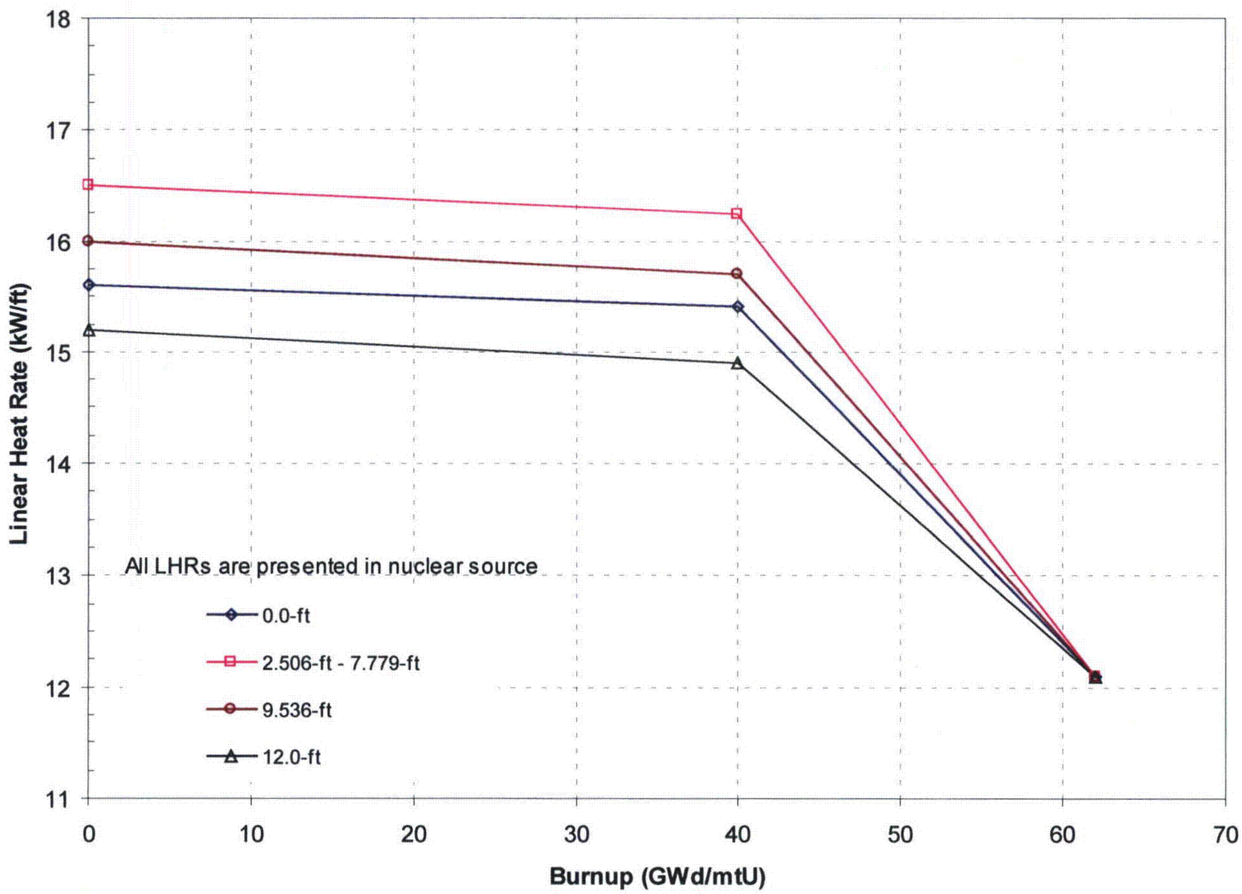


Figure 2-3: CR-3 Mark-B-HTP 4-w/o Gadolinia LOCA LHR Limits for EPU with Burnup

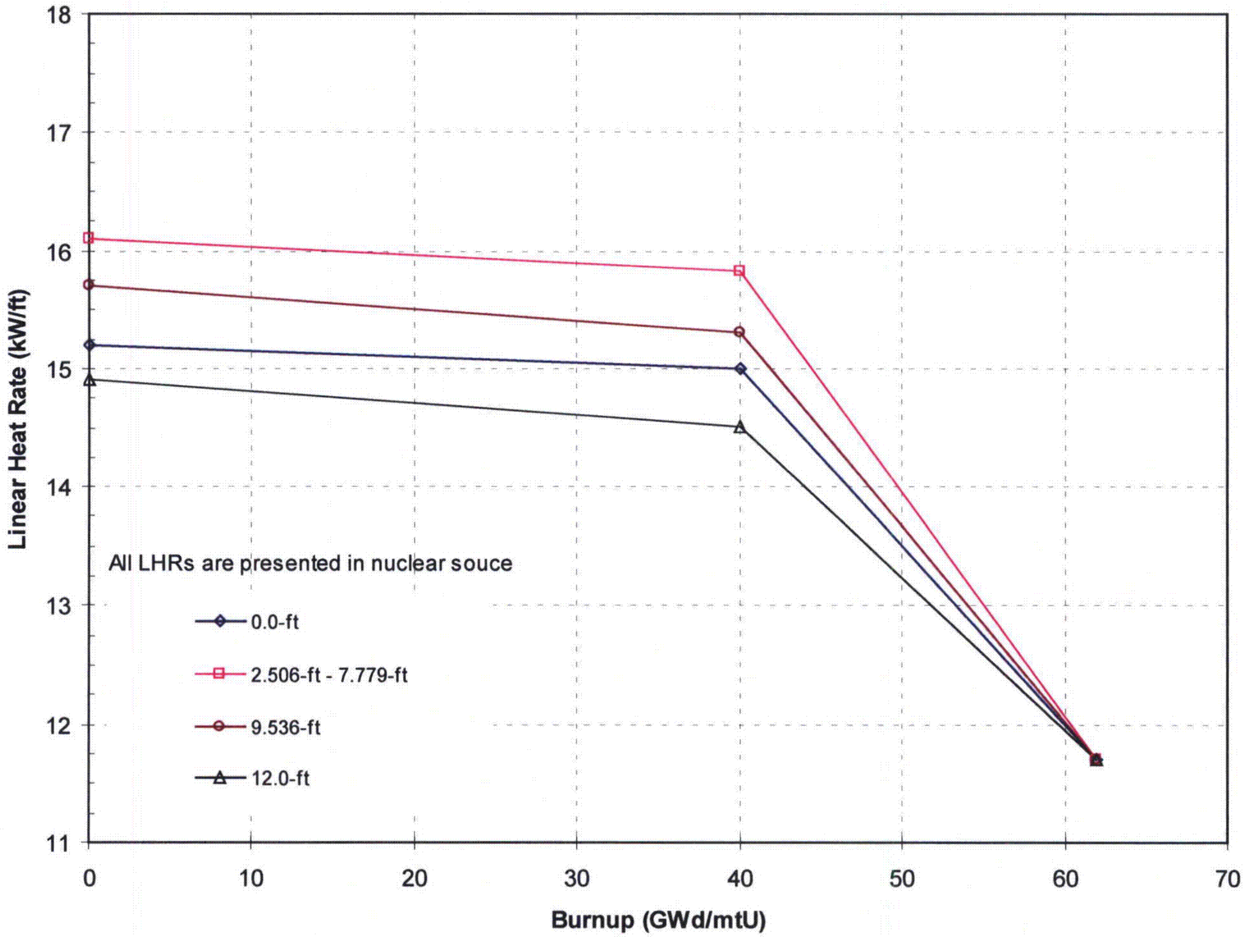


Figure 2-4: CR-3 Mark-B-HTP 6-w/o Gadolinia LOCA LHR Limits for EPU with Burnup

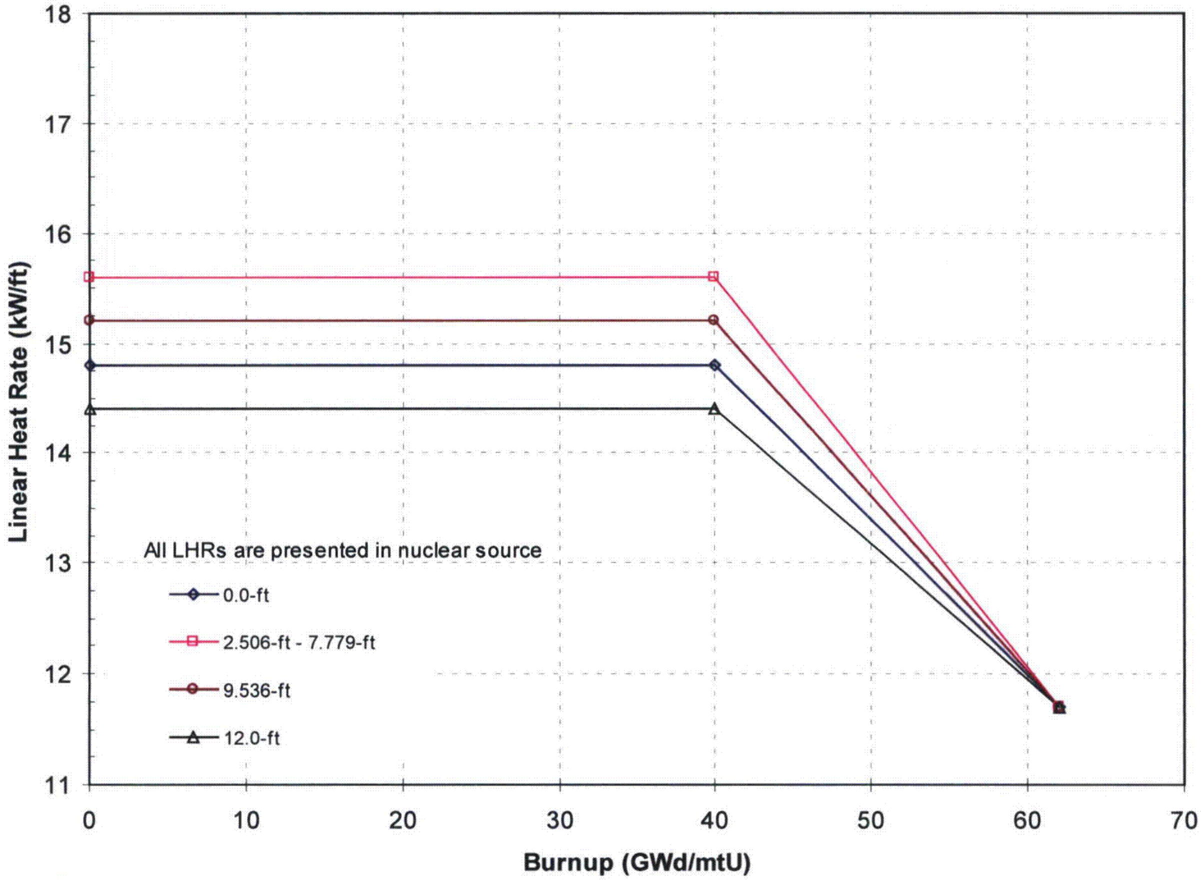


Figure 2-5: CR-3 Mark-B-HTP 8-w/o Gadolinia LOCA LHR Limits for EPU with Burnup

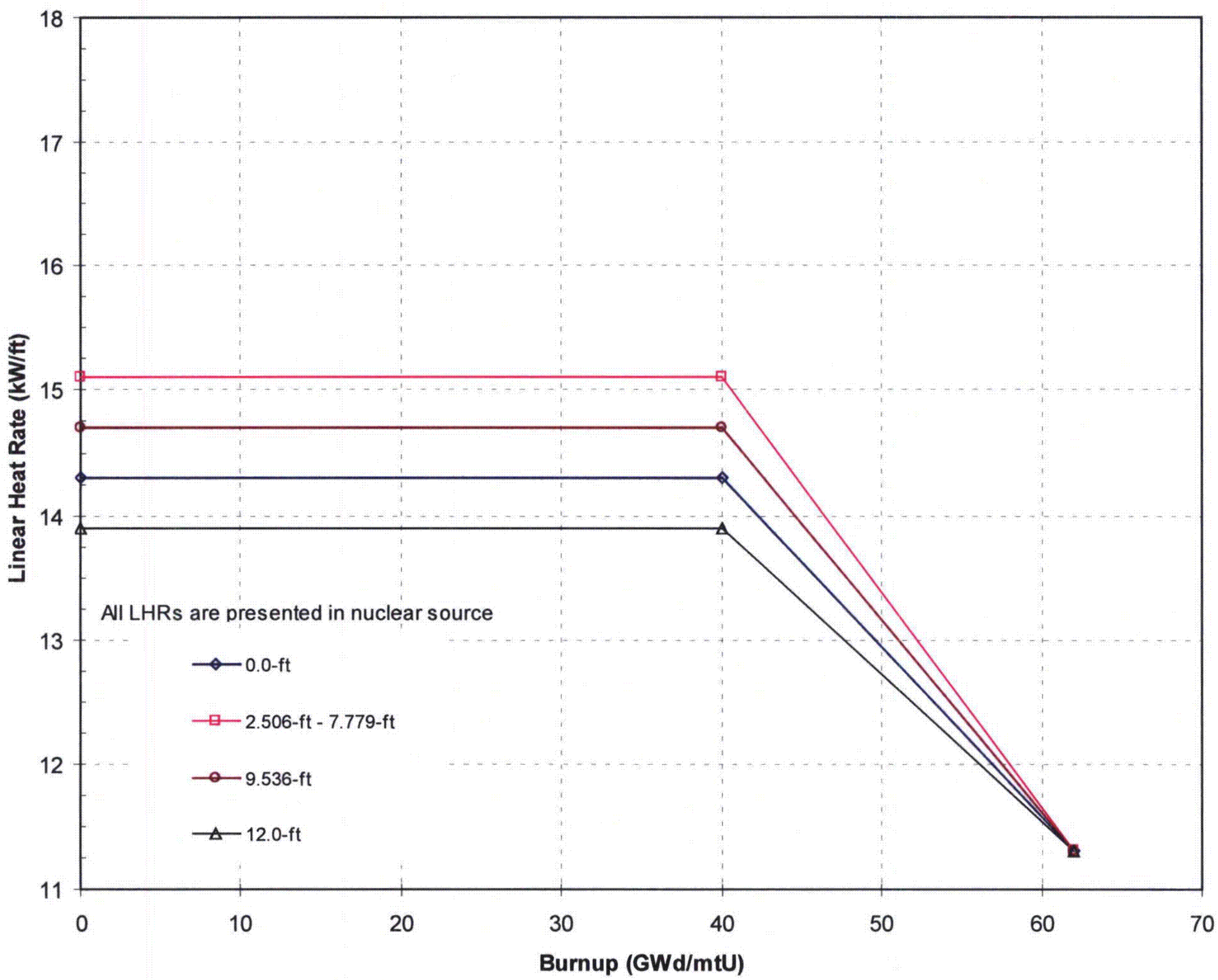
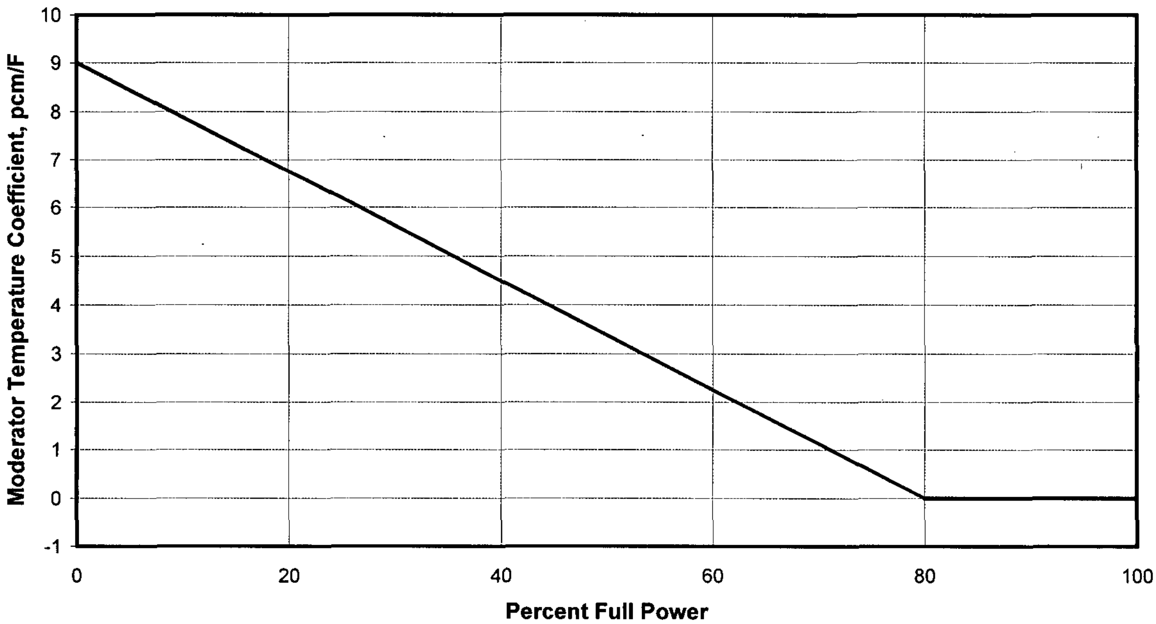


Figure 2-6: MTC Limit versus Power Level



Note: The MTC curve shown in Figure 2-6 is for LOCA analyses at the EPU power level (100% Full Power = 3014 x 1.004 = 3026.1 MWt).

Figure 2-7: One HPI Full Power SBLOCA with FCS PCT versus Break Size

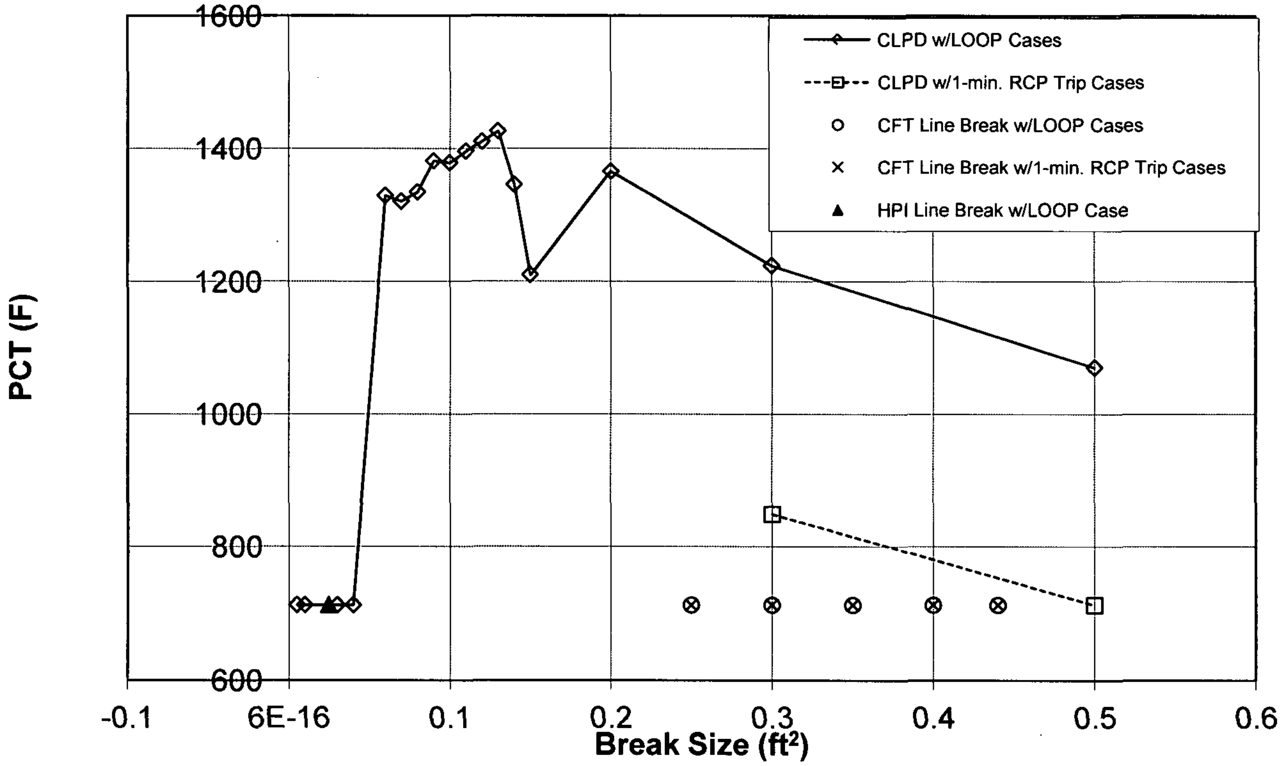


Figure 2-8: One HPI Reduced Power SBLOCA without FCS PCT versus Break Size

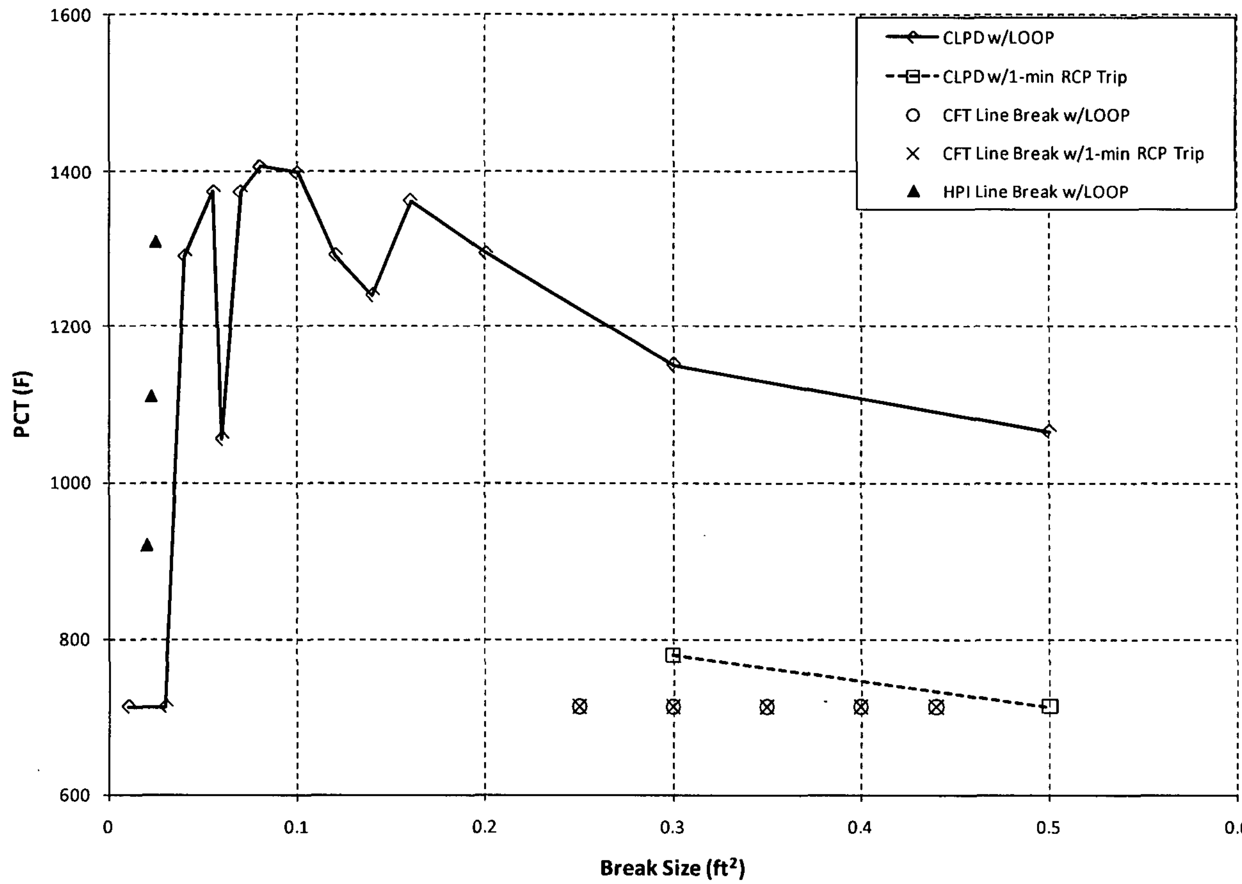
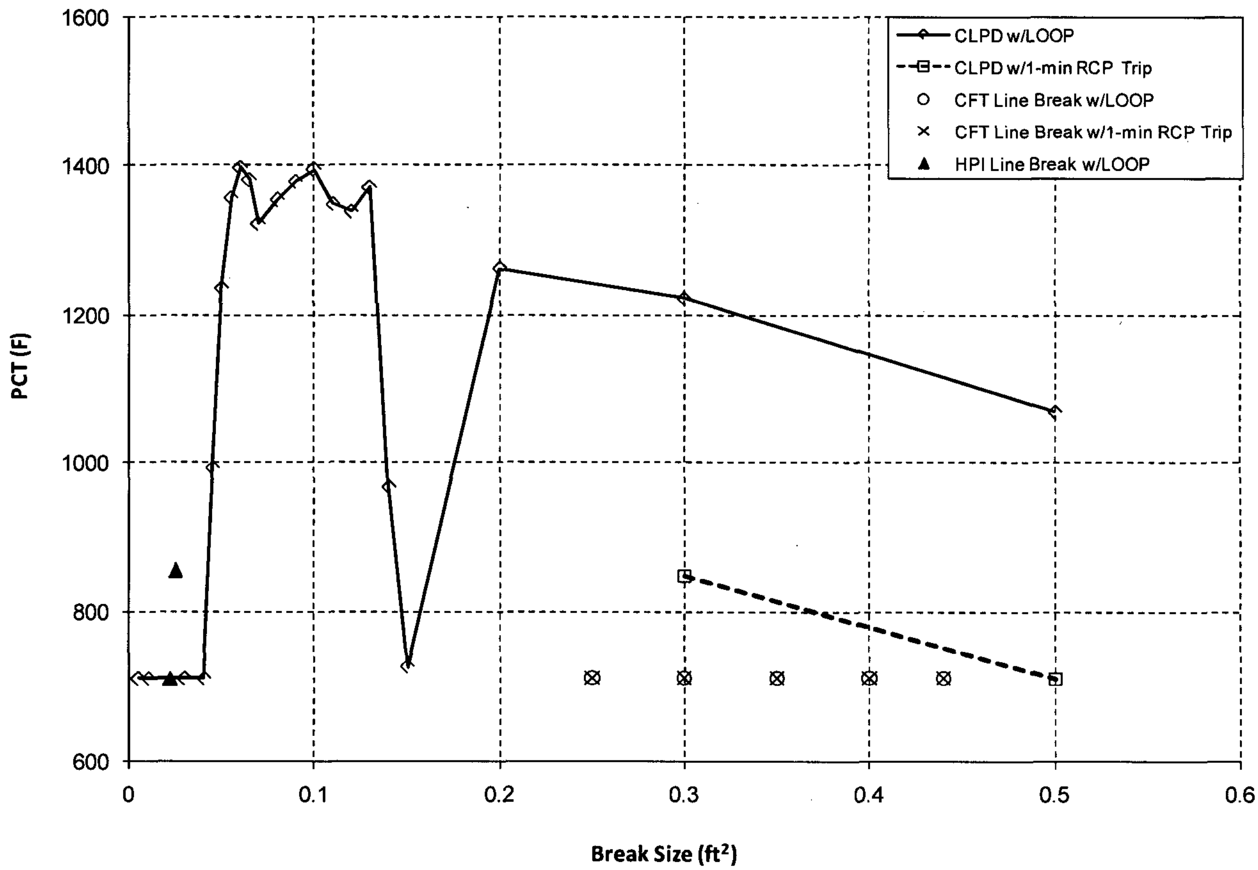


Figure 2-9: Two HPI Full Power SBLOCA without FCS PCT versus Break Size



3.0 ANALYSIS METHODS

The LOCA analyses summarized herein were performed according to the NRC approved RELAP5-based EM contained in BAW-10192P-A, Rev. 0 [1] as amended by any NRC-approved code topical revisions, 10 CFR 50.46 changes made associated with preliminary safety concern (PSC) resolutions, and method changes from the NRC-approved M5® topical report. The methods applied are consistent with Revision 2 of BAW-10192P, which is currently being reviewed by the NRC.

3.1 LBLOCA

The CR-3 specific LBLOCA applications used the NRC-approved methods contained in Volume I of BAW-10192P-A, Rev. 0 [1]. The NRC-approved topical reports identified in BAW-10192P-A are:

BAW-10162P-A, Rev. 0, TACO3	[11]
BAW-10095-A, Rev. 1, CONTEMPT	[12]
BAW-10164P-A, Rev. 3, RELAP5/MOD2-B&W	[13, Rev. 3]
BAW-10171P-A, Rev. 3, REFLOD3B	[14]
BAW-10166P-A, Rev. 4, BEACH	[15, Rev 4]

Since the approval of BAW-10192P-A, Rev. 0, the codes and methods have evolved through approved code revisions, identification of specific codes not identified in the EM, and the addition of new methods and error corrections made under 10 CFR 50.46. The following NRC-approved topical reports have been added as part of the EM for LBLOCA analyses, and they are included in the new revision of the EM topical report that is being reviewed by the NRC (BAW-10192P, Rev. 2 [70]).

BAW-10164P-A, Rev. 4, RELAP5/MOD2-B&W [13, Rev. 4]
- hot pin modeling, decreased fuel temperature uncertainty in hot assembly and average channel

BAW-10166P-A, Rev. 5, BEACH [15]
- extended ranges of application

BAW-10227P-A, Rev. 0, M5® Cladding [16, Rev. 0]
- M5 cladding properties (Rev. 1 not necessary for B&W plants)

BAW-10184P-A, Rev. 0, GDTACO [17]
- Gadolinium steady-state fuel conditions

BAW-10164P-A, Rev. 6, RELAP5/MOD2-B&W [13]
- B-HTP CHF correlation

The LBLOCA analyses also used several EM changes made under 10 CFR 50.46 to assure that Appendix K requirements are met. These items and others are discussed in Section 5.2.7.

1. Uncertainty adjusted core flood tank parameters (PSC 5-94) discussed in the 1994 and 1995 Draft B&W Annual ECCS Report [18 and 19].
2. LBLOCA reactor coolant pump two-phase degradation modeling (PSC 1-99) discussed in the 1998 and 1999 Draft B&W Annual ECCS Reports [20 and 21].

The LBLOCA methodology uses four computer codes to analyze the transient and steady-state fuel pin data from the NRC-approved TACO3 or GDTACO fuel performance codes. The RELAP5/MOD2-B&W code calculates system thermal-hydraulic responses, core power generation, and the clad temperature response during the blowdown portion of the transient. The REFLOD3B code uses initial conditions from the end-of-blowdown from the RELAP5/MOD2-B&W case to determine the length of the lower plenum refill period, and then it determines the system thermal-hydraulic response and core reflooding rate during the reflood phase. Through iteration, CONTEMPT uses the mass and energy release from RELAP5 and REFLOD3B to determine the appropriate minimum containment pressure boundary conditions. Finally, the BEACH code, which is the RELAP5/MOD2-B&W core model with the 2-D reflood fine-mesh rezoning heat transfer option activated, determines the clad temperature response during the reflood period with input of the flooding rate, upper plenum pressure, and core inlet temperatures from the REFLOD3B analysis. Demonstration that the analyses are in compliance with the limitations and restrictions placed on the EM and associated computer codes is provided in Section 7 by the information contained in the most recent revision of the EM limitations and restriction document [22]. A completed input checklist based on this reference is included in the LOCA documentation.

3.2 SBLOCA

The SBLOCA applications used the NRC-approved methods contained in Volume II of BAW-10192P-A, Rev. 0 [1]. The NRC-approved topical reports identified in BAW-10192P-A are:

BAW-10162P-A, Rev. 0, TACO3	[11]
BAW-10164P-A, Rev. 3, RELAP5/MOD2-B&W	[13, Rev. 3]
BAW-10095A, Rev. 1, CONTEMPT	[12]

Since the approval of BAW-10192P-A, Rev. 0, the codes and methods have evolved through approved code revisions and the addition of new methods and error corrections made under 10 CFR 50.46. The following NRC-approved topical reports have been added as part of the EM for SBLOCA analyses, and they are included in the new revision of the EM topical report that is being reviewed by the NRC (BAW-10192, Rev. 2 [70]).

BAW-10164P-A, Rev. 4, RELAP5/MOD2-B&W [13, Rev. 4]
- void-dependent cross-flow model, and supplemental pins

BAW-10227P-A, Rev. 0, M5 Cladding [16, Rev. 0]
- M5 cladding (Rev. 1 not necessary for B&W plants)

BAW-10164P-A, Rev. 6, RELAP5/MOD2-B&W [13]
- B-HTP CHF correlation

Gadolinia fuel typically has a lower LHR limit versus that for UO_2 fuel that results in less limiting SBLOCA PCTs. If the BOL and MOL LHR limits for the Gadolinia fuel are not lower than those for UO_2 by at least the volumetric heat capacity ratio of these metals, the LOCA initialization will be performed for these analyses using the GDTACO code listed below this paragraph. Note that the code is approved by the NRC and it is included in the new revision of the EM topical report that is being reviewed by the NRC (BAW-10192P, Rev. 2 [70]).

BAW-10184P-A, Rev. 0, GDTACO [17]
- Gadolinium steady-state fuel conditions

The SBLOCA analyses also used several EM changes made under 10 CFR 50.46 to assure that Appendix K requirements are met. Those 50.46 changes that have not subsequently been approved within a revised topical report include use of:

1. Uncertainty-adjusted core flood tank parameters (PSC 5-94) discussed in the 1994 and 1995 Draft B&W Annual ECCS Report [18 and 19];
2. SBLOCA reactor coolant pump two-phase degradation modeling (PSC 2-00) was described in the 2000 and 2001 B&W Annual ECCS Reports [23 and 24]. The SERs relating to PSC 2-00 are not associated with a specific topical report. The original SER [25] imposed a limitation that required that the two-phase degradation model used in the SBLOCA analyses be demonstrated to the NRC to justify application of the pump model to the B&W plants. Additional information was provided to the NRC via [26] to justify generic applicability of the model to the B&W plants. In response to this

information, the NRC revised the SER to remove the limitation [27]. Therefore, the results of PSC 2-00 and associated SER are generically applicable to the B&W plants.

A new consideration regarding axial power shapes was developed while performing scoping studies for SBLOCA analyses. The potential for extended core uncovering for EPU conditions called to question the bounding nature of the EM axial power shapes. Accordingly, the EPU SBLOCA analyses used a skewed EOC 11-ft axial peak of 1.7 for all cases to bound the power shapes at any time in cycle [3]. The 9.536-ft axial peak used in all previous SBLOCA EM analyses is bounding at beginning of cycle (BOC), but it is not limiting for end-of-cycle (EOC) conditions. Since no burnup studies are performed for SBLOCA, the limiting EOC peaking at 11-ft, which is located in the control volume centered about 10.811-ft, will be used for each set of SBLOCA analyses needed to support the EPU conditions.

The SBLOCA methodology uses only the RELAP5/MOD2-B&W code to calculate the system thermal hydraulics. The containment pressure is not critical for most SBLOCA analyses since the calculations are stopped before the RCS pressure reaches conditions where the break could unchoke. For those scenarios that reach a lower RCS pressure where break unchoking could occur, a conservative containment pressure is used. In cases where the containment pressure is more important, such as for a core flood line break with the new LPI cross-tie arrangement, CONTEMPT is used to determine the minimum containment pressure. The mass and energy releases from the RELAP5 code result are used in CONTEMPT to determine the appropriate minimum containment pressure boundary conditions. Generally, it takes a couple of iterations to obtain a converged containment pressure solution.

Demonstration that the SBLOCA analyses are in compliance with the limitations and restrictions placed on the EM and associated computer codes is provided in Section 7 by the information contained in the most recent revision of the EM limitations and restriction document [22]. A completed input checklist based on this reference is included in the LOCA documentation.

4.0 PLANT PARAMETERS AND INPUT

A brief summary of the specific plant parameters and inputs used in the LBLOCA and the three sets of SBLOCA analyses is presented in Table 4-1 through Table 4-6, and Table 4-8 through Table 4-11. The AIS input is complex because of evolving plant design changes and their supporting analyses for the EPU. The original models were developed for scoping studies and to establish design concepts in early 2007 and the design changes have evolved over a four year time interval. Some analyses were performed near the beginning of that time span and others were completed near the end. Some of the later plant changes and results of analysis sensitivity studies were found to have an adverse effect on the previously completed work and others a favorable effect based on the inputs used for the analyses. This variation makes it difficult to describe in an AIS without considerable additional discussion. Perhaps the best way to identify the changes and evolutions is through a simple chronology of the plant inputs and analyses. This chronology is provided in the following subsection followed by a subsection describing the key inputs for the different sets of SBLOCA analyses that support the CR-3 EPU.

4.1 Chronology of LOCA Related Analyses and Key Plant Design Changes

In early 2007, the CR-3 2619 MWt analyzed core power SBLOCA model was reinitialized to the EPU power level for use in preliminary scoping analyses. Several key design changes were identified as needed to support LOCA analyses at 3026 MWt including uncertainties. They included automatic cross tie of the LPI lines, with a portion of the LPI reaching a continuously open hot leg injection (HLI) path, and the addition of new safety related ADVs combined with manual operator action to bypass the feed-only-good-generator (FOGG) logic and open at least one valve at 20 minutes following LSCM which assist primary depressurization to achieve CFT flow, augmenting the HPI injection. Work began on the system design changes while the CR-3 LOCA models were updated with the original OTSGs removed and replaced by the ROTSGs. Other EPU changes necessary to model the design changes were also included. At that point, manual operator actions were credited for the 1-minute RCP trip and 20-minute LSCM EFW level reset, FOGG bypass, and ADV opening. The HPI system was not modified but the LPI system was being changed. The LBLOCA analyses were performed using a minimum cold side LPI flow rate for core cooling credit. No HLI flow credit or penalty was necessary.

The design changes continued to evolve as portions of detailed design work were completed, which resulted in some additional changes to the LPI system to replace the continuous passive HLI with dual isolation valves. The changes improved the cold side LPI injection rates for LBLOCA, large SBLOCAs, and CFT line breaks. Since more flow was better from a short-term core cooling or PCT analysis, the completed analyses were not repeated, but evaluations and assessments of minimum containment pressure were performed.

While working on the details of the steam generator cooldown plant design modifications, namely safety related ADV depressurization and manual bypass of FOGG, it was concluded that the ADV cooldown should not be continuous. Instead, the steam generator secondary side depressurization should stop at 350 psig, to limit SG tube-to-shell temperature differences to an easily manageable value but still dump a portion of the CFT to assist with the core matchup HPI shortfall. The number of manual operator actions associated with the SG depressurization was beginning to add up, so the manual actions were replaced with an automatic safety related actuation and control system, called the fast cooldown system (FCS). In addition to the automatic FCS actuation, it was determined that FOGG bypass was no longer required because both ADVs will be opened. Near the same time, review of the preliminary EPU core maneuvering analyses indicated that the 9.5-ft axial peak used in the SBLOCA analyses may not be bounding for the CR-3 EPU EOC conditions. When a more skewed axial peak was used in some SBLOCA scoping analyses, the PCTs increased considerably. This PCT increase was managed by adjusting the time for the FCS to automatically actuate from the previous 20 minute action to 10 minutes. New EPU SBLOCA analyses were performed with the 11-ft axial peak, and new automatic FCS credit in the fall of 2009 and spring of 2010. The limiting PCT was predicted as 1426 F with FCS from the EPU full power level and one train of ECCS in operation.

In the summer of 2010, after the new EPU FCS analyses were completed, a question was asked about whether or not FCS is required when two HPI pumps are operating. Full flow from two HPI pumps based on the LOCA BWST inputs and degraded pump curves was not available at that time, but the expected increase in the actual

HPI flow from two pumps was believed to be sufficient such that credit for FCS was not needed. SBLOCA analytical work and HPI hydraulic analyses were initiated in parallel to expedite a decision on how much flow was needed and how much was available. The SBLOCA analysis goal was to determine how much HPI flow was needed to keep the PCT below the 1426 F value from the EPU FCS analyses. Iterations of multiplicative increases to the CR-3 one HPI pump flows with the throttled HPI control valves were performed. It was determined that a 1.3 increase in the one HPI pump flow rate was sufficient to keep the PCT below the target value for all SBLOCA break sizes. In addition, the hydraulic analyses showed that the actual two-pump degraded flow was much larger than this value.

Another question was asked in the fall of 2010, about what to do if the FCS system was declared out-of-service or unavailable. The solution was to reduce the core power to a partial power level at which the PCT was less than the EPU FCS bounding PCT value. An analyzed core power of 2619 MWt was shown to produce a PCT less than the target value for all break sizes. In addition, an EFW flow sensitivity study was proposed to see if the results produced with an EFIC level rate controlled model could be worse with minimum or maximum EFW flow rates and credit for manual reset of the LSCM SG level at or before 20 minutes following LSCM.

In parallel with the last two sets of SBLOCA analyses that did not credit FCS, decisions were implemented to include automatic safety-related RCP trip and automatic reset of the LSCM level setpoint in the planned plant modifications supporting the EPU. In addition, there was an effort to relate the indicated HPI flow from two HPI pumps to the uncertainty adjusted minimum flow that was assured and could be credited for SBLOCA core cooling analyses. When the RCS pressure and measured HPI flow uncertainties were independently combined, there was an overlap of the required 1.3 times the flow from one HPI pump and the minimum uncertainty adjusted available flow. This overlap effectively meant that the FCS may be initiated on a LSCM due to the instrument uncertainty imposed. This overlap was precluded when the throttled HPI valves were unthrottled. By reducing the resistance in the HPI lines, the indicated HPI flow increased and there was no overlap of the required and available HPI flow even with the uncertainty adjustment. Unthrottling the HPI valves increases the available HPI flow that will reach the core for CLPD, CFT, and hot leg break locations. Conversely, unthrottling increases the HPI flowing to a broken HPI line for the HPI line break, which reduces the HPI flow to the core for a break in this location. New hydraulics analyses were performed with the valves unthrottled and those inputs were considered in new HPI line break analyses as described. Since more flow was better from a short-term core cooling or PCT analysis for other break types, the completed analyses were not repeated because the results remain bounding. However, evaluations and assessments were performed with the higher HPI flows to support the LBLOCA minimum containment pressure input.

A revised HPI line break case was performed for the EPU full power level with FCS using the unthrottled HPI flow rates. For this case, the credit for the FCS remained sufficient to augment the HPI flow and it did not predict core uncovering with the lower HPI flows. None of the other CLPD or CFT line break cases were reanalyzed with the higher HPI flows because the PCTs are similar or bounded by the analyzed and reported values.

The unthrottled HPI flow was included in the HPI line break analyses of the partial power SBLOCA analyses without FCS. The CLPD and CFT line breaks were already in progress so they were completed with the lower throttled HPI flow rates. Since the flow rates are lower than expected, the PCT predicted for the CLPD and CFT line breaks are similar or bounded by the analyzed and reported values and they do not need to be reanalyzed.

The EFW flow study completed in early 2011 for the partial power SBLOCA spectrum without FCS showed that maximum EFW flow produces worse PCT results for smaller break sizes that rely on SG heat transfer. The EFIC level rate control is limiting for larger break sizes that do not rely on SG heat transfer. Break sizes of 0.06-ft^2 and less are more limiting with maximum EFW flow. The results supplied in this document reflect these higher PCTs. In some cases, the PCTs were worse if the LSCM secondary level reset was early (~ 5 minutes or before the natural circulation level was reached initially) and in some cases it was worse with a 20 minute reset of the level. The variation in PCT is also a function of LSCM level reset timing for the HPI line break sizes.

Based on the EFW sensitivity study results (See Section 6.1.4) , the EPU two-HPI pump no FCS analyses of the smaller SBLOCA breaks sizes were reanalyzed with maximum EFW flow in the spring of 2011. In addition to the maximum EFW flow, the HPI line breaks considered lower HPI flows to the core at moderate to high RCS pressures from unthrottling of the HPI valves. As a result, several of the smaller CLPD breaks produced PCTs higher than the EPU FCS target value when the longest 20 minute delay was applied to the LSCM level reset time. However, part of the plant design change includes automatic reset to the LSCM level setpoint within 10 minutes following LSCM. When a 10 minute LSCM level reset delay is used, the PCTs are all bounded by the value predicted for the EPU full power level with FCS credit. The HPI line breaks with two HPI pumps continued to use a 20 minute delay, but the limiting CLPD breaks credited the 10 minute automatic action.

One of the last issues addressed revolved around the actuation of FOGG logic in the course of the FCS blowdown. FOGG stops feedwater to a steam generator when that generator pressure is either less than 600 psig, or is at a pressure 125 psid lower than the other SG when both SG pressures are below 600 psig. As such, when the FOGG logic is not bypassed during an SBLOCA event, the secondary side depressurization can cause the existing FOGG circuitry to occasionally but only briefly interrupt EFW to whichever SG meets one of the above conditions. However, the FOGG signal does reset, restoring EFW when the SG pressure is above 600 psig, or when the difference decreases below 125 psid at SG pressures less than 600 psig. The net effect of the briefly interrupted EFW was found to be negligible on the transient progression of the CR-3 EPU SBLOCA analyses with FCS and did not adversely affect compliance with 10 CFR 50.46 acceptance criteria [75].

The chronology discussion relates some of the sequencing of the EPU LOCA analyses and identifies the differences in the credit for manual operator actions initially with specific inputs. As the plant design work progressed, additional analyses were needed to address plant changes and evolutions in the manual versus automatic actions for some key sequences. In addition, the HPI valve unthrottling added yet another variable to the mix that further complicates the discussion of inputs used or actions credited. When an action was initially described as "manual" but changed to "automatic", it is now described as "either manual or automatic" to cover both scenarios. This chronology can be used to clarify the reasoning behind the different inputs used by each analysis.

4.2 Summary of LOCA AIS Parameters

From the chronology, it is clear that three sets of SBLOCA spectrum analyses are performed with different inputs which make development of one AIS table complex. The approach used was to have four columns of analyses: one for LBLOCA and three for the SBLOCA spectra listed for each parameter. Rather than simply repeat the same information multiple times, common inputs for multiple columns were merged together when possible. This approach helps delineate the key input differences between the analyses. The SBLOCA columns considered were:

1. The 100 percent EPU power level (3026 MWt with uncertainties) with credit for only one train of ECCS and automatic or manual FCS initiation at 10 minutes.
2. The 86.6 percent EPU power level (2619 MWt with uncertainties) with credit for only one train of ECCS and no FCS because it was declared unavailable.
3. The 100 percent EPU power level (3026 MWt with uncertainties) with credit for partial to full flow from two trains of HPI and no automatic or manual FCS.

It should also be noted that the HPI inputs are a conservative representation of two different HPI throttle valve positions based on the current throttled valve settings and a modified unthrottled position. When the valves are unthrottled the HPI line resistance is lower and the total flow increases for CLPD, CFT line, and hot leg breaks. For conservatism, these break locations were modeled with the throttled HPI flow. However, the HPI line breaks have lower HPI flows into the RCS at higher pressures because of the unthrottling and the reduced resistances in the broken line. Therefore, the unthrottled flows are used in the HPI line break scenarios.

Specific operator actions or automatic plant features that are included in the AIS are described in Table 4-7. A detailed discussion and basis for these plant parameters and inputs are provided in [28]. The chronology in Section 4.1 should be used to help identify or explain any change in inputs or manual versus automatic actions. When the actions are changed from manual to automatic, they can be credited at earlier times during the event.

Table 4-1: LOCA Inputs

Parameter	Full Power with FCS		Reduced Power no FCS	Full Power no FCS
	LBLOCA	SBLOCA	SBLOCA	SBLOCA
Single Failure	LOCA: loss of one bus or train of emergency power Minimum Containment: all ECCS available			No single failure is assumed since the intent is to determine how much HPI flow is needed to obtain acceptable results without FCS actuation.
Offsite Power	LOOP coincident with break	LOOP coincident with reactor trip		
	For cases with offsite power available, the RCPs are manually or automatically tripped 1 minute after LSCM			
LSCM	Table 4-8			
Primary and Secondary Initial Conditions				
Rated Core Power, MWt	3014		$PP_{rated} \times 1.004 = PP_{analyzed}$ $PP_{rated} = 2619.4 \div 1.004 = 2609 MWt$	3014
Core Power Uncertainty, %	0.4			
RCP Power, MWt	16.16			
RCS Average Temperature, F	582 nominal 570 for LBLOCA EOC T_{ave} reduction maneuver			
RCS Pressure, psia	2170			
RCS Flow Rate, gpm	374,880 (106.5% of design)			
Core Bypass Flow Rate, %	7.5			
Indicated PZR Level, in	220 on 320 inch scale			
Makeup & Letdown	Not explicitly modeled but considered in the effective pump heat inputs			
MFW Temperature, F	460		442	460

Parameter	Full Power with FCS		Reduced Power no FCS	Full Power no FCS
	LBLOCA	**SBLOCA**	**SBLOCA**	**SBLOCA**
Steady-state MFW Flow Rate, lbm/s/SG, *(Note 1)*	1820	1829	1520	1829
Turbine Header Pressure, psia *(Note 2)*	907	898	920	898
SG Tube Plugging, %/SG	5 (up to this value in each SG) Up to 10% of total wetted region is plugged for SBLOCA (e.g., 1% of 10% of the total tubes in the wetted region)			
Decay Heat Parameters				
Decay Heat Standard	ANS 1971 + 20%			
Actinides	B&W Heavy Actinide Model	Default RELAP5/MOD2 Actinide Model		
Pressurizer Parameters				
PZR Heater and Sprays	Not explicitly modeled but included in initial conditions consider their effects			
PSV and PORV	Not modeled because they will not be actuated			
RCP Parameters				
Pump Manufacturer	Byron-Jackson			
RCP Type, Single Minus Two-Phase Fully Degraded Performance	RELAP5 Semiscale Head Difference			
Two-Phase Void-Dependent Degradation Multiplier	M3-Modified			
RCP Trip, s	LOOP	LOOP or 1 minute after LSCM		
RCP Trip Delay, s	0			
RCP Rated	Appendix B of [22] with RCP head adjusted to achieve targeted RCS flow rate			

Parameter	Full Power with FCS		Reduced Power no FCS	Full Power no FCS
	LBLOCA	**SBLOCA**	**SBLOCA**	**SBLOCA**
Conditions				
MFW System Parameters				
MFW Trip	LOOP: coincident with LOOP Offsite Power Available: coincident with reactor trip			
MFW Coastdown	2 seconds full flow then linear reduction to zero flow over 12 seconds			
Turbine & Main Steam System Parameters				
Turbine Trip	Coincident with break	Coincident with reactor trip		
Turbine Trip Delay, s	0.5			
Turbine Stop Valve Stroke Time, s	0.1			
MSSV Setpoints	Table 4-6			
ADV Capacity	Not credited in the model	589,000 lbm/hr per valve at 540 F saturated (620,000 lbm/hr less 5%) *(Note 3)*	Not modeled	
ADV Actuation	Not credited in the model	Two ADVs credited for SG blowdown 10 minutes after LSCM and then modulated to control at the uncertainty adjusted maximum pressure of 350 psig.	ADVs inaccessible due to FCS out of service	Not credited
EFW Temperature, F	130			
EFW Actuation	Not credited in the model	LOOP: coincident with reactor trip Offsite power available: ESAS or manual/automatic RCP trip		
EFW Delay Time, s	40			
EFW Flow Rate, gpm	EFW not credited in the model	Maximum or EFIC level rate control; limited to a flow of 300 gpm/SG *(Note*	EFIC level rate control limited to a flow of 300 gpm/SG with minimum and maximum EFW flow sensitivity studies *(Note 4)*	Maximum or EFIC level rate limited to a flow of 300 gpm/SG *(Note 4)*

Parameter	Full Power with FCS		Reduced Power no FCS	Full Power no FCS
	LBLOCA	SBLOCA	SBLOCA	SBLOCA
		4)		
EFW Shroud Bypass, %	EFW not credited in the model	35		
Automatic SG Natural Circulation Level Control, ft	EFW not credited in the model	20.7 (with respect to UFLTS of OTSG)		
Time to Raise Level, min	EFW not credited in the model	Manual/automatic action 20 after LSCM (Note 5)		Automatic Action 10 after LSCM (Note 5)
LSCM SG Level Control, ft	EFW not credited in the model	26.3 (with respect to UFLTS of OTSG)		
Reactor Protection System & ESAS				
RPS Low RCS Pressure Setpoint, psia	1890 (in-plant less uncertainty)			
Reactor Trip Delay Time, s	at EOB	0.6		
ESAS Low RCS Pressure, psia	1640			
ESAS Low-Low RCS Pressure, psia	515			
ESAS HPI Signal and Delay Time, s	ESAS Low RCS Pressure + 67			
ESAS LPI Signal and Delay Time, s	ESAS Low RCS Pressure + 35			
	ESAS Low-Low RCS Pressure + 10			
ECCS Parameters				
BWST Temperature, F	120			
HPI Flow Rate	HPI not credited for core cooling in LBLOCA (Table 4-2 for containment)	Table 4-2 HPI Line Unthrottled CLPD Throttled CFT Throttled		

Parameter	Full Power with FCS		Reduced Power no FCS	Full Power no FCS
	LBLOCA	SBLOCA	SBLOCA	SBLOCA
LPI Flow Rate	Table 4-3			
CFT Liquid Volume, ft^3/tank	970 – 1070 (Volume used maximizes PCT)			
CFT Cover Gas Pressure, psia	577 – 653 (Pressure used maximizes PCT)			
CFT Surge Line Area, ft^2	0.7213			
CFT Surge Line Length, ft	Line A: 84.26 Line B: 97.18			
CFT Liquid Temperature, F	130			
CFT Line Resistance (form plus friction)	6.84	684, except 6.84 for CFT Line Break		
CFT Line Elevation Change, ft	-6.16			
Reactivity Control Parameters				
Control Rod Insertion Begins, s	0.0 after Reactor Trip plus Delay			
Fully Inserted Control Rod Worth, %Dk/k	-4.5			
Control Rod Drop Time, s	Table 4-4			
Control Rod Insertion Curve	Table 4-5 for +0 pcm/F			
MTC Curve	Positive curves in [29] Negative curves for T_{ave} Reduction in [30]			
Doppler Reactivity Coefficient, Dk/k/F	-1.69×10^{-5} at 1420 F	1700 pcm for T_{fuel} from HFP to T_{ave}		
Delayed Neutron Fraction (β)	0.007102			

Parameter	**Full Power with FCS**		**Reduced Power no FCS**	**Full Power no FCS**
	LBLOCA	**SBLOCA**	**SBLOCA**	**SBLOCA**
Prompt Neutron Generation Time (λ), s	0.248×10^{-4}			
Steady-State EDF	0.973 for UO_2 at BOL & MOL Calculated for EOL (or Gad) per [40]			
Transient EDF	1.0 for UO_2 at BOL & MOL Calculated for EOL UO_2 per [40] & EOL Gad per [62]			
Fuel Parameters				
Fuel Design	Mark-B-HTP			
UO_2 Enrichment, w/o	3.0 – 5.1			
Gadolinia Concentrations	4 concentrations: 3-, 4-, 6-, & 8-w/o			
Containment Parameters				
Containment Parameters	Figure 4-1 based on Table 4-9, Table 4-10, and Table 4-11	Constant 70 psia. If break flow becomes unchoked, linearly reduce from 70 to 14.7 psia over first 600 seconds of event or perform case specific containment pressure analysis.		

Notes for Table 4-1 provided on the following page.

Notes for Table 4-1:

1. Initial values will be used to approximate the initial MFW flow to each SG at full power. The actual values are expected to vary from the target values when a steady-state initialization is performed. Small variations in SG initial conditions compared to actual plant operating conditions will not significantly affect the transient results.
2. The AIS states that the targeted turbine header pressure is 930 psia for all power level conditions. The SBLOCA and LBLOCA values have been adjusted to achieve steady-state initialization. This was necessary due to the composite plant configuration (e.g., core power plus uncertainty, 5% SGTP, minimum RCS flows) in order to achieve a balance of heat transfer generation and removal between the primary and secondary system at the desired conditions.
3. This capacity corresponds to the expected ADV capacity reduced by 5% to provide a margin of safety ([28, Section 5.8.4]), but reflects an increase above the existing capacity of 301,246 lbm/hr steam at 540 F, 960 psia (each ADV) [45]. So long as the installed ADV capacity is within an acceptable range (e.g. ± 10% of the nominal capacity) of what is modeled, the analyses remain applicable. A variation on the maximum ADV flow is not the critical parameter for SBLOCA because the valve is fully open for only a short time period, after which it is modulated to control secondary side pressure. The key parameter for SBLOCA is the secondary side modulation pressure because it determines the volume of CFT liquid injected and also determines the pressure for the HPI flow.
4. The AIS [28] states that the EFW flow rate will be the EFIC fill rate limited to a maximum of 300 gpm/SG. The SBLOCA analyses modeled the EFIC fill rate in the analyses presented in [3] since it was determined to be appropriate for SBLOCA EPU with FCS analyses. Non-FCS cases consider higher EFW flow rates for smaller break sizes. Constant minimum flow rates of 200 gpm/SG were also considered. See Section 6.1.4 for details on the EFW sensitivity study.
5. Manual operator action to raise the level to the LSCM level is credited within 20 minutes following LSCM for full power with FCS and reduced power without FCS SBLOCA analyses. The full power without FCS analysis credits an automatic LSCM level reset at 10 minutes. Justification for this can be found in Section 4.1.

Table 4-2: HPI Flow Rates

Pressure (psia)	CLPD Break		HPI Line DE Break		CFT Line Break
	Broken CL Flow (gpm)	Intact CLs Total Flow (gpm)	Broken CL Flow (gpm)	Intact CLs Total Flow (gpm)	Total Flow to RCS (gpm)
HPI Flow with Throttled Valves					
15	135.7	332.4	0	332.4	468.1
615	121.9	298.5	0	281.2	420.4
915	114.1	279.5	0	253.1	393.6
1215	105.6	258.7	0	222.7	364.3
1515	96.1	235.6	0	189.2	331.7
1815	85.4	209.2	0	141.0	294.6
2115	72.8	178.1	0	90.2	250.9
2415	56.7	139.0	0	25.7	195.7
HPI Flow with Unthrottled Valves					
15	127.3	374.9	0	374.9	502.2
315	-	-	0	331.6	-
915	108	318	0	243.2	426
1515	-	-	0	144.2	-
1815	82.2	241.9	0	92.6	324.1
2115	70.5	207.5	0	37.2	278
2215	-	-	0	14.2	-
2615	39.6	116.6	-	-	156.2

Note: The flow rates were converted from the volumetric flow rates listed to a mass flow rate using atmospheric pressure and the BWST liquid temperature of 120 F. The HPI flow rates are based on a BWST elevation of 1.75 ft above the bottom of the tank which corresponds to a minimum BWST inventory [9 and 28]. The throttled HPI valves refer to MUV-590, MUV-591, MUV-592, and MUV-593.

Table 4-3: LPI Flow Rates

LBLOCA[2 & 6]

Pressure (psia)	Flow Rate (gpm)
0	2685
124	2685
180	1000
190	675
195	0

SBLOCA CFT Line Break[3 & 5]

ΔP (P_{RCS} - P_{RB}) (psid)	Total Flow (gpm)
0.0	1435
30.0	930
60.0	417
69.0	236
69.1	0

SBLOCA CLPD Line Breaks

Pressure (psia)	Total Flow (gpm)
14.7	2886
84.0	2886
100.0	2687
125.0	2286
150.0	1715
173.0	625
175.0	200
176.0[Note 7]	0

Notes for Table 4-3 provided on the following page.

Notes for Table 4-3:

1. The flow rates were converted from the volumetric flow rates listed to a mass flow rate using atmospheric pressure and the BWST liquid temperature of 120 F
2. The LBLOCA LPI flow rates are based on a BWST liquid inventory of 161 ft [28, Note to Table 5-5]. This liquid inventory corresponds to ~80% full BWST based on a reference elevation of 120.5 ft [28]. No credit is taken for the new LPI cross-tie modification. LPI flowrates and alignments for long-term core cooling (e.g., throttled, HPI piggyback) are discussed in [76].
3. The CFT Line Break LPI flow rates are based on a BWST liquid inventory of 131 ft [28, Note to Table 5-5]. This liquid inventory corresponds to ~20% full BWST based on a reference elevation of 120.5 ft [28].
4. The SBLOCA LPI flow rates are based on a BWST liquid level of 122.25 ft [28, Note to Table 5-5]. This liquid inventory corresponds to a minimum BWST inventory based on a reference elevation of 120.5 ft [28].
5. The basis pressure for determining the delta pressures is a reactor building pressure of 43 psia. The delta pressures are appropriate for 43 psi or lower [28, Note to Table 5-5].
6. The LPI flow rates that were utilized in the LBLOCA analyses (Table 4-3) do not consider the LPI cross-tie modification. The LPI flow rates for the final LPI cross-tie design are included in Table A-2 of Reference [68]. The effect of the higher LPI flows with the cross-tie design was considered in Reference [68] and it was concluded that the LBLOCA analyses summarized in Reference [2] that utilized LPI flow rates included in Table 4-3 continues to remain appropriate for the CR-3 EPU.
7. The LPI flow rate was ramped to zero at a pressure of 176 psia in the SBLOCA analyses [3].

Table 4-4: SCRAM Curve

Time (sec)	Reactivity		
	%	%Δk/k	$
0.0	0.0	0.00000	0.0000
0.2	0.58	-0.02610	-0.0368
0.3	0.99	-0.04455	-0.0627
0.4	1.83	-0.08235	-0.1160
0.6	5.29	-0.23805	-0.3352
0.8	12.33	-0.55485	-0.7813
1.0	21.41	-0.96345	-1.3566
1.2	33.09	-1.48905	-2.0967
1.4	50.75	-2.28375	-3.2156
1.6	72.96	-3.28320	-4.6229
1.8	91.30	-4.10850	-5.7850
2.0	99.26	-4.46670	-6.2894
2.2	99.99	-4.49955	-6.3356
2.3	100.0	-4.50000	-6.3362

Note: The reactivity in $ was obtained using a β_{eff} of 0.007102.

Table 4-5: Moderator Density Reactivity Inputs

(0 pcm/F with β_{eff} = 0.007102)

Reactivity	Density
%Δk/k	fraction
-50.0	0.0
-21.7898	0.1383
-13.9183	0.2235
-9.1373	0.3101
-5.9666	0.3966
-3.8057	0.4832
-2.3246	0.5684
-1.3163	0.6550
-0.6604	0.7416
-0.2423	0.8282
-0.0425	0.9134
-0.0027	0.9567
0.0033	0.9791
0.0	1
-0.0119	1.0321
-0.0500	1.10
-0.3000	1.20
-1.2000	1.40

Table 4-6: MSSV Setpoints and Capacities

Number of MSSVs	Setpoint (psig)	P inlet at Rated Capacity (psia) (1050 psig x 1.09 + 14.7)	Rated Capacity (lbm/hr)
2	1050	1159.2	845,759
2	1070	1159.2	845,759
2	1090	1159.2	845,759
1	1100	1159.2	583,574
1	1100	1159.2	845,759

Note: One of the lowest pressure MSSVs in each steam line is assumed to be out-of-service as specified in [28, Section 5.8.3].

Table 4-7: Operator Actions

LBLOCA	
1.	A continuous ECCS source is maintained. Operators will transfer the LPI pump suction from the BWST to the RB emergency sump as the BWST empties. The HPI pump suction will be aligned to the discharge of the LPI pumps if needed during sump recirculation phase for long-term cooling. The pumps will be throttled as necessary to preserve NPSH or manage EDG electrical loads.
2.	Appropriate boric acid concentration control is initiated and maintained to prevent precipitation or recriticality during the long-term cooling phase.
3.	For LBLOCA analyses that do not postulate LOOP (not explicitly analyzed), automatic or manual operator action to trip the RCPs within one minute of the LSCM indication is modeled.
SBLOCA	
1.	The LSCM setpoint (minimum actual level of 73 percent operate range) will be selected either automatically or by operator actions at or before 20 minutes after the LSCM. The *automatic* action is credited at 10 minutes and the *manual* action is credited at 20 minutes (Note that the automatic level reset was added after some of the SBLOCA analyses were performed with credit for manual action). At the reset point, EFW will begin raising level to 73% operate range. If EFIC is credited, it will control the fill rate as a function of pressure between 2 and 8 inches/min. If the EFIC level rate controller is not available or does not operate properly, the operators will manually assure at least a minimum EFW flow until the LSCM level is reached. Inadequate subcooling margin occurs at the approximate time of reactor trip. The level setpoint at the plant must consider appropriate instrument error and uncertainty to ensure that 73 percent operate range is protected. This level is approximately two feet above the RCP spillover elevation and ensures that a condensing surface is available before core uncovering occurs.
2.	For SBLOCA analyses that do not postulate LOOP (not explicitly analyzed), automatic or manual operator action to trip the RCPs after LSCM is modeled. The CR-3 offsite power analyses will credit pump trip at one minute after LSCM. .
3.	For scenarios where sufficient HPI flow is not obtained (e.g. more than the flow from one HPI pump but less than full flow from two HPI pumps) and FCS is available, either automatic or operator action to open the ADV in each loop is credited by 10 minutes after LSCM. Once the FCS is initiated, the ADVs will remain open until secondary side is depressurized to 350 psig and they will be modulated at the 350 psig pressure for at least 4 hours (350 psig is the uncertainty adjusted maximum value).
4.	A continuous ECCS source is maintained. Operators will transfer the LPI pump suction from the BWST to the RB emergency sump as the BWST empties. The HPI pump suction will be aligned to the discharge of the LPI pumps if needed during sump recirculation phase for long-term cooling. The pumps will be throttled as necessary to preserve NPSH or manage EDG electrical loads.
5.	Appropriate boric acid concentration control is initiated and maintained to prevent precipitation or recriticality during long-term cooling phase.

Table 4-8: LSCM Curve

Temperature (F)	Pressure (psig)
197.0	67 Note 1
276.9	100
339.4	200
377.7	300
407.2	400
431.6	500
479.4	750
516.0	1000
551.3	1300
580.4	1600
589.1	1700
597.4	1800
605.4	1900
613.0	2000 Note 2
620.3	2100 Note 2
627.3	2200 Note 2
634.0	2300 Note 2
640.5	2400 Note 2

Notes:

1. This value is maintained at the point corresponding to the instrument error corrected value for 212 F and 0 psig.
2. The polynomial fit used to develop this input only included data to 610.58 F. However, the values identified in the table are extrapolated using the same curve fit. Since the fit is well behaved, this extrapolation is appropriate

Table 4-9: Containment Inputs – LBLOCA Minimum Backpressure Analysis

Parameter	Value
Initial Containment Pressure, (psia/psig)	13.7 / -1.0
Initial Containment Temperature (F)	100
Relative Humidity (%)	100
Outside Ambient Temperature (F)	40
Containment Free Volume (ft^3)	$2.15x10^6$ Note
RB Fan Cooler Delay (s)	0
RB Spray Delay (s)	50
RB Spray Water Temperature (F)	40
RB Spray Efficiency (%)	100
Number of RB Fan Coolers	1
RB Cooler Water Temperature (F)	40
RB Spray Flow Rate per Header (gpm)	1800
Number of RB Spray Headers	2
ECCS Injection	2 x minimum ECCS train flow
RB Areas and Thicknesses	Table 4-10
RB Thermophysical Properties	Table 4-11
Heat Removal Rate per Fan Cooler (BTU/s)	$0.877632\ T^2 - 76.8666\ T + 1670.45$

Note: The nominal containment free volume and heat structure areas were increased by 5 percent to account for uncertainties. This is appropriate to ensure a conservative minimum containment pressure response for the LOCA ECCS analyses.

Table 4-10: Containment Heat Sinks for Mark-B-HTP LBLOCA Analyses

(Table 4-1 in [31], Revision 0)

Heat Structure		Surface Area (ft^2)		Material	Thickness Relative to Containment Internal Surface (ft)
'HS' number	Description	Without Uncertainty	With 5% Uncertainty Note		
1	RB Walls	63304	66470	Paint	0.00083
				Steel	0.03208
				Concrete	0.53208
				Concrete	3.53208
2	RB Dome	18138	19045	Paint	0.00083
				Steel	0.03208
				Concrete	0.53208
				Concrete	3.03208
3	RB Internal (Concrete)	105941	111239	Paint	0.00083
				Concrete	0.50083
				Concrete	1.43583
4	RB Internal Steel (Framing)	149335	156802	Paint	0.0005
				Steel	0.03172
5	RB Internal Steel (Ventilating Ductwork)	111040	116592	Paint	0.0005
				Steel	0.00349
6	RB Internal Steel (Instruments)	180	189	Paint	0.0005
				Steel	0.0153
7	RB Internal Steel (Hangers and Supporting Steel)	10000	10500	Paint	0.0005
				Steel	0.0267
8	RB Internal Steel (Pipes & Valves)	12000	12600	Paint	0.0005
				Steel	0.0238
9	RB Internal Steel (Cable Trays)	45820	48111	Paint	0.0005
				Steel	0.00675
10	RB Internal Steel (Left Over)	81442	85515	Paint	0.0005
				Steel	0.018238
11	RB Internal Stainless Steel	9361	9830	SS	0.01563
12		1475	1549	SS	0.0417
13		11000	11550	SS	0.0676
14		15500	16275	SS	0.00249
15		8732	9169	SS	0.00625

Note: The surface area for each HS has been increased by 5 percent and rounded up to account for uncertainty. This is appropriate to ensure a conservative minimum containment pressure response for the LOCA ECCS analyses.

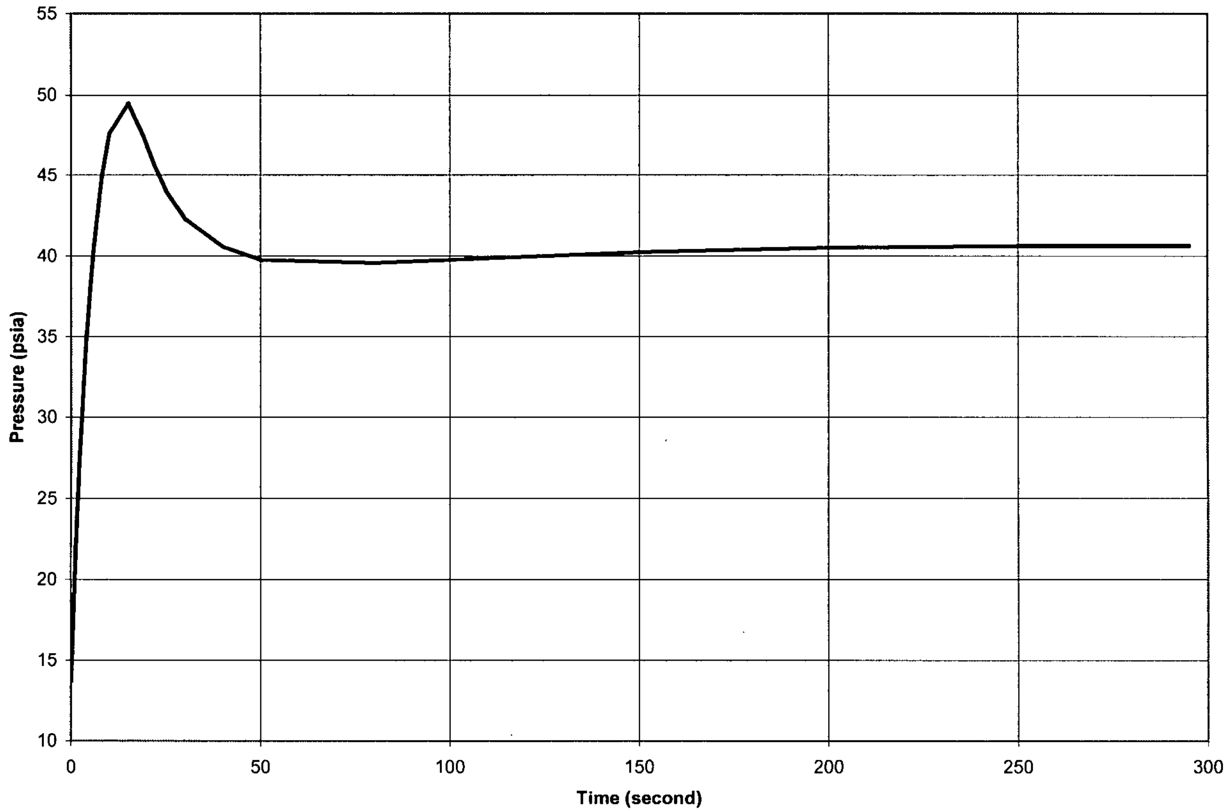
Table 4-11: Containment Heat Sink Thermophysical Properties

(Table 4-2 in [31], Revision 0)

Material		Thermal Conductivity		Heat Capacity, BTU/ft^3-F
		BTU/hr-ft-F	BTU/s-ft-F	
1	Paint (Plasite)	0.6215	0.0001726	40.42
2	Steel	27.0	0.0075	58.8
3	Concrete	0.92	0.0002556	22.62
4	Stainless Steel	9.1836	0.002551	54.263

Figure 4-1: LBLOCA Minimum Containment Pressure

(Figure 6-1 from [31], Revisions 0 & 1)



5.0 LBLOCA SENSITIVITY STUDIES AND ANALYSES

LBLOCA licensing analyses are completed with a model that is constructed based on Volume I of the NRC-approved BWNT LOCA Evaluation Model [1] and any changes required based on the information contained in Section 3.1. There are a variety of sensitivity studies that are performed to demonstrate model convergence and conservatism before the LBLOCA analyses are performed. Many of the studies are generic in nature and reported in the BWNT LOCA EM topical. Other studies are applicable to a specific plant-type (i.e., lowered-loop 177-FA plant category which includes the CR-3 plant). In some special circumstances there are plant-specific studies that are required because of unique design features of the plant. The LBLOCA sensitivity studies are presented in Section 5.1. These develop the limiting inputs that were used in the transient results that are presented in Section 5.2.

5.1 LBLOCA Sensitivity Studies

LBLOCA analyses require that various sensitivity studies be performed with the evaluation model to demonstrate model convergence and to identify the most limiting set of boundary conditions or break locations that should be used to show compliance with the five criteria in 10 CFR 50.46. As part of the LBLOCA EM [1], AREVA performed numerous LBLOCA sensitivity studies to confirm modeling techniques and methods. Although the EM was based on a slightly different plant design (205-FA RL), the safety evaluation report for BAW-10192P-A [1] supports the application of the EM to the 177-FA plants. As discussed in Section 5.1.1, AREVA has determined that the generic LBLOCA sensitivity studies performed in the EM are directly applicable to, and appropriate for use in, the CR-3 EPU analyses. As discussed in Section 5.1.2 and 5.1.3, AREVA also performed the necessary plant-type and plant-specific sensitivity studies to confirm that the most limiting set of plant boundary conditions were applied to the licensing analyses.

5.1.1 EM Generic Studies

The majority of the LBLOCA sensitivity studies presented in the EM topical report [1, Volume I] are generic and apply to any LBLOCA analysis for the B&W-designed nuclear steam system. An example is the RELAP5/MOD2-B&W time-step study, which showed that the automatic time step selection in RELAP5/MOD2-B&W would produce converged results. This demonstration need not be repeated for plant-specific applications in which the modeling techniques used are represented by those in the EM studies. The following is a listing of the sensitivity studies considered to be generic with a discussion of why the conclusions of the study are applicable to this LBLOCA applications report. For convenience, each discussion is referenced to the section in the EM topical report where the study is documented.

5.1.1.1 RELAP5/MOD2-B&W Time-Step Study

The study using the generic EM, documented in BAW-10192P-A [1], Volume I, Appendix A, Section A.2.1, verified that, for light water reactor geometry, the RELAP5 time-step controller governs the code solution sufficiently to assure convergent results. In RELAP5/MOD2-B&W, the user specifies a maximum time step that can be modified internally by the code in the event of convergence or Courant limitations. The LBLOCA EM time-step studies justified use of a 2.5-millisecond maximum time-step size for the first two seconds of the transient and a 25-milisecond maximum time-step size thereafter as appropriate for B&W-plant LBLOCA analyses. The EM controls the plant input models such that no significant deviation in the number or size of the control volumes or heat structures critical to the model results can be included between plant designs. Since the LBLOCA analytical model is similar to the model used for the EM time-step study, and the maximum time-step size in the CR-3 EPU LBLOCA analyses is the same as or less than that used in the EM time-step study, the RELAP5/MOD2 time-step controller will also adequately control the problem advancement for these applications. The EM study remains valid, therefore, and this study does not have to be repeated.

5.1.1.2 RELAP5/MOD2-B&W Pressurizer Location Study

Studies performed with the LBLOCA EM (BAW-10192P-A, Volume I, Appendix A, Section A.2.2) showed that there is little difference in results when the pressurizer is connected to the broken loop instead of the intact loop. This result is expected since the LBLOCA transient is dominated by such factors as leak flow and initial fuel stored energy. Therefore, the pressurizer location study performed with the EM is applicable to the CR-3 LBLOCA EPU analyses and need not be repeated.

5.1.1.3 RELAP5/MOD2-B&W Break Noding Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.2.3) verified that hydraulic stability is achieved by providing at least one control volume in the pipe between any adjacent component and the break node and by maintaining an L/D greater than approximately 1.5 in the break control volumes. This lower limit is suggested by the benchmarks to the Marviken Tests [32]. The calculated L/Ds for the LBLOCA model are 2.8 [2]. Therefore, the break noding study performed with the EM is applicable to the CR-3 LBLOCA analyses and need not be repeated.

5.1.1.4 RELAP5/MOD2-B&W Core Crossflow Study

Core crossflow is modeled in the base model through the use of RELAP5/MOD2-B&W crossflow junctions between the hot and average channels in the core region. This study (BAW-10192P-A, Volume I, Appendix A, Section A.2.4) verified that a crossflow K-factor of 72 in a B&W-type reactor produced converged results and is reasonable for two-channel EM applications. The results of the study were dominated by the axial core flow response to the large cold leg break and not strongly dependent on the fuel design.

For the EPU evaluation with Mark-B-HTP fuel, the EM method used the NRC-approved modeling approach for lower stored energy in the hot and average channels. The NRC approved the use of a separate heat structure with the 95/95 fuel temperature in the hot pin [13, Rev. 4] and lower stored energy elsewhere. This hot pin heat structure has a temperature uncertainty for burnups up to 40 GWd/mtU of 11.51 percent based on the TACO3 fuel code. The hot assembly, which consists of the remaining pins in the hot bundle at the hot pin peaking, has an initial volume average fuel temperature uncertainty of three percent. Finally, the average channel initial fuel volume average temperature uncertainty is reduced to zero, which is equivalent to the best estimate fuel temperature. (In the original release of the EM, all of the heat structures in the core had an initial fuel volume average temperature uncertainty of 11.51 percent.) This sensitivity study was repeated for the 177-FA LL plant (Category 1 plant defined in [1]) using the Oconee model with the Mark-B11 fuel design [33] with the modification in the core heat structures and stored energy to confirm the conclusion of the original EM was not altered.

The results of this 177-FA LL plant study demonstrated that the introduction of the three core heat structure methodology with the consequent redistribution of the initial fuel temperature uncertainties does not alter the previously observed results and stated conclusions from the EM. The study is not sensitive to fuel design used, because the LOCA dominates the core axial flow behavior. Therefore, the results can be extended to all of the Category 1 plants with the new multiple pin EM model. Since the results of this study can be applied to all Category 1 plants, it is not necessary to demonstrate these results for the CR-3 EPU LBLOCA application analyses.

5.1.1.5 RELAP5/MOD2-B&W Core Noding Study

In conjunction with the core crossflow study, this study (BAW-10192P-A, Volume I, Appendix A, Section A.2.5) verified that modeling the reactor core with two fluid channels adequately predicted the blowdown transient. The results of the study showed that the axial modeling detail used in the two channel model were of sufficient detail to adequately calculate the cladding temperature response to the LOCA transient. The results were not strongly dependent on the fuel design, and they are applicable to all plants considered by the evaluation model. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.6 RELAP5/MOD2-B&W ECCS Bypass Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.2.8) verified a non-mechanistic bypass model based on Upper Plenum Test Facility (UPTF) test results to remove the ECCS liquid injected during blowdown. This study is applicable to all plants with downcomer injection and reactor vessel vent valves. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.7 REFLOD3B Loop Noding Study

This study (BAW-10192, Volume I, Appendix A, Section A.3.1) verified the noding detail used in the REFLOD3B code. It is applicable to all plants considered by the evaluation model. A minor change from the EM noding arrangement was included in this lowered-loop noding arrangement. The intact cold legs were combined in the 205-FA RL EM model, but were separated for application of the 177 FA LL plants (shown in Figure 4-5 on page LA-133 of [1], Volume III) to accommodate a single blocked loop seal if predicted. The analyses performed for CR-3, however, did not predict any loop seal formations. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.8 REFLOD3B RCP Locked versus Free-Spinning Rotor Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.3.2) showed a considerable reduction in flooding rate under a locked-rotor condition. The study affirms the generally held understanding of loop resistance effects on reflooding rates and is applicable for all plant types covered by the evaluation model. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.9 BEACH Time Step Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.4.1) verified that the BEACH (RELAP5/MOD2-B&W) time-step controller would check and adjust time step size sufficiently to assure converged results provided the set of inputs described as the "Decreased Time Step" case on Table A-10 of BAW-10192P-A is used. In response to NRC Question 16 on the evaluation model (BAW-10192P-A, Volume III), a reanalysis of the BEACH time-step study was performed with the BEACH inlet subcooling methodology. The results of the revised study also confirm that the time-step inputs given in Table A-10 of Volume 1 of BAW-10192P-A produce converged results. Alternate plant designs within the range of designs covered by the evaluation model will not change these results. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.10 BEACH Axial Fuel Segmentation Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.4.2) verified that the use of eight fine-mesh intervals was sufficient to produce converged results. Alternate plant designs within the range of designs covered by the evaluation model will not change that result. Therefore, the study is applicable to the CR-3 EPU analyses.

5.1.1.11 Axial versus Radial Core Peaking Factor Study

This study (BAW-10192P-A, Volume I, Appendix A, Section A.5) showed that representative LOCA limits were obtained with a method that specifies a constant axial peak of 1.7 and adjusts the radial peaking factor to give the maximum allowable linear heat rate limit. Typical core power distribution analyses obtain radial and axial peaking factors similar to those used in the EM. Therefore, AREVA views this technique to be reasonable for all EM applications; however, the NRC has imposed a restriction on this method. AREVA has developed a method that considers the available LOCA margin from the core power distribution analyses and reduces the LOCA LHR limit to preserve the limiting PCT if the radial and axial peaks are not within the defined criteria based on EM sensitivity studies. See Section 7.0 for further information.

5.1.2 EM Plant-Type Studies

Although a considerable portion of the analysis inputs are set or controlled by the evaluation model and its sensitivity studies, some parameters are dependent on inputs specific to a plant type and should be established by separate studies. These studies are performed to identify a limiting case to use in calculating the LBLOCA LHR limits. This section presents the studies performed with the LBLOCA evaluation model for the 177-FA LL plant that helped to define the final plant model configuration used in the CR-3 EPU LHR limit analyses.

5.1.2.1 RELAP5/MOD2-B&W Pump Degradation Study

This study was performed as part of the generic evaluation model sensitivity studies contained in BAW-10192P-A (Volume I, Appendix A, Section A.2.6), which were based on the 205-FA RL plant design. The results established a limiting, maximum pump degradation multiplier set (M1) to be used in all EM analyses. PSC 1-99 identified that the 177-FA LL plants could produce significantly higher PCTs when a minimum two-phase pump degradation model is used (M3-modified). These mixed conclusions resulted in subsequent supporting analyses performed for the Oconee units confirming this assertion [34].

The results of the Oconee study clearly demonstrated that the minimum two-phase degradation (M3-modified curve) produces more severe results than the maximum degradation case (M1 curve). The minimum degradation multiplier reduces the resistance of the pumps in the HVN octant of the pump homologous curves. As a result, the core flow reverses direction later in the transient and produces lower core flow rates. The decrease in removal of fuel stored energy leads to higher fuel temperatures at end of blowdown than for the maximum degradation case. Furthermore, there is less liquid available for input to REFLOD3B in the lower plenum of the reactor vessel. As a result, the adiabatic heatup time will be longer resulting in a PCT increase. From these results it is concluded that for all Category 1 plants, the minimum pump two-phase degradation will produce more severe results than the maximum pump degradation. Therefore, it is not necessary to demonstrate these results for the CR-3 EPU analyses.

5.1.2.2 RELAP5/MOD2-B&W RC Pump Power Study

In the evaluation model (BAW-10192P-A, Volume I, Appendix A, Section A.2.7), this study indicated that the RCS response with the pumps powered is less severe from a core cooling perspective than the configuration with the pumps unpowered. To confirm this pump configuration for the 177-FA LL plants, a pumps-powered analysis was performed based on the Oconee units [35].

The results of the Oconee study clearly demonstrated that the pumps-tripped case produces more severe results than the pumps powered case. With the pumps powered, the core flow was more positive in the first few seconds of the blowdown because the pumps produced higher loop flows. During this first portion of blowdown, the increase in the core flow allows for removal of additional fuel stored energy, decreasing the end-of-blowdown fuel temperatures. Also, in the pumps-powered case, more liquid was available for input to REFLOD3B in the lower plenum of the reactor vessel, so the adiabatic heatup period is shorter. From these results, it is concluded that for all Category 1 plants, the pumps-tripped configuration will produce more severe results than the pumps-powered configuration. Therefore, it is not necessary to demonstrate these results for the CR-3 EPU analyses.

5.1.2.3 LBLOCA Break Spectrum Study

The 10 CFR 50, Appendix K requires that a spectrum of breaks be considered in determining the worst-case break size, configuration, and location. Results of analyses documented in the EM [1] determined that the typical worst break is a full-area double-ended guillotine (DEG) break located in the CLPD piping with a discharge coefficient (C_D) of 1.0. This break location causes a significant reduction in the core flow and fuel pin heat removal during the first third of the blowdown period. The proximity of the break to the ECCS injection location also maximizes the potential for ECCS bypass during the later stages of blowdown. These two effects result in less fuel pellet stored energy removal and an increase in the reactor vessel lower plenum refill time. To confirm these results for a 177-FA LL B&W plant, a break spectrum analysis, which considered break size, configuration, and location, was performed for the Oconee plant using the LOCA evaluation model [36].

Discharge Coefficient Analysis – The case with a C_D of 1.0 resulted in the smallest positive hot spot core flow between one and eight seconds of the blowdown phase. The smaller flow reduced the fuel pin surface heat transfer. The liquid mass remaining in the lower plenum at the end of blowdown was also a minimum for this analysis, requiring a longer refill time during which the fuel pins heat up adiabatically. The calculated hot rod PCT was produced by the ruptured cladding segment. The calculated PCTs declined with decreasing discharge coefficient and switched to an unruptured segment, directly adjacent to the ruptured location. Further reductions in the discharge coefficient would result in additional surface heat transfer that would continue to reduce the calculated PCT. Therefore, no other calculations with small discharge coefficients were warranted. These results also confirmed that the transition break sizes discussed in the LBLOCA EM did not need to be analyzed. The full-area, DEG CLPD break with a discharge coefficient of 1.0 produced the most limiting results of the discharge coefficients studied. Since the results of this study can be applied to all Category 1 plants, it is not necessary to demonstrate these results for the CR-3 EPU analyses.

Break Type Analysis - Appendix K of 10 CFR 50 requires that instantaneous double-ended guillotine and longitudinal split break configurations be considered. The guillotine break is modeled as an instantaneous severance of the pipe, allowing separate discharges through the full pipe area from each side of the break without flow interference between the two broken pipes. The split break assumes discharge from a split in the pipe through an area up to twice the cross-sectional pipe area. Because the pipe does not totally separate, flow is allowed to continue through the split pipe. The blowdown rates and system flow splits are somewhat different for the two break types, which can lead to differences in core flows and fuel pin heat removal.

Both breaks use discharge coefficients of 1.0. The split break produced higher core downflows during the later portion of blowdown, leading to better cooling and lower end-of-blowdown fuel pin and clad temperatures. The lower pin temperatures produce less boiling, decreasing the liquid carryout, such that a higher core flooding rate is obtained. Consequently, the calculated PCT for the full-area split break with a discharge coefficient of one is lower than that produced by the guillotine break.

Split breaks with smaller discharge coefficients would increase the positive core flows during the first portion of blowdown. These higher flows would improve the cladding heat removal and cause additional reductions in the calculated PCTs. Therefore, CLPD split breaks will not produce core thermal-hydraulic conditions that can result in a PCT higher than that calculated for the guillotine break with a discharge coefficient of 1.0. Since the results of this study can be applied to all Category 1 plants, it is not necessary to demonstrate these results for the CR-3 EPU analyses.

Break Location Analysis - There are three locations to consider for the large break LOCA: the hot leg piping, the cold leg pump suction piping, and the cold leg pump discharge piping. The hot leg break has been consistently shown to result in peak cladding temperatures far below those predicted for cold-leg breaks (see BAW-10192P-A, Section A.6.5). The large positive core flow and no ECCS bypass combine to provide high fuel pin heat removal for all hot leg breaks. Therefore, a hot leg LOCA analysis is not required to demonstrate that a hot leg break is not limiting for the 177-FA LL plant.

The pump suction break was analyzed to compare with the cold leg pump discharge break to determine the worst break location. The broken leg pump provided a significant resistance to flow trying to reach the break through the broken leg (RV side). The liquid was forced to reach the break via the hot legs, leading to positive core flows throughout blowdown and significantly increased hot pin heat removal. The lower pin temperatures allowed a higher core flooding rate and faster quench front advancement, and the amount of liquid remaining in the reactor vessel at EOB led to a significantly shortened adiabatic heatup time. The PCT for the pump suction break was significantly lower than that for the pump discharge break. Therefore, a break in the CLPD will produce more severe results. Since the results of this study can be applied to all Category 1 plants, it is not necessary to demonstrate these results for the CR-3 EPU analyses.

Transition Breaks - Although not considered a separate category, the LBLOCA spectrum is divided into two break ranges for the purpose of EM methods: breaks large enough to initially exceed DNB up to 2.0 ft^2 and breaks greater than 2.0 ft^2. The smaller range is analyzed using the transition LOCA method. A set of LBLOCAs at the lower end of the spectrum were analyzed to verify the larger, double-ended breaks were more limiting and to demonstrate the transition methodology. A 2.0-ft^2 CLPD analysis was performed using both the large break methodology and the transition methodology to provide a comparison of methods. Additionally, 1.5-, 1.0- and 0.75-ft^2 CLPD split breaks were analyzed using the transition methodology. The results of these analyses are provided in the LOCA EM (see Section A.6.4, Volume 1 of BAW-10192P-A). A comparison of the results show that the transition breaks are typically much less limiting than the larger break sizes in terms of the PCT consequences. The conclusions of the sensitivity study are generic and apply to CR-3 analyses at the EPU conditions with the ROTSG and Mark-B-HTP fuel design since any affect of these changes would be equally observed in the sensitivity studies.

5.1.2.4 CFT Initial Conditions Study

This study was not performed as part of the generic evaluation model sensitivity studies contained in BAW-10192P-A. A study was performed, however, for the Oconee plants to investigate which combination of CFT initial pressure and liquid inventory was most conservative for use in the LBLOCA analyses being performed with the evaluation model [37, Rev 00 and 02]. Four cases were included in the Oconee study: (1) minimum inventory with minimum pressure, (2) maximum inventory with minimum pressure, (3) maximum inventory with maximum pressure, and (4) nominal inventory with nominal pressure.

The results of the Oconee study showed that the maximum inventory with minimum pressure case produced the most conservative set of initial CFT conditions. These initial conditions combine to produce the smallest initial gas volume and mass. As the CFT empties, the nitrogen overpressure reduces more quickly, resulting in a lower CFT flow during the lower plenum refill or adiabatic heatup period. Because the PCTs at all core elevations occur within 10 seconds of Bottom of Core Recovery (BOCR), the beneficial effects of more CFT liquid on long-term reflooding rates and the clad cooling are not realized.

Two additional cases were examined in which the CFT liquid inventory was further reduced below the current minimum value for the Oconee plants. The smaller inventories were combined with maximum initial CFT pressure to investigate the potential for a significant delay between the CFTs emptying and the LPI initiating. This scenario can allow the downcomer level to drop sufficiently such that the long-term flooding rates are lower and a higher PCT occurs later in the transient. The reduced inventories investigated were 920 ft^3 and 860 ft^3. The 920-ft^3 case resulted in a delay of 16 seconds between the CFTs emptying and the initiation of LPI flow, but the PCT still occurred near the beginning of core recovery and was less than the PCT calculated for the maximum inventory/minimum pressure case. Reducing the inventory further to 860 ft^3, however, produced a delay of 18 seconds, which produced a PCT at approximately 70 seconds that approached the PCT calculated for the maximum inventory/minimum pressure case.

The results of the Oconee analyses can be directly applied to the CR-3 plant by confirming that the variation in the CFT liquid volumes and initial pressures for the CR-3 plant have been sufficiently considered in the Oconee study. The CFT initial pressure and volume variations for CR-3 and the Oconee study are almost identical. The surge-line form-loss coefficient used in the Oconee analyses was 5.70, which is less than the 6.84 value used in the CR-3 analyses. The calculated nominal value of 6.3 for CR-3 [38] also exceeds the value used in the Oconee analyses. Therefore, the Oconee study sufficiently covers the CR-3 CFT conditions, and it is not necessary to demonstrate these results for the CR-3 application analyses. It should be noted that at this time, Progress Energy has no plans to alter the CFT conditions. If Progress Energy decides to reduce the CFT nominal liquid volume for CR-3, this study may need to be reassessed specifically for CR-3.

5.1.3 EM Plant-Specific Studies

Although a considerable portion of the analysis inputs are set or controlled by the evaluation model and its sensitivity studies, some parameters are dependent on inputs specific to a plant and should be established by separate studies. These studies are performed to identify a limiting case to use in calculating the LBLOCA LHR limits. This section presents the studies performed with the LBLOCA evaluation model for CR-3 that helped to define the final plant model configuration used in the EPU LHR limit analyses.

5.1.3.1 Containment Pressure and ECCS Configuration Study

The results of Volume I, Appendix A, Section A.10 of BAW-10192P-A recommended that this study be performed for each plant classification for specific LOCA applications studies. The containment pressure is used as input to the PCT analyses, and it may be generated based on a slightly more conservative set of initial conditions. In general, the amount of ECCS may either be consistent with that modeled in the PCT calculation, or it may be specified to result in a more conservative minimum containment pressure.

LBLOCA applications frequently use a composite set of boundary conditions to cover a variety of possible system configurations based on a myriad of potential limiting single failures. For the 177-FA LL plants, the PCTs are generally predicted to occur during the CFT emptying phase and prior to the time that the pumped ECCS injection begins. Given this PCT timing, the PCT is insensitive to the minimum versus maximum pumped injection and its impact on the containment pressure. The post-PCT cooldown is dependent on the pumped injection rates and containment pressure response.

The containment pressure is minimized during the reflood phase with maximum pumped injection. Lower containment pressures create the worst steam binding and result in lower core flooding rates with no other parameter changes. The lower core flooding rates delay the whole core quench time and generally maximize the local oxidation and whole core hydrogen generation calculation during the transient. The flooding rate is also a strong function of the downcomer level. Maximum pumped injection rates generally keep the downcomer full, while a minimum pumped injection may not. If the downcomer level is not full with the minimum ECCS flow, then this condition produces the lowest flooding rates. If the downcomer is full with the minimum ECCS flow, then the maximum ECCS flow reduces the long-term core flooding rate due to the reduced manometric pressure from the increased condensation in the upper downcomer region.

For the CR-3 EPU analyses, the downcomer is not full with minimum ECCS flow. In lieu of performing multiple containment pressure analyses, the CR-3 EPU LBLOCA analyses were performed with a composite set of pumped ECCS boundary conditions. The containment pressure was minimized by using a maximum pumped ECCS flow from two ECCS trains to increase the steam binding and generate the most limiting condition for the long-term flooding rate. This containment pressure was combined with the LBLOCA PCT analyses that credited minimum pumped injection (1 LPI pump) to further decrease the flooding rate because the downcomer level was not full. This composite set of boundary conditions minimizes the number of analyses and sensitivity studies required. It also assures that the core quench time is not under predicted and the result is the most limiting local oxidation and whole core hydrogen generation rate for any consistent set of ECCS flow boundary conditions. The minimum containment pressure response [31] for the CR-3 LBLOCA analyses was generated specifically for CR-3 EPU using the CONTEMPT inputs described in Section 4.0 of this report.

5.2 LBLOCA Analyses

The LOCA analyses are performed to show compliance with 10 CFR 50.46 for the limiting core power and peaking conditions that are used to set core operational limits and trip setpoints (i.e., the LOCA limits). These LBLOCA analyses serve as the bases for the allowable local power. Numerous cases are performed to determine a curve of allowable peak LHR as a function of core elevation for all times in life of fuel operation. This curve is either contained in, or referenced by, the plant technical specifications.

5.2.1 Base Model

The results of the evaluation model and plant classification sensitivity studies define the base model configuration for the CR-3 EPU LHR limit analyses. The base model is a full double-area, guillotine break in the cold leg pump discharge piping at the elevation of the reactor vessel inlet nozzle. A discharge coefficient of 1.0 is used to maximize the break flow and the PCT. A loss of offsite power is modeled at the time of break opening, so the reactor coolant pumps and main feedwater pumps are not powered during the transient. Byron-Jackson RCPs with the appropriate homologous head flow curves are modeled. The RELAP5 two-phase head difference curves and head degradation using the M3-modified two-phase multiplier maximizes the PCT (minimizes core cooling during blowdown). Tube plugging in the steam generators is considered. Both loops contain ROTSGs that are 5 percent plugged for a plant average 5 percent tube plugging.

The non-mechanistic ECCS bypass method is used during blowdown to discard the ECCS liquid injection prior to predicting the end of bypass. The maximum time delay of 35 seconds is assumed to initiate pumped ECCS injection (LPI). For the refill and reflood system analysis, the reactor coolant pump rotors are assumed to be in a fixed position. The maximum ECCS fluid temperature is assumed to minimize the core cooling potential. Minimum (one train) ECCS with a minimum containment pressure response was used to produce more conservative local oxidation and whole-core hydrogen generation. The CFT initial conditions are set to maximum liquid inventory and minimum initial gas pressure to assure a conservative calculation of the PCT. Additional plant conditions specific to CR-3 EPU are summarized in Table 4-1.

The Mark-B-HTP LBLOCA model considers three heat structures in the core, each using the BHTP CHF correlation. As allowed by RELAP5/MOD2-B&W Revision 6 [13], a hot pin heat structure has been separated from the hot assembly heat structure with both connected to the hot assembly fluid channel. The radial and axial peaking factors used for the hot pin are identical to that used for the hot assembly. The only difference is in the fuel initial temperature uncertainty. The hot pin includes an uncertainty of 11.51 percent to the best-estimate fuel temperature from TACO3 (or GDTACO), and the hot assembly includes an uncertainty of 3 percent. Four additional hot pins are modeled in the hot assembly to represent rods with different Gadolinia weight fractions. The average channel uses the best-estimate fuel temperature. The BHTP CHF correlation is utilized for analysis of the HTP spacer grid on the Mark-B-HTP assembly, and this correlation is described in [13].

LOCA analyses performed with the BWNT LOCA EM typically consider batch fuel pin enrichments in the range of 3 to approximately 5 percent. The method of analysis bounds the fuel initial temperatures and decay heat contributions for fuel pin enrichments in this range. Bulk or batch fuel assembly enrichments lower than this range can be used, provided justification of appropriate fuel initial temperatures near BOL and bounding actinide decay contributions for both the local assembly power and the total core decay heat are included in the LOCA analyses or evaluations.

The B&W heavy actinide model utilized in the RELAP5-based LBLOCA analyses does not vary with enrichment or TIL. It was determined to be generally appropriate for enrichments between 4 and 5 weight percent ([42, Rev 00] and [43, Section 3.11.5.1]) depending on the assembly or the core average burnup. From Figure 1 in [42, Rev 00], a reduction in enrichment increases the actinide decay heat power contribution (P/Po). The increase in the actinide contribution for the lower enriched fuel assemblies is considered in the LBLOCA evaluations by calculating a LHR penalty that is applied to the LHR limits for these assemblies. The LHR penalty can be offset by calculation of the initial fuel temperature with the actual fuel enrichment. The stored energy in the fuel pellets is reduced with lower fuel enrichment since the initial fuel temperature is reduced. The reduction in initial fuel temperature at lower enrichments effectively reduces the net LHR and it generally more than compensates for the increased actinide power such that the calculated consequences produced by the high enriched fuel assembly analyses are bounding for the lower enriched fuel assemblies. These enrichment checks with any adjustments or necessary penalties are determined during each reload process on a cycle-specific basis as necessary.

5.2.2 Transient Progression

Large break loss-of-coolant accidents can be treated analytically in three separate phases: blowdown, refill, and reflood. The blowdown phase is characterized by the rapid depressurization of the reactor coolant system to a condition nearly in pressure equilibrium with its containment surroundings. Core flow is variable and dependent on the nature, size, and location of the break. Departure from nucleate boiling (DNB) is calculated to occur very quickly, and core cooling is by a film boiling process. Since film boiling accounts for only a small fraction of the core decay heat cooling, the cladding temperature increases by 600 F to 1200 F. CFT flow begins after the RCS depressurizes below the CFT fill pressure. The condensation induced by the CFT liquid accelerates the negative core flows and reduces the fuel pin temperatures during the middle blowdown period. During the last phases of blowdown, cooling is by convection to steam, and the cladding temperature begins to rise again.

Following blowdown, a period of time is required for the CFTs to refill the bottom of the reactor vessel before final core cooling can be established. During this period, core cooling is marginal, and the cladding experiences a near-adiabatic heatup. This period is designated as the refill phase. When the CFT water reaches the bottom of the core, the reflood phase begins. Core cooling is by steam generated below the rising core water level. The cladding temperature excursion is generally terminated before a particular elevation is covered by water since the steam-water mixture is sufficient to remove the relatively low decay heat power being generated at this time. A two-phase mixture eventually covers the core, and the path to long-term cooling is established through initiation of LPI near the time that the CFTs empty.

The RELAP5/MOD2-B&W code [13] calculates system thermal-hydraulics, core power generation, and the clad temperature response during blowdown. The REFLOD3B code [14] determines the length of the refill period and the core flooding rate during reflood. BEACH [15], which is the RELAP5/MOD2-B&W core model with the 2-dimensional reflood fine-mesh rezoning option activated, determines the clad temperature response during the refill and reflood period with input from REFLOD3B. The CONTEMPT code [12] is used to determine the minimum containment pressure response based on the mass and energy release from the RCS as predicted by RELAP5 and REFLOD3B. The containment pressure is developed via several iterations between the mass and energy releases and containment pressure boundary conditions with these three codes.

5.2.3 Mark-B-HTP LHR Limits

The model identified in Section 5.2.1 for the Mark-B-HTP fuel assembly was used as the base model for the CR-3 Mark-B-HTP LOCA limit analyses at the EPU power level with ROTSGs.

For analyses of the UO_2 fuel pins, five axial power peaks centered at the middle of the five grid spans (at elevations of 2.506-, 4.264-, 6.021-, 7.779-, and 9.536-ft) were analyzed with a constant axial peak of 1.7; the radial peak was adjusted to obtain an allowable LHR limit. Figure 5-1 identifies the axial power shapes analyzed. The initial fuel conditions for the desired peaking conditions are obtained from the TACO3 fuel performance code for UO_2 fuel pellets and GDTACO for the Gadolinia fuel pellets. Generally, the goal is to establish the maximum LOCA LHR limits that result in a PCT within the range of 1950 F to 2050 F. This PCT range was chosen as reasonable, given the sensitivity of the PCT to the metal-water reaction energy contributions at elevated temperatures.

Results for UO_2 fuel at all five elevations for the BOL and MOL are discussed below. Figures that demonstrate the transient results are included at the end of this section for the 2.506-ft elevation at BOL and MOL. The figures show (1) the pressure in the upper plenum during blowdown, (2) the mass flow rate through the break during blowdown, (3) the mass flow rate at the ruptured and peak unruptured locations in the hot channel during blowdown, (4) the reflooding rate, (5) the hot pin fuel and clad temperatures at the ruptured location, (6) the hot pin fuel and clad temperatures at the peak unruptured location, (7) the hot pin heat transfer coefficients at the ruptured and peak unruptured locations, and (8) the quench front advancement in the hot and average channels. These figures are representative of the results that are seen at all core elevations and times in life. The 2.506-ft elevation EOL case results are also discussed.

5.2.3.1 Beginning of Life

The BOL UO_2 hot pin initial conditions from TACO3 for each elevation are presented in Table 5-1. The results of the UO_2 BOL LOCA limit analyses are tabulated in Table 5-3. Figures 5-2 through 5-9 show the results for the BOL case with the axial peak at the 2.506-ft location. These cases are documented in [2].

The PCTs for the BOL cases are below the targeted PCT range of 1950 to 2050 F; however, the LHR limit of 17.8 kW/ft used in the analyses produces a hot spot decay heat power during the reflooding phase that is at the maximum power range for which BEACH application is approved (Appendix B of [2]). The LHR limit of 17.3 kW/ft at the 9.536-ft peak location was set to be the same as the LHR limit at the 11-ft peak location used for the SBLOCA analyses (Section 6.2.1). Given these limitations, the LHR limits cannot be increased to produce PCTs in the targeted range. The lower BOL PCTs can however be beneficial for establishing the MOL burnup. The goal is to preserve the BOL LHR limit up to the MOL burnup that pushes the MOL into the targeted range at MOL.

The BOL UO_2 and Gadolinia endpoint LHR limits (0.0- and 12.0-ft elevations) and associated PCTs are discussed in Section 5.2.5.

5.2.3.2 Middle of Life

Previous LOCA analyses have shown that BOL LHR limits can be held constant until the MOL burnup where the fuel volume-averaged temperature is roughly 100 F less than the BOL value to obtain similar PCTs at BOL and MOL. These time-in-life studies, documented in BAW-10192P-A, Volume I, Section A.7, are appropriate provided mid-blowdown rupture is not predicted. The time-in-life analyses performed for CR-3 are justified by maintaining the BOL allowable LHR limits for all core elevations at constant values up to a burnup of 40 GWd/mtU. The UO_2 hot pin initial conditions obtained from TACO3 for each elevation at MOL are shown in Table 5-1. The results of the MOL UO_2 LOCA limit analyses are tabulated in Table 5-4. Figures 5-10 through 5-17 show the results for the MOL case at 2.506-ft location. These cases are documented in [2].

The PCTs for the MOL cases are near the lower end of the targeted PCT range of 1950 to 2050 F. The MOL burnup could not be extended to a higher TIL because additional burnup would have resulted in fuel temperatures and pin pressures that would have produced PCTs above the targeted range.

The MOL UO_2 and Gadolinia endpoint LHR limits (0.0- and 12.0-ft elevations) and associated PCTs are discussed in Section 5.2.5.

5.2.3.3 End of Life

At EOL, the UO_2 LHR limits are established based on TACO3 fuel pin initializations that keep the pin pressure below the licensing above system pressure (LASP) limit. The EOL LOCA LHR that preserves the LASP limit is typically much lower than the MOL LHR limits. Therefore, the initial fuel temperature and analyzed PCT is much lower than the BOL or MOL values. The results are not PCT limited.

The EOL UO_2 LOCA limits results are tabulated in Table 5-5 and confirm that the EOL analysis is not PCT-limited. The EOL UO_2 LHR limits were held constant for all elevations. Unlike the BOL and MOL UO_2 0.0- and 12.0-ft elevations, which reduce the endpoint LHR limits and keep the PCTs the same as the adjacent elevations, a PCT increase of 70 F was added to the adjacent elevations and then applied to the endpoints as discussed in more detail in Section 5.2.5. The remaining elevations, 4.264- through 9.536-ft, had PCT estimates based on the PCT trends observed among the elevations at BOL and MOL.

The LHR limits after 40 GWd/mtU include increased uncertainty factors on the fuel volume-average temperature to account for decreases in the fuel thermal conductivity as discussed in Section 5.2.7.2. For the EOL (62 GWd/mtU) case, the uncertainty factor used was 1.1811 for the hot pin and 1.096 for the hot assembly (Reference [2]).

5.2.3.4 Gadolinia

The fuel cycle designers frequently use a small number of Gadolinia doped-fuel pins for plants with longer cycle lengths to control the assembly pin peaks. These Gadolinia fuel pins are distributed within the assembly that remains primarily UO_2 fuel pins. The Gadolinia fuel pin geometries are effectively identical to the UO_2 fuel pins, however, some of the fuel properties remain different. Therefore, a subset of LOCA analyses are performed to develop the allowed Gadolinia LOCA LHR limits for use in the core power peaking analyses with these pins and to assure that these pins remain within the 10 CFR 50.46 acceptance criteria.

Four separate Gadolinia concentrations (3-, 4-, 6- and 8-w/o) were analyzed at the 2.506-ft axial power peak location for all TIL with a constant axial peak of 1.7 for the Mark-B-HTP fuel design. The Gadolinia fuel has a slightly lower thermal conductivity and volumetric heat capacity versus that of UO_2. These small property differences are accounted for by reducing the LHR limits for the Gadolinia fuel to keep the calculated results for Gadolinia fuel pins similar to UO_2 results.

The LBLOCA LHR limit analyses modeled four Gadolinia hot pins in the UO_2 hot bundle LOCA model with the 2.506-ft elevation axial peak of 1.7. The initial fuel conditions for the Gadolinia fuel were determined by the GDTACO fuel performance code. The Gadolinia pin initial conditions for each weight percent are presented in Table 5-2. The results for the 3-, 4-, 6-, and 8-w/o Gadolinia analyses for all TIL performed at the 2.506-ft elevation are presented in Table 5-6, Table 5-7, Table 5-8, and Table 5-9, respectively. These cases are documented in [2].

Analyses that considered Gadolinia fuel pins were not explicitly performed for the other core elevations because of the similarities between the UO_2 and Gadolinia fuel. The analyses show that the LHR limit reductions for the Gadolinia fuel compensates for the small property differences at the 2.506-ft axial peak and the similar results are expected at the other core axial elevations. The core inlet power shape was used for the Gadolinia confirmation cases because the LOCA core inlet axial peaks are generally the only ones that could set the core operating limits for fuel cycle operation. LOCA LHRs are checked in the core power distribution analyses, but they are generally not limiting at any other core axial elevations.

The Gadolinia LHR limits for all TIL were obtained by multiplying the UO_2 LHR limits at that TIL by the Gd-to-UO_2 ratio used in the 2.506-ft analyses. The analyses showed that this reduction in the LHR compensates for the thermal conductivity and volumetric heat capacity property differences. The PCT differences between the Gadolinia and the UO_2 fuel predicted by the 2.506-ft at BOL was applied to the UO_2 PCTs at all other elevations to establish estimated Gadolinia BOL PCTs for every elevation. A similar technique was used for the MOL Gadolinia limit with the MOL specific Gd-to-UO_2 LHR limit ratio and PCT difference applied to establish the MOL limits and results.

At BOL and MOL for Gadolinia concentrations, the differences between the UO_2 and each analyzed Gadolinia concentration at the 2.506-ft elevation is used with the corresponding UO_2 results at the other axial peaks to establish the Gadolinia results for the unanalyzed elevations. The UO_2 LHR limits are generally multiplied by the Gd-to-UO_2 LHR ratios to set the Gadolinia LHR limits. These differences in the analyzed Gadolinia and UO_2 PCTs are added to the UO_2 PCTs for all other core elevations to develop the Gadolinia PCTs. The analyzed and estimated Gadolinia LHR limits and PCTs are given in Tables 2-4 through 2-7. It should be noted that typically the Gadolinia LHR limits were both reduced by 0.3 kW/ft to keep the estimated PCTs for the Gadolinia pins at the MOL less than the analyzed values of the UO_2 fuel.

At EOL, the Gadolinia LHR limits are established based on consideration of the Gd-to-UO_2 LHR limit ratios and fuel pin initializations that keep the pin pressure below the LASP limit. Since the EOL LOCA LHR is typically limited in terms of the pin pressure instead of the PCT, this method maintains substantially lower PCTs for both the UO_2 and Gadolinia pins. In addition, Gadolinia LHR limits after 40 GWd/mtU include increased uncertainty factors on the fuel volume-average temperature to account for decreases in the fuel thermal conductivity as discussed in Section 5.2.7.2. For the EOL (62 GWd/mtU) case, the uncertainty factor used was 1.1811 for the Gadolinia pins (Reference [2])

The Gadolinia LHR limits at EOL were maintained constant for all of the remaining elevations. The EOL Gadolinia PCT estimates were determined by applying the same PCT delta added to the remaining UO_2 EOL elevations.

5.2.4 Partial-Power LHR Limits

Core power distribution analyses are performed at different core power levels for plant operation with four RCPs and also with three RCPs in operation. The LOCA analyses must establish LHR limits to support these power distribution analyses. In addition, the LOCA analyses need to confirm that the calculated LOCA consequences at 100 percent full power is bounding for all other power levels for both three and four RCP operation. At partial power levels, the goal is to maintain the full power LHR limit for all core power levels above 50-percent full power. By preserving the full power LHR limit, the allowable peaking margins are increased in inverse proportion to the power level. The main challenge to maintaining a bounding PCT at the full power LHR limit is related to increases in the moderator temperature coefficient as power level decreases.

Various three and four RCP LBLOCA analyses are performed with the 100 percent full-power LHR limit to determine the maximum allowable MTC as a function of core power that preserves the PCT calculated for the 100 percent full-power cases.

Three power levels (nominal levels of 86.51, 80, and 50 percent of the full power plus 0.4 % uncertainty of the uprated power of 3014 MWt) were analyzed for four RC pump operation with appropriate MTC curves determined in the analyses [56]. The MTC curves used for each analysis were 0, +1, and +5 pcm/F for the nominal 86.51, 80, and 50 percent of the full power, respectively. The results of the study demonstrated that the calculated PCT for the 100 percent full-power case would bound the partial-power operation with the allowed MTC. Figure 2-6 presents the allowable MTC as a function of percent full power with the key condition of preserving the full power LHR limit.

A study was also performed in [55] with three operating RCPs at 80 percent full power with an MTC curve of +1 pcm/F. The inoperative pump was modeled in the broken cold leg to maximize the calculated PCT for this mode of operation based on the results of Section A.8. of [1]. The results of the study showed that the calculated PCTs for the most limiting three-pump case would be bounded by the four-pump operation 100 percent full-power case.

5.2.5 Core-Wide LHR Limits

LHR limits at elevations between the 2.506-ft and the 9.536-ft elevation can be determined by linear interpolation using the five LBLOCA elevations analyzed at BOL and MOL. A sensitivity study was performed to establish the LHR limits below the 2.506-ft core elevation and above the 9.536-ft elevation [37, Revision 01]. The conclusion of that study determined that the allowable LHR at bottom of the core can be calculated as 95 percent of the LHR at the 2.506-ft elevation and the allowable LHR at the top of the core can be calculated as 95 percent of the 9.536-ft elevation to preserve a PCT bounded by the respective analyzed cases. The 95 percent extrapolated limits are not dependent on the fuel type, because any core flow effects resulting from differing pin dimensions are already included in the 2.506- and 9.536-ft analyses on which the inlet and outlet limits are based. It is applicable to both UO_2 and Gadolinia fuel pins. Changes to the core power level and/or SG design are included in the 2.506- and 9.536-ft analyses and would similarly translate to the core inlet and outlet limits. Additionally, the flow effects resulting from changes in assembly dimensions are uniform and not typically elevation dependent.

The EOL limits are held constant for all elevations, thus a PCT increase is applied to the 0.0- and 12.0-ft elevations.

5.2.6 EOC T_{ave} Reduction Maneuver

The LBLOCA analyses are performed at full power and partial power with a nominal RCS average temperature (T_{ave}) of 582 F plus or minus 2 F. The plant is allowed to reduce the RCS average temperature at the end of the cycle to extend the period at which full power can be maintained. When the average temperature is decreased, the blowdown core flows and RCS pressure response are slightly changed and this can adversely affect the DNB timing and fuel pin heat removal during the blowdown phase. Use of a negative moderator temperature coefficient corresponding to extensive time in cycle operation can be used to compensate for these adverse core cooling consequences at the reduced T_{ave}.

An analysis was performed to assess the conditions under which an end of cycle (EOC) T_{ave} reduction maneuver could be performed [39]. The EOC reduction in T_{ave} LBLOCA analyses was completed specifically for CR-3 at the EPU core power level at the 2.506-ft elevation with an RCS average temperature of 570 F, which is the nominal RCS Tave of 582 F reduced by 12 F (including uncertainties). With a moderator temperature coefficient profile that was 10 pcm/F lower than the 0 pcm/F MTC analyzed value (i.e., –10 pcm/F), the results show that the fuel and clad at or near the peak power elevation are lower in temperature than for the nominal T_{ave} analysis. This produces a lower PCT for the reduced T_{ave} analysis. In the event that an EOC T_{ave} reduction maneuver is planned, operation at a reduced T_{ave} at the end of a cycle with a MTC of no greater than -10 pcm/F is bounded by operation at a zero MTC with a nominal T_{ave}.

5.2.7 Discussion of LBLOCA EM Inputs and Changes

Several items affecting generic LBLOCA analysis inputs and methods have been addressed and incorporated in the current analyses consistent with the methodology described in Section 3.0. These changes are characterized as either input changes consistent with the EM, new reload licensing checks to confirm the EM analyses are applicable, or EM changes made to remain in compliance with 10 CFR 50 Appendix K. Each of these items is applied consistent with what is included and described in BAW-10192P, Rev. 02 [70]. Input changes consist of use of more conservative steady state and transient energy deposition factors (EDFs) as described in Section 5.2.7.1. The new reload licensing checks relate to the fuel thermal conductivity decrease as a function of burnup and actinide decay heat are discussed in Sections 5.2.7.2 and 5.2.7.3, respectively. This includes provision for LHR limit changes related to fuel pin enrichments outside the normal range of 3 to 5 percent as discussed in Section 5.2.7.3. Discussion of changes incorporated to address preliminary safety concerns (PSCs) to ensure the results are in compliance with 10 CFR 50 Appendix K are discussed in Section 5.2.7.4.

5.2.7.1 Energy Deposition Factors

The energy deposition factor is defined as the energy absorbed (thermal source) in the fuel pellet and clad divided by the energy produced by the pellet (nuclear source).

$$EDF = P_{thermal\ source} / P_{nuclear\ source}$$

The BWNT LOCA evaluation model reports that an EDF of 0.973 will be used for the steady-state initialization and during the blowdown portion of the transient, and an EDF of 0.96 will be used during reflood for LBLOCA analyses. New methods and predictions for the EDFs appropriate for use in LOCA analyses at various times in life have been evaluated by AREVA [40]. These calculations do not support the 0.973 steady-state EDF values for high burnup, low power fuel or fuel that may be surrounded by higher power fuel. As a result, the LOCA evaluations may use higher EDFs, depending on the time in life and allowed LHR limits. The LOCA transient EDF values of 0.973 and 0.96 are not supported for some transient applications. The transient EDF is increased for most LOCA applications and in some cases it may exceed a value of 1.0.

The steady-state and transient EDF values for the CR-3 EPU LBLOCA analyses were calculated using the methods described in [40]. The values used are included on the results tables. It is important to note that the RELAP5-based LOCA LHR limits are reported based on nuclear source power and the EDF is accounted for in the LOCA EM transient calculations. Therefore, the LHR limits provided in Section 2.0 represent the total power generated by the fuel pin (i.e., represent the nuclear source).

In the core maneuvering analyses, the LOCA LHR limit should be greater than or equal to the LHR calculated at the limits of normal operation in the peaking analysis.

$$LHR_{LOCA} \geq LHR_{peaking\ analysis} = Fq_{peak} * F_{aug} * LHR_{ave}$$

where Fq_{peak} is the product of the axial peak and the radial peak, F_{aug} is the product of all augmentation factors (including committed LOCA target margin), and LHR_{ave} is the core average LHR as calculated by

$$LHR_{ave} = [(P_{rated} * FOP) / (N_{pin} * N_{assy} * L_{fuel})] * EDF.$$

In this equation P_{rated} is the 100 percent rated power, FOP is fraction of the core power (including uncertainty), N_{pin} is the number of fuel pins in an assembly, N_{assy} is the number of fuel assemblies in the core, L_{fuel} is the length of the active fuel, and EDF is the energy deposition factor. The LHR_{ave} (and hence the LHR in the peaking analysis) is in terms of the energy produced ($P_{nuclear\ source}$) when the EDF is not applied (or EDF = 1.0).

The LHR limits are reported in this document in terms of energy generated by the pin (nuclear source). As long as the limits are defined this way, an EDF would not be used in calculating the core average linear heat rate that is used in a peaking margin calculation to convert the peak calculated by the nuclear design code to a calculated LHR. Therefore, the maneuvering analysis should set the EDF to 1.0 for an appropriate calculation of margin to the reported LOCA LHR limits.

5.2.7.2 Burnup Fuel Thermal Conductivity

The NRC-approved fuel performance codes [11 and 17] use a conductivity model that varies only with temperature and not with burnup. SIMFUEL data has been used to adjust the fuel temperature uncertainty factor to demonstrate that the effect of fuel thermal conductivity decreases with extended burnup [41] is accounted for in the applications. The TACO3 and GDTACO fuel models are based on a beginning-of-life fuel thermal conductivity curve. In the evaluation of Condition Report WebCAP 2009-4152, which is related to NRC Information Notice 2009-23, AREVA confirmed that the method of LOCA initialization (e.g., bounding power histories and 1000 GWd/mtU hold at LOCA power peaks) and use of increased fuel volume-average temperatures at high burnups provide appropriate to conservative inputs for use in LOCA analyses. Justification for not using a variable thermal conductivity versus burnup model in TACO3 and GDTACO is supported by high power fuel pin benchmarks and the increases in the fuel volume-average temperature uncertainty factor for pin burnups exceeding 40 GWd/mtU. The NRC, as discussed in the technical evaluation report (TER), has approved this method for BAW-10186 [41]. The value of the increased uncertainty factors used in the LHR calculations at burnups greater than 40 GWd/mtU are discussed in Section 5.2.3.3 and 5.2.3.4 for the EOL analyses for UO_2 and Gadolinia fuel. The CR-3 EPU LBLOCA analyses were completed prior to the origin of WebCAP 2009-4152. Since the time the WebCAP was closed, some reload analyses have included an additional 0.5 kW/ft penalty to the analyzed EOL pin pressure-limited LHR limits as additional assurance that the degraded thermal conductivity with burnup is adequately accounted for in the LOCA applications. If this penalty is applied, it is included in the core reload analysis process.

5.2.7.3 Actinide Decay Heat for Low Enrichment

LOCA analyses performed with the BWNT LOCA EM typically consider batch fuel pin enrichments in the range of 3 to approximately 5 percent for the fuel volume average temperatures. This method of analysis bounds the fuel initial temperatures for fuel pin enrichments in this range. The actinide decay heat contribution is also a function of fuel pin enrichments. The average core bulk or batch fuel assembly enrichments have a smaller range of burnup and core average enrichment than the hot pin values considered. The BOC average core burnup are generally in the 10 to 15 GWd/mtU range while the EOC burnup range from 35 to 40 GWd/mtU. The B&W heavy actinide model utilized in the RELAP5-based LBLOCA analyses bounds the actinide contributions over this burnup range at the average core enrichments. The CR-3 cycles are two-year cycles and they have higher fuel enrichments than the 18 month cycle plants. The PCT-limited cases at BOL or MOL are evaluated based on the hot pin local actinide power to ensure the B&W heavy actinide model is conservative to bounding for both the hot pin powers and the total core decay heat are included in the LOCA analyses or evaluations.

The B&W heavy actinide model utilized in the RELAP5-based LBLOCA analyses does not vary with enrichment or TIL. It was determined to be generally appropriate for enrichments between 4 and 5 weight percent ([42, Rev 00] and [43, Section 3.11.5.1]) depending on the assembly or the core average burnup. From Figure 1 in [42, Rev 00], a reduction in enrichment increases the actinide decay heat power contribution (P/Po). The increase in the actinide contribution for the lower enriched fuel assemblies is considered in the LBLOCA evaluations by calculating a LHR penalty that is applied to the LHR limits for these assemblies. At MOL or EOL, the LHR penalty can be offset by using the reduction in the initial fuel pin temperatures with lower fuel enrichments. For LBLOCA, the fuel temperature more than compensates for the increased actinide power such that the calculated consequences produced by the high enriched fuel assembly analyses are bounding for the lower enriched fuel assemblies. During the evaluation process, any necessary penalties will be determined on a cycle-specific basis and applied to the LHR limits as necessary.

5.2.7.4 Preliminary Safety Concerns

Since the EM described in BAW-10192P-A has been approved, a number of PSCs have been generated. The results of these PSCs have been incorporated into the LOCA analyses to ensure the LOCA results include the considerations in 10 CFR 50 Appendix K. This section summarizes the LBLOCA PSCs and indicates how they have been used to change the inputs or methods of analyses with respect to the CR-3 specific LOCA analyses.

PSC 4-94 – MTC for Partial Power Operation

Interpretation of the B&W plant Tech Specs on MTC versus power level can lead to the conclusion that a +9 pcm/F MTC is allowable at power levels below 95 percent. This interpretation led to the initiation of PSC 4-94. As a result of this PSC, an MTC versus power level curve has been provided to the B&W plants (Figure 2-6), which shows the conditions under which the full power LOCA analyses remain limiting. A discussion of these studies for CR-3 is presented in Section 5.2.4.

PSC 5-94 Uncertainties on CFT and PZR

The EM allows the initial Core Flood Tank and Pressurizer inventories and pressures to be set by nominal operation design levels. The PZR has active methods to control to the nominal value, therefore maintaining a nominal level for analyses is appropriate. However, the CFT does not have an active method for controlling to nominal conditions. PSC 5-94 identified that the CFT initial conditions would affect the transient results as applied to the CRAFT2-based evaluation model. Therefore, the B&W plant analyses performed with the RELAP5-based evaluation model also evaluated the combination of minimum and maximum CFT initial liquid volumes and gas pressures for each plant type. A discussion of these studies for CR-3 is presented in Section 5.1.2.4.

PSC 1-99 – Two Phase RCP Degradation (M1 versus M3)

The EM states that the "M1" two-phase degradation multiplier is used for LBLOCAs. This was determined based on sensitivity studies related to the 205-FA RL plant type. Similar sensitivity studies on the 177-FA LL and 177-FA RL plants show that the M3-modified curve provides limiting results. The NRC was notified that the limiting curve would be used based on plant-type specific sensitivity studies. A discussion of these studies for CR-3 is presented in Section 5.1.2.1.

PSC 2-98 – Design LOCA Loads for OTSG Tube Repair Products

This PSC only pertained to the original OTSGs, not the ROTSGs. Since the OTSGs have been replaced this concern is no longer applicable. The challenges to the steam generator tube integrity following a hot leg U-bend

LOCA have been ensured by Progress Energy and B&W Canada. References [44] and [46] comprise the proprietary justifications used for this purpose.

Table 5-1: Mark-B-HTP UO_2 Hot Pin Initial Conditions Used for the LOCA LHR Limit Analyses

Parameter	2.506 ft	4.264 ft	6.021 ft	7.779 ft	9.536 ft
BOL Initial Conditions					
Peak LHR, kW/ft (Note)	17.8	17.8	17.8	17.8	17.3
Pin Pressure, psia	681	680	678	676	669.
Peak Fuel Temperature, F	2424	2437	2440	2439	2393
Inside Oxide Thickness, ft	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}
Outside Oxide Thickness, ft	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}
MOL Initial Conditions					
Peak LHR, kW/ft (Note)	17.8	17.8	17.8	17.8	17.3
Pin Pressure, psia	2304	2323	2326	2319	2311
Peak Fuel Temperature, F	2382	2409	2390	2389	2334
Inside Oxide Thickness, ft	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}
Outside Oxide Thickness, ft	6.61×10^{-6}	6.61×10^{-6}	6.61×10^{-6}	6.61×10^{-6}	6.61×10^{-6}
EOL Initial Conditions					
Peak LHR, kW/ft (Note)	13.4	N/A	N/A	N/A	N/A
Pin Pressure, psia	2972				
Peak Fuel Temperature, F	2061				
Inside Oxide Thickness, ft	2.35×10^{-5}				
Outside Oxide Thickness, ft	1.16×10^{-5}				

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source).

Table 5-2: Mark-B-HTP Gadolinia Initial Conditions Used for the LOCA LHR Limit Analyses

Parameter	2.506 ft	2.506 ft	2.506 ft	2.506 ft	2.506 ft
BOL Initial Conditions	UO_2	3 w%	4 w%	6 w%	8 w%
Peak LHR, kW/ft (Note)	17.8	16.5	16.1	15.6	15.1
Pin Pressure, psia	681	674	674	673	673
Peak Fuel Temperature, F	2424	2381	2393	2411	2433
Inside Oxide Thickness, ft	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}	9.15×10^{-7}
Outside Oxide Thickness, ft	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}	7.59×10^{-7}
MOL Initial Conditions	UO_2	3 w%	4 w%	6 w%	8 w%
Peak LHR, kW/ft (Note)	17.8	16.2	15.8	15.6	15.1
Pin Pressure, psia	2304	2285	2279	2198	2146
Peak Fuel Temperature, F	2382	2328	2331	2357	2355
Inside Oxide Thickness, ft	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.74×10^{-5}
Outside Oxide Thickness, ft	6.61×10^{-6}	7.39×10^{-6}	7.86×10^{-6}	8.73×10^{-6}	8.05×10^{-6}
EOL Initial Conditions	UO_2	3 w%	4 w%	6 w%	8 w%
Peak LHR, kW/ft (Note)	13.4	12.1	11.7	11.7	11.3
Pin Pressure, psia	2972	2681	2605	2349	2541
Peak Fuel Temperature, F	2061	2003	1990	2030	2063
Inside Oxide Thickness, ft	2.35×10^{-5}	3.26×10^{-5}	3.53×10^{-5}	4.51×10^{-5}	3.94×10^{-5}
Outside Oxide Thickness, ft	1.16×10^{-5}	1.33×10^{-5}	1.38×10^{-5}	1.57×10^{-5}	1.46×10^{-5}

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source).

Table 5-3: CR-3 Mark-B-HTP UO_2 BOL LOCA LHR Limits Summary

Parameter	2.506 ft		4.264 ft		6.021 ft		7.779 ft		9.536 ft	
Peak LHR[Note], kW/ft	17.8		17.8		17.8		17.8		17.3	
End of Bypass, s	21.1		21.1		21.0		21.0		21.0	
End of Blowdown (EOB), s	23.2		23.2		23.1		23.1		23.3	
Liquid Mass in RV Lower Plenum at EOB, lbm	17029		17593		17033		17809		19275	
RV Lower Plenum Filled (EOAH), s	30.4		30.3		30.3		30.1		30.0	
LPI Flow Begins, s	35.1		35.1		35.1		35.1		35.1	
CFTs Empty, s	48.4		48.4		48.4		48.3		48.2	
	<u>*HP*</u>	<u>*HA*</u>	<u>*HP*</u>	<u>*HA*</u>	<u>*HP*</u>	<u>*HA*</u>	<u>*HP*</u>	<u>*HA*</u>	<u>*HP*</u>	<u>*HA*</u>
Clad Rupture Time, s	23.8	26.1	24.1	26.5	25.5	28.3	25.8	28.7	26.8	29.5
Unruptured Segment	6	6	10	10	13	13	16	16	17	16
PCT, F	1819.3	1748.3	1853.0	1788.1	**1850.6**	1779.1	**1883.0**	1819.6	1839.3	1809.9
Time, s	30.9	36.3	35.9	38.8	38.1	40.9	39.9	40.0	37.1	82.4
Local Oxidation, %	0.908	0.738	1.317	1.140	1.389	1.225	1.460	1.293	1.348	1.540
Ruptured Segment	7	7	9	9	12	12	15	15	18	18
PCT, F	**1883.9**	1760.2	**1879.7**	1756.6	1818.2	1714.8	1869.9	1758.0	**1863.0**	1753.3
Time, s	30.9	30.9	30.8	30.8	30.8	30.8	37.4	37.5	37.1	37.1
Local Oxidation, %	1.713	1.157	1.862	1.269	1.835	1.282	2.082	1.427	1.843	1.322
Average Oxidation Increase, %										
Hot Channel	0.308		0.348		0.344		0.372		0.351	
Average Channel	0.013		0.019		0.026		0.030		0.034	
Whole-Core Hydrogen Generation, %	<0.13		<0.15		< 0.15		< 0.16		< 0.16	
Average Channel Quench Time, s	191.6		197.9		207.0		210.8		213.8	

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). A steady-state EDF of 0.973 and transient EDF of 1.0 were used for these cases. The bolded values represent the maximum PCT at <u>each elevation</u>, for either ruptured or unruptured segment.

Table 5-4: CR-3 Mark-B-HTP UO_2 MOL LOCA LHR Limits Summary

Parameter	2.506 ft		4.264 ft		6.021 ft		7.779 ft		9.536 ft	
Burnup, GWd/mtU	40		40		40		40		40	
Peak LHR(Note), kW/ft	17.8		17.8		17.8		17.8		17.3	
End of Bypass, s	21.2		21.1		21.0		21.0		21.0	
End of Blowdown (EOB), s	23.2		23.2		23.1		23.1		23.3	
Liquid Mass in RV Lower Plenum at EOB, lbm	17282		17558		16887		17773		19158	
RV Lower Plenum Filled (EOAH), s	30.4		30.3		30.3		30.1		30.0	
LPI Flow Begins, s	35.1		35.1		35.0		35.1		35.1	
CFTs Empty, s	48.5		48.4		48.4		48.3		48.2	
	HP	*HA*	*HP*	*HA*	*HP*	*HA*	*HP*	*HA*	*HP*	*HA*
Clad Rupture Time, s	20.1	20.9	20.3	21.3	21.4	22.9	22.3	24.0	23.5	24.5
Unruptured Segment	6	8	10	10	12	13	16	16	17	16
PCT, F	1902.6	1778.1	1933.2	1837.1	**1921.2**	1798.4	**1947.2**	1808.1	1851.2	1773.7
Time, s	30.8	35.9	38.0	38.0	37.7	40.4	37.2	37.3	39.1	77.4
Local Oxidation, %	1.816	1.628	2.215	1.906	2.335	2.050	2.232	1.908	1.972	2.126
Ruptured Segment	7	7	9	9	11	11	15	15	18	18
PCT, F	**1942.3**	1753.2	**1934.3**	1738.6	1790.5	1670.6	1905.9	1727.0	**1869.3**	1710.7
Time, s	33.2	33.2	32.9	32.9	34.9	35.0	37.2	37.3	39.3	39.3
Local Oxidation, %	2.562	1.767	2.769	1.841	2.044	1.633	2.351	1.735	2.292	1.714
Average Oxidation Increase, %										
Hot Channel	0.175		0.209		0.218		0.200		0.193	
Average Channel	0.013		0.019		0.026		0.030		0.034	
Whole-Core Hydrogen Generation, %	< 0.08		< 0.09		< 0.1		< 0.1		< 0.1	
Average Channel Quench Time, s	191.7		199.3		207.0		210.9		213.8	

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). A steady-state EDF of 0.973 and transient EDF of 1.0 were used for these cases. The bolded values represent the maximum PCT at each elevation, for either ruptured or unruptured segment.

Table 5-5: CR-3 Mark-B-HTP UO_2 EOL LOCA LHR Limits Summary

Parameter	2.506 ft	
Burnup, GWd/mtU	62	
Peak LHR(Note), kW/ft	13.4	
End of Bypass, s	21.1	
End of Blowdown (EOB), s	23.2	
Liquid Mass in RV Lower Plenum at EOB, lbm	16952	
RV Lower Plenum Filled (EOAH), s	30.4	
LPI Flow Begins, s	35.1	
CFTs Empty, s	48.4	
	HP	*HA*
Clad Rupture Time, s	24.4	25.7
Unruptured Segment	7	7
PCT, F	1592.5	1535.8
Time, s	35.6	35.6
Local Oxidation, %	1.754	1.719
Ruptured Segment	6	6
PCT, F	**1602.4**	1543.7
Time, s	30.8	30.8
Local Oxidation, %	1.847	1.775
Average Oxidation Increase, %		
Hot Channel	0.036	
Average Channel	0.013	
Whole-Core Hydrogen Generation, %	<0.03	
Average Channel Quench Time, s	192.7	

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). A steady-state EDF of 0.987 and transient EDF of 1.062 were used for this case. The bolded values represent the maximum PCT at this elevation, for either ruptured or unruptured segment.

Table 5-6: CR-3 Mark-B-HTP 3-w/o Gadolinia LOCA LHR Limits Summary

Parameter	BOL	MOL	EOL
Burnup, GWd/mtU	0	40	62
Peak LHR(Note), kW/ft	16.5	16.2	12.1
Axial Peak Elevation, ft	2.506	2.506	2.506
Steady-State EDF	0.973	0.973	0.984
Transient EDF	1.03	1.03	1.09
Peak Initial Fuel Temperature, F	2381	2328	2003
Initial Pin Pressure, psia	674	2285	2681
End of Bypass, s	21.1	21.2	21.1
End of Blowdown (EOB), s	23.2	23.2	23.2
Liquid Mass in RV Lower Plenum at EOB, lbm	17029	17282	16952
RV Lower Plenum Filled (EOAH), s	30.4	30.4	30.4
LPI Flow Begins, s	35.1	35.11	35.1
CFTs Empty, s	48.4	48.5	48.4
Clad Rupture Time, s	24.9	20.8	26.9
Unruptured Segment	6	8	7
PCT, F	1778.9	1847.2	**1551.4**
Time, s	30.9	33.2	33.0
Local Oxidation, %	0.790	1.741	2.234
Ruptured Segment	7	7	6
PCT, F	**1832.4**	**1855.0**	1546.0
Time, s	30.9	33.1	30.8
Local Oxidation, %	1.435	2.103	2.278
Average Channel Quench Time, s	191.6	191.7	192.7

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). The bolded values represent the maximum PCT at each TIL, for either ruptured or unruptured segment.

Table 5-7: CR-3 Mark-B-HTP 4-w/o Gadolinia LOCA LHR Limits Summary

Parameter	BOL	MOL	EOL
Burnup, GWd/mtU	0	40	62
Peak LHR(Note), kW/ft	16.1	15.8	11.7
Axial Peak Elevation, ft	2.506	2.506	2.506
Steady-State EDF	0.973	0.974	0.985
Transient EDF	1.03	1.04	1.10
Peak Initial Fuel Temperature, F	2393	2331	1990
Initial Pin Pressure, psia	674	2279	2605
End of Bypass, s	21.1	21.2	21.1
End of Blowdown (EOB), s	23.2	23.2	23.2
Liquid Mass in RV Lower Plenum at EOB, lbm	17029	17282	16952
RV Lower Plenum Filled (EOAH), s	30.4	30.4	30.4
LPI Flow Begins, s	35.1	35.1	35.1
CFTs Empty, s	48.4	48.5	48.4
Clad Rupture Time, s	24.9	21.0	27.8
Unruptured Segment	6	6	7
PCT, F	1781.0	1840.4	**1541.1**
Time, s	30.9	30.8	30.8
Local Oxidation, %	0.788	1.664	2.383
Ruptured Segment	7	7	6
PCT, F	**1836.6**	**1841.9**	1535.4
Time, s	30.9	33.1	30.6
Local Oxidation, %	1.449	2.055	2.421
Average Channel Quench Time, s	191.6	191.7	192.7

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). The bolded values represent the maximum PCT at each TIL, for either ruptured or unruptured segment.

Table 5-8: CR-3 Mark-B-HTP 6-w/o Gadolinia LOCA LHR Limits Summary

Parameter	BOL	MOL	EOL
Burnup, GWd/mtU	0	40	62
Peak LHR(Note), kW/ft	15.6	15.6	11.7
Axial Peak Elevation, ft	2.506	2.506	2.506
Steady-State EDF	0.974	0.974	0.985
Transient EDF	1.05	1.05	1.10
Peak Initial Fuel Temperature, F	2411	2357	2030
Initial Pin Pressure, psia	673	2198	2349
End of Bypass, s	21.1	21.2	21.1
End of Blowdown (EOB), s	23.2	23.2	23.2
Liquid Mass in RV Lower Plenum at EOB, lbm	17029	17282	16952
RV Lower Plenum Filled (EOAH), s	30.4	30.4	30.4
LPI Flow Begins, s	35.1	35.1	35.1
CFTs Empty, s	48.4	48.5	48.4
Clad Rupture Time, s	24.9	21.0	29.1
Unruptured Segment	6	6	6
PCT, F	1786.0	1841.0	1535.3
Time, s	30.9	30.8	30.8
Local Oxidation, %	0.788	1.682	2.926
Ruptured Segment	7	7	7
PCT, F	**1844.3**	**1852.1**	**1536.9**
Time, s	30.9	33.1	30.8
Local Oxidation, %	1.476	2.105	2.969
Average Channel Quench Time, s	191.6	191.7	192.7

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). The bolded values represent the maximum PCT at each TIL, for either ruptured or unruptured segment.

Table 5-9: CR-3 Mark-B-HTP 8-w/o Gadolinia LOCA LHR Limits Summary

Parameter	BOL	MOL	EOL
Burnup, GWd/mtU	0	40	62
Peak LHR(Note), kW/ft	15.1	15.1	11.3
Axial Peak Elevation, ft	2.506	2.506	2.506
Steady-State EDF	0.975	0.975	0.987
Transient EDF	1.06	1.06	1.12
Peak Initial Fuel Temperature, F	2433	2355	2063
Initial Pin Pressure, psia	673	2146	2541
End of Bypass, s	21.1	21.2	21.1
End of Blowdown (EOB), s	23.2	23.2	23.2
Liquid Mass in RV Lower Plenum at EOB, lbm	17029	17282	16952
RV Lower Plenum Filled (EOAH), s	30.4	30.4	30.4
LPI Flow Begins, s	35.1	35.1	35.1
CFTs Empty, s	48.4	48.5	48.4
Clad Rupture Time, s	24.8	21.1	27.2
Unruptured Segment	6	6	7
PCT, F	1786.8	1833.6	**1559.6**
Time, s	30.9	30.8	33.0
Local Oxidation, %	0.777	1.645	2.617
Ruptured Segment	7	7	6
PCT, F	**1849.8**	**1842.8**	1549.3
Time, s	30.9	33.1	30.8
Local Oxidation, %	1.494	2.037	2.658
Average Channel Quench Time, s	191.6	191.7	192.7

Note: The LHR limits presented represent the power generated by the pin (i.e., nuclear source). The bolded values represent the maximum PCT at each TIL, for either ruptured or unruptured segment.

Figure 5-1: Axial Power Shapes

(Reference [67])

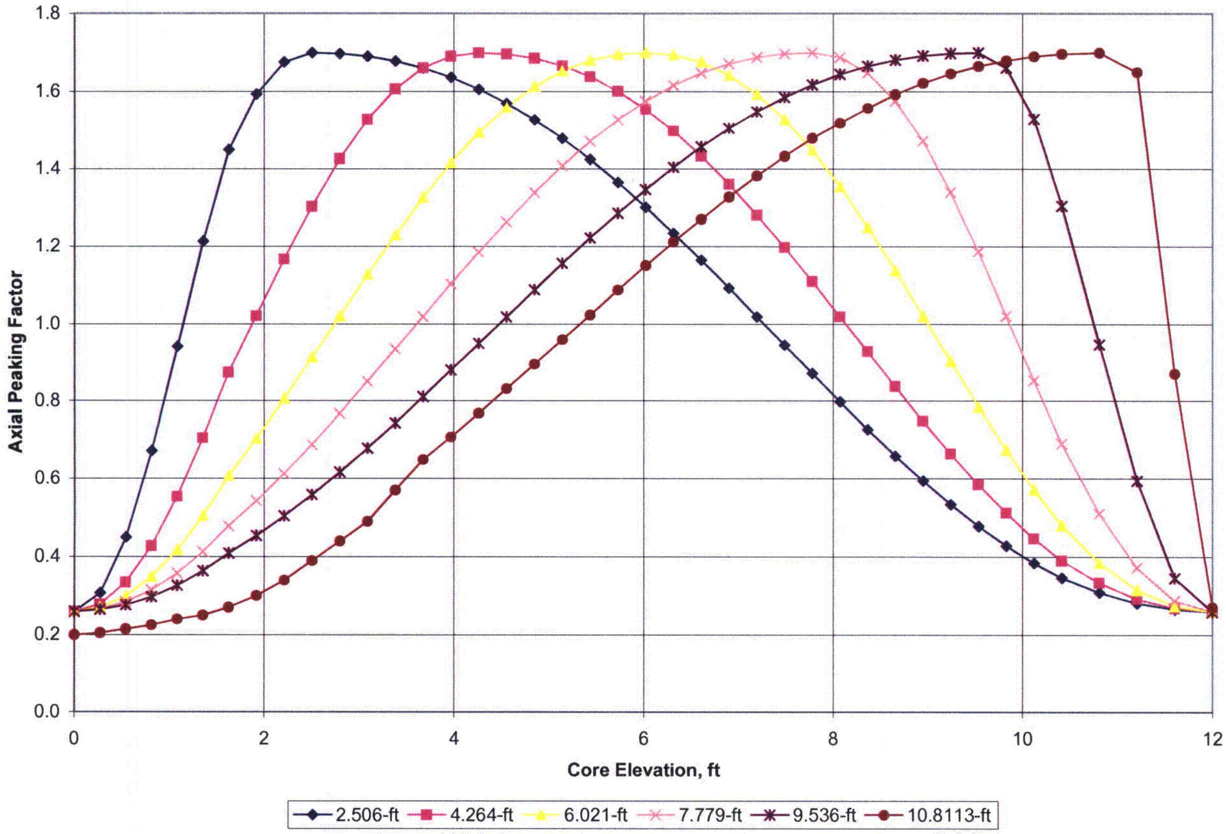


Figure 5-2: 2.506-ft, Mark-B-HTP BOL LOCA Limit case – Reactor Vessel Upper Plenum Pressure

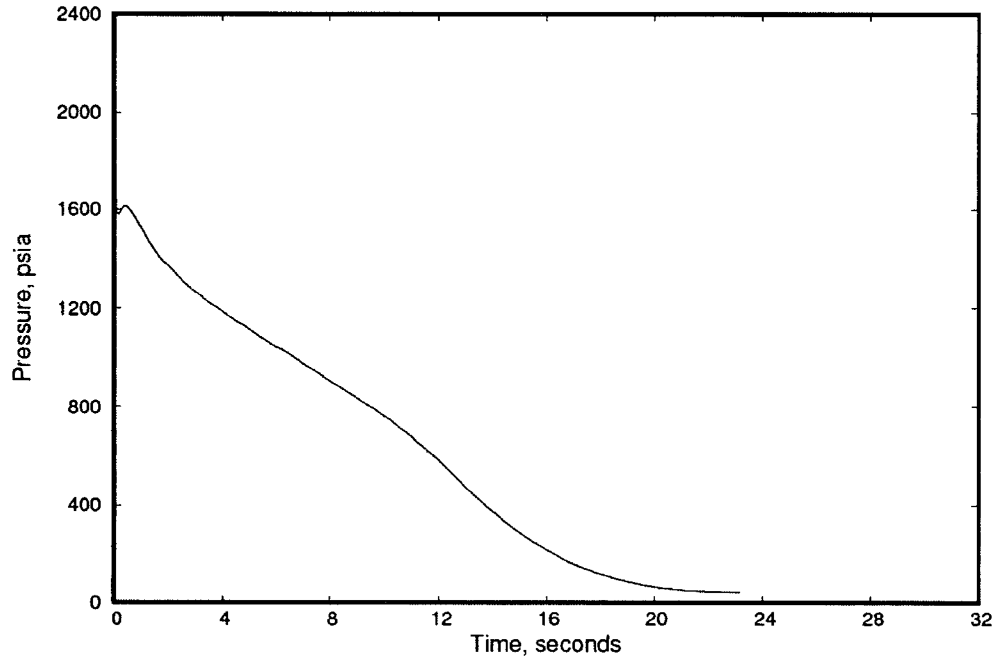


Figure 5-3: 2.506-ft Mark-B-HTP BOL LOCA Limit Case – Break Mass Flow Rates

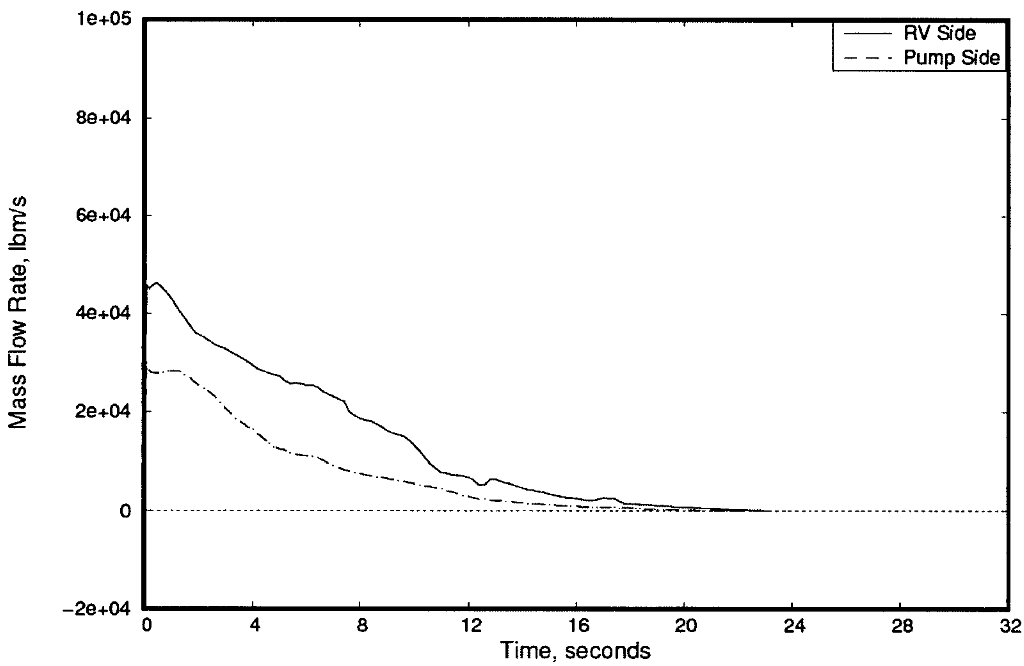


Figure 5-4: 2.506-ft, Mark-B-HTP BOL LOCA Limit Case – Hot Channel Mass Flow Rates

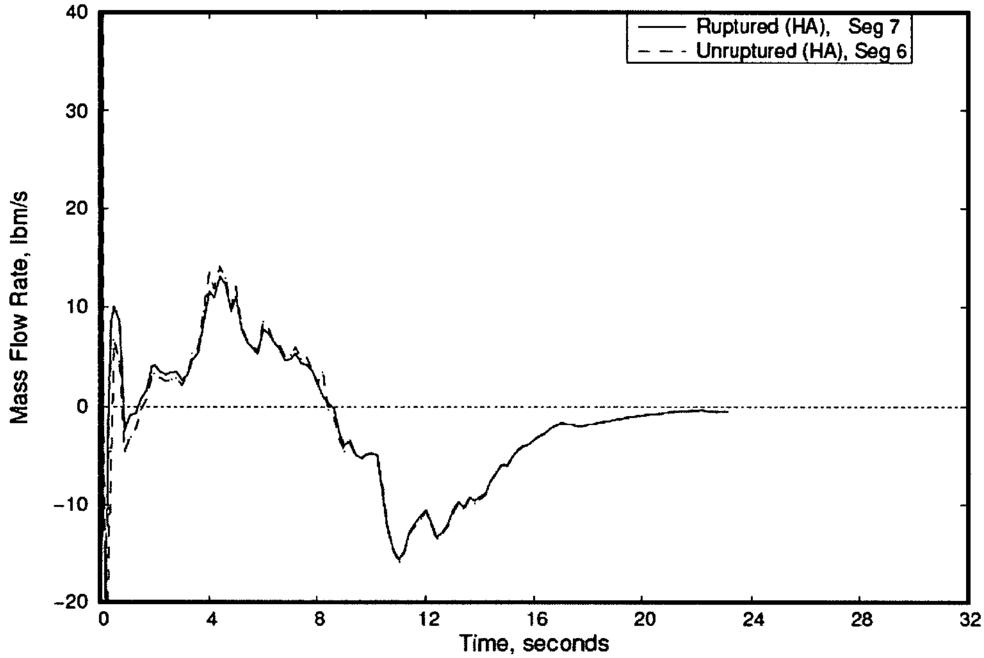


Figure 5-5: 2.506-ft, Mark-B-HTP BOL LOCA Limit Case – Core Flooding Rate

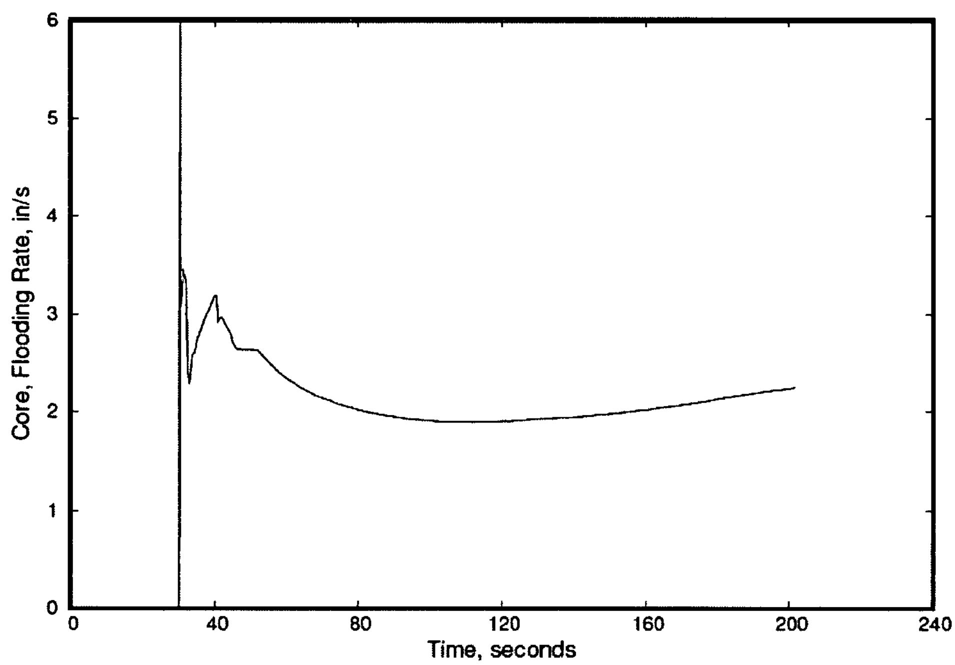


Figure 5-6: 2.506-ft, Mark-B-HTP BOL LOCA Limit Case – HP Fuel & Clad Temperatures at Peak Unruptured Location

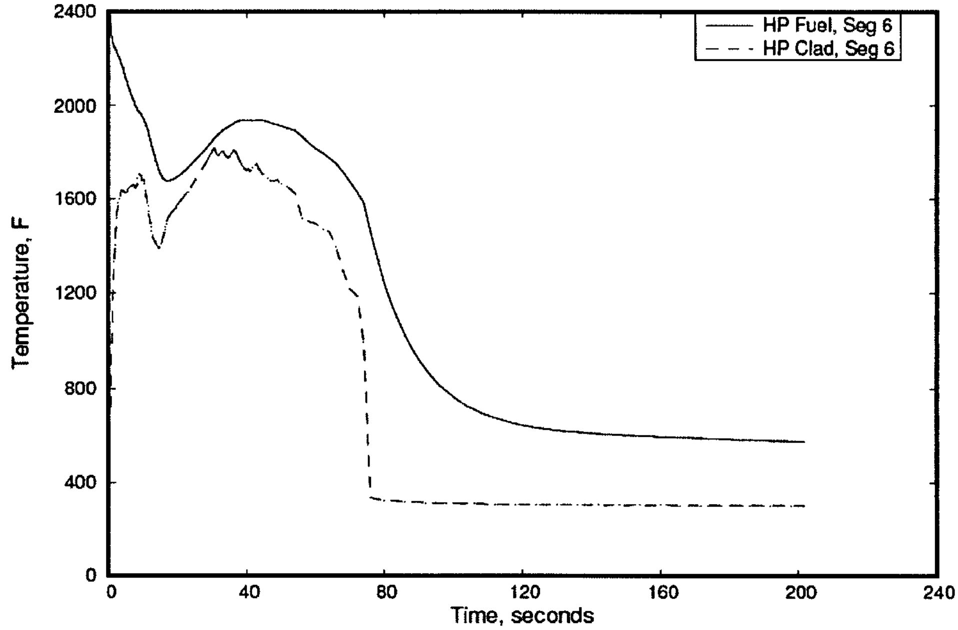


Figure 5-7: 2.506-ft, Mark-B-HTP BOL LOCA Limit Case – HP Fuel & Clad Temperatures at Peak Ruptured Location

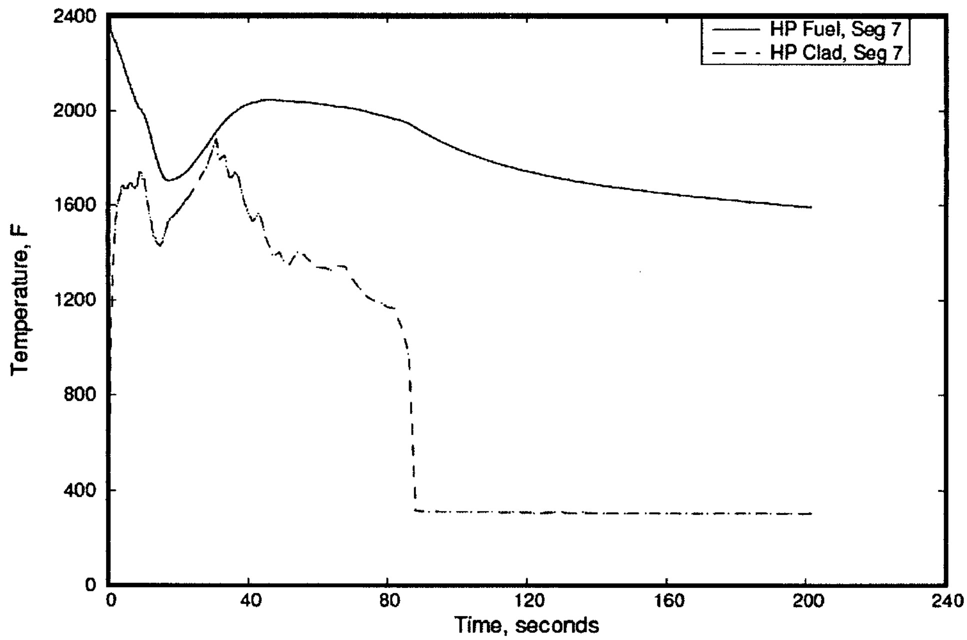


Figure 5-8: 2.506-ft, Mark-B-HTP LOCA Limit Case – HP Heat Transfer Coefficients

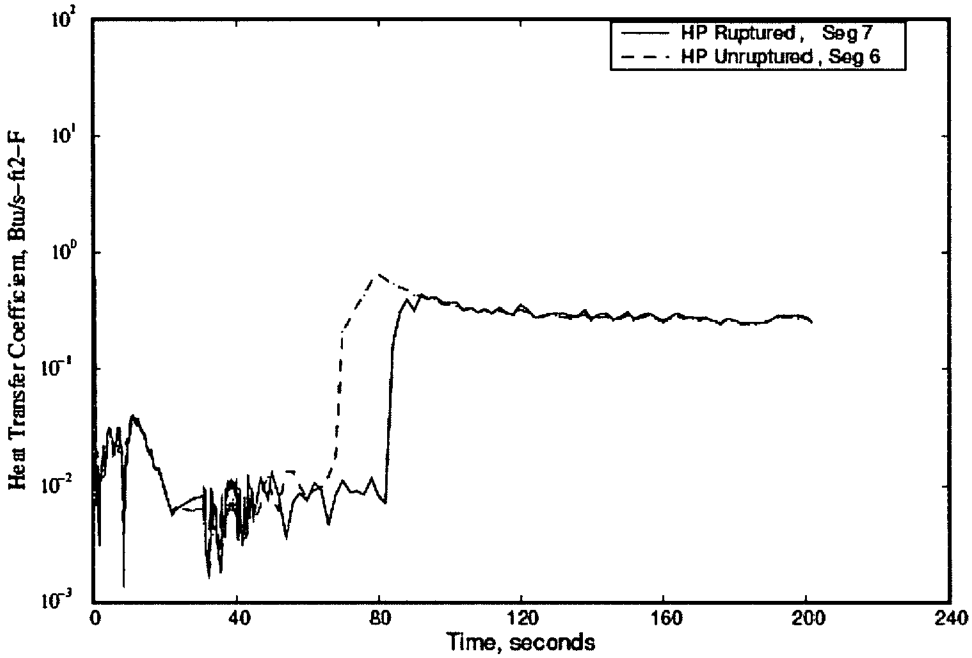


Figure 5-9: 2.506-ft, Mark-B-HTP BOL LOCA Limit Case – Quench Front Advancement

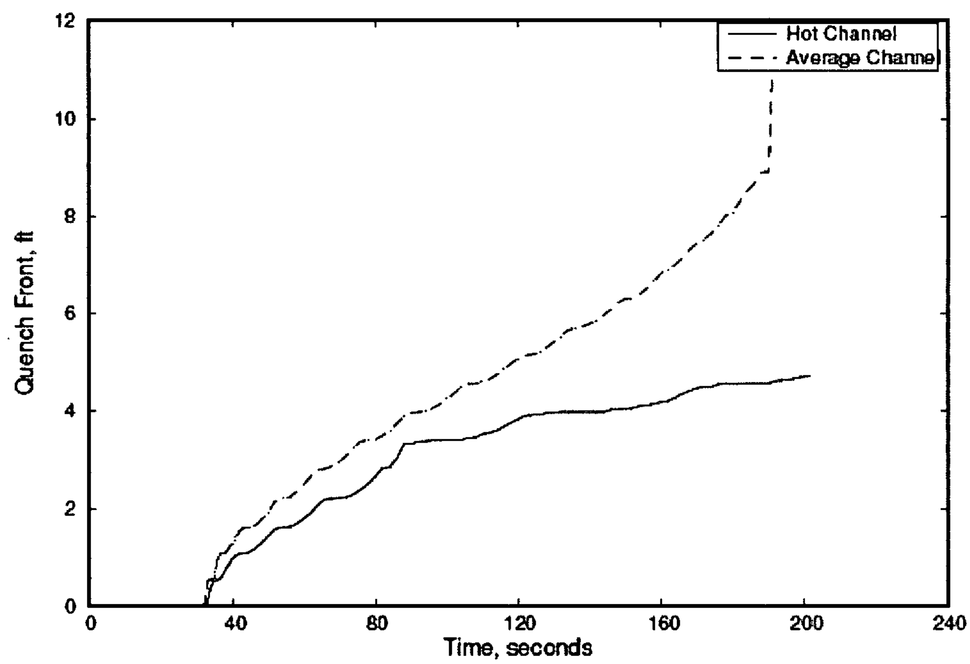


Figure 5-10: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – Reactor Vessel Upper Plenum Pressure

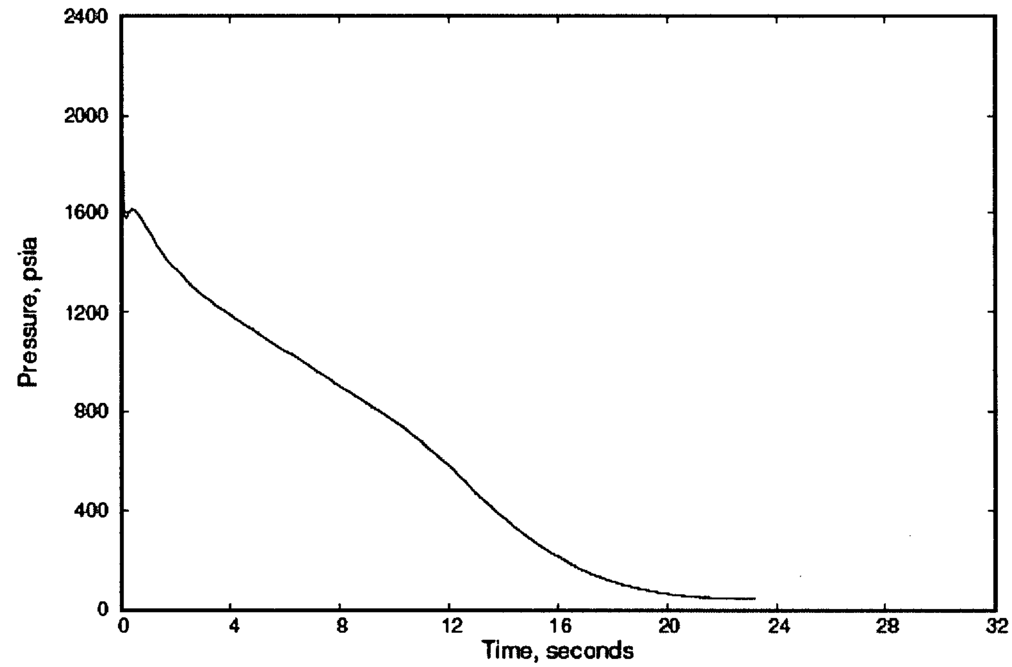


Figure 5-11: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – Break Mass Flow Rates

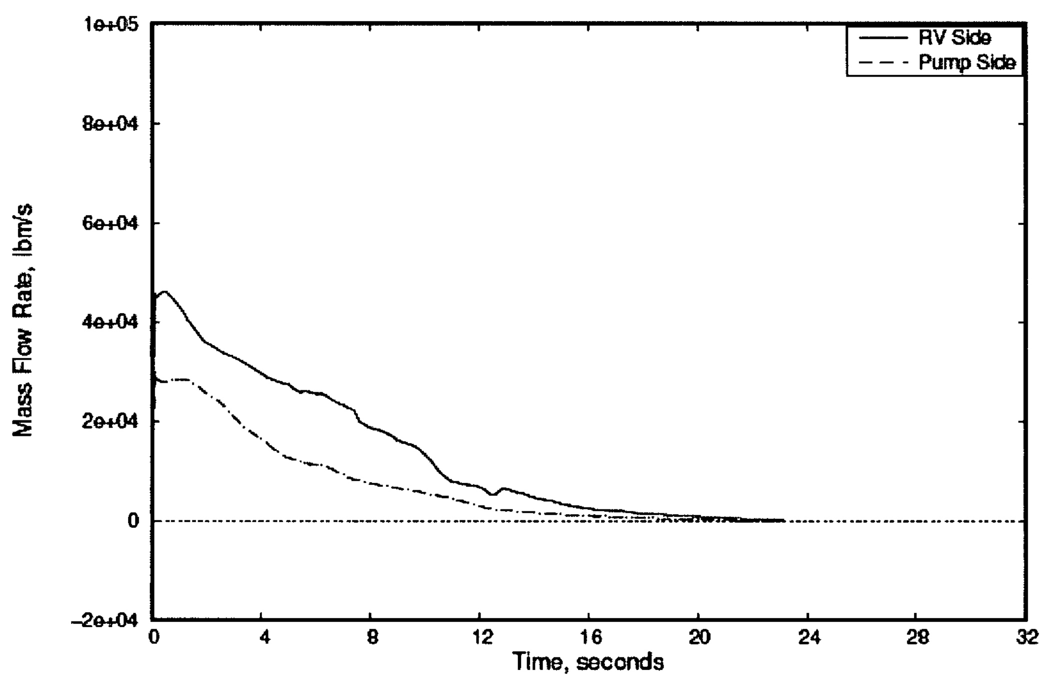


Figure 5-12: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – Hot Channel Mass Flow Rates

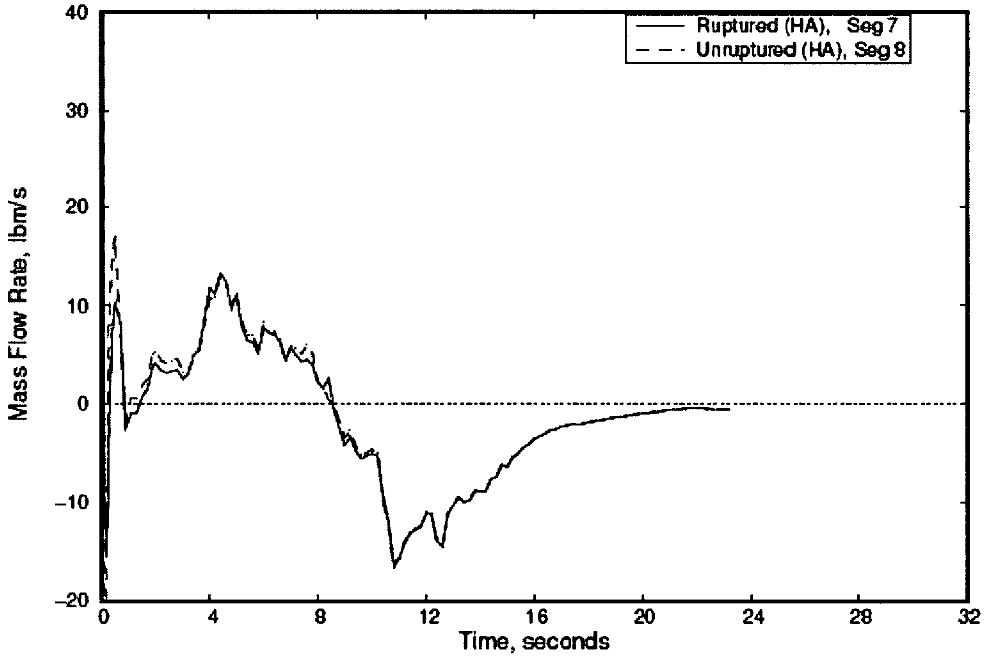


Figure 5-13: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – Core Flooding Rate

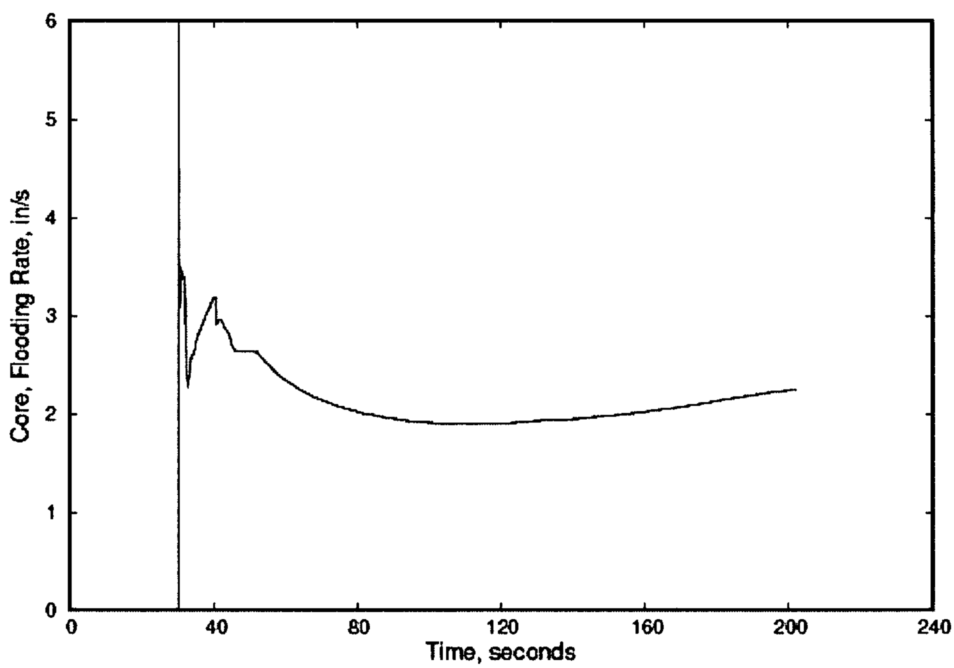


Figure 5-14: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – HP Fuel & Clad Temperatures at Peak Unruptured Location

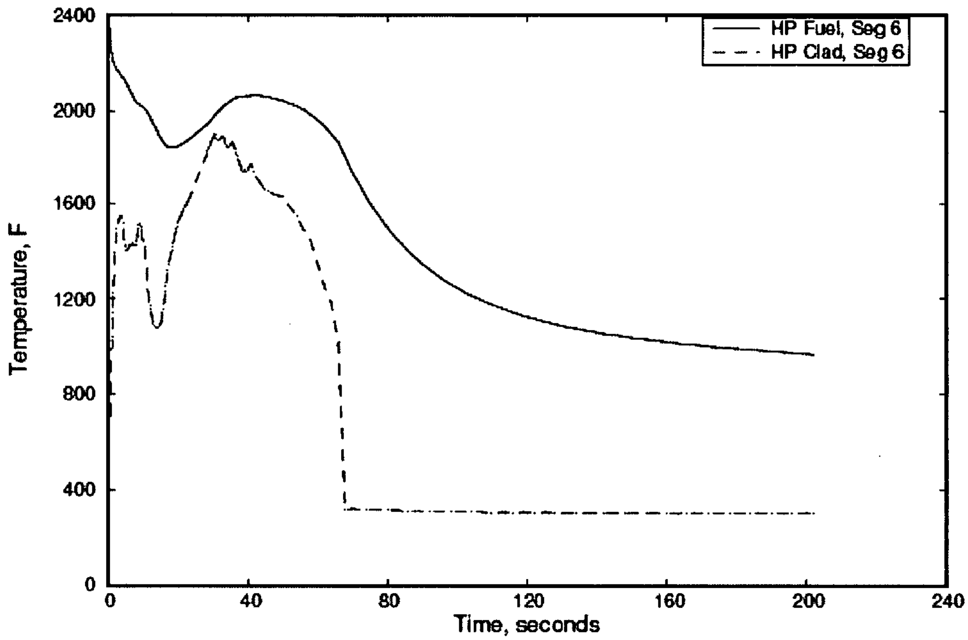


Figure 5-15: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – HP Fuel & Clad Temperatures at Peak Ruptured Location

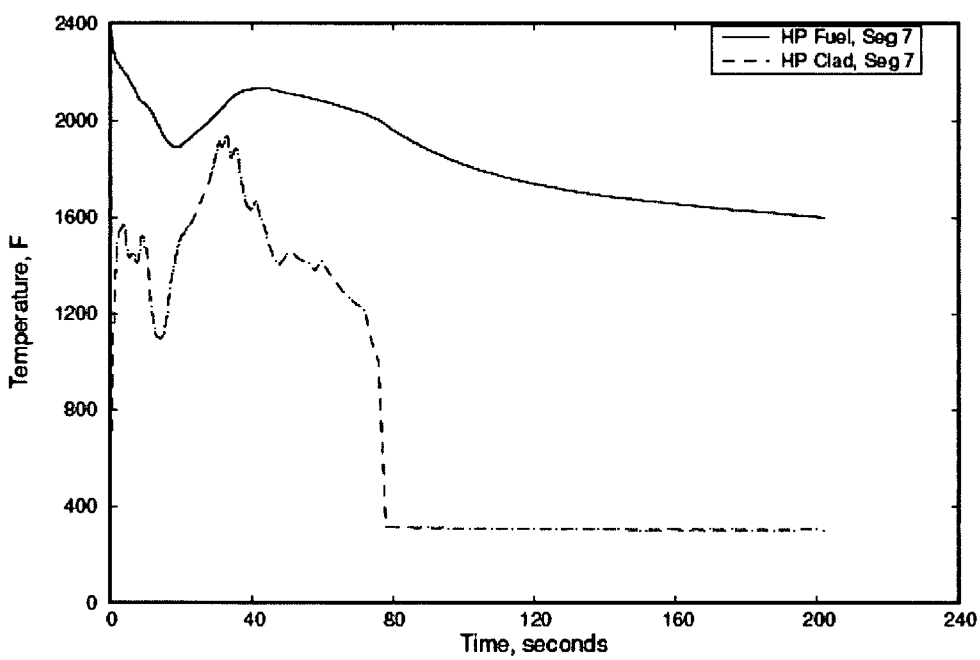


Figure 5-16: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – HP Heat Transfer Coefficients

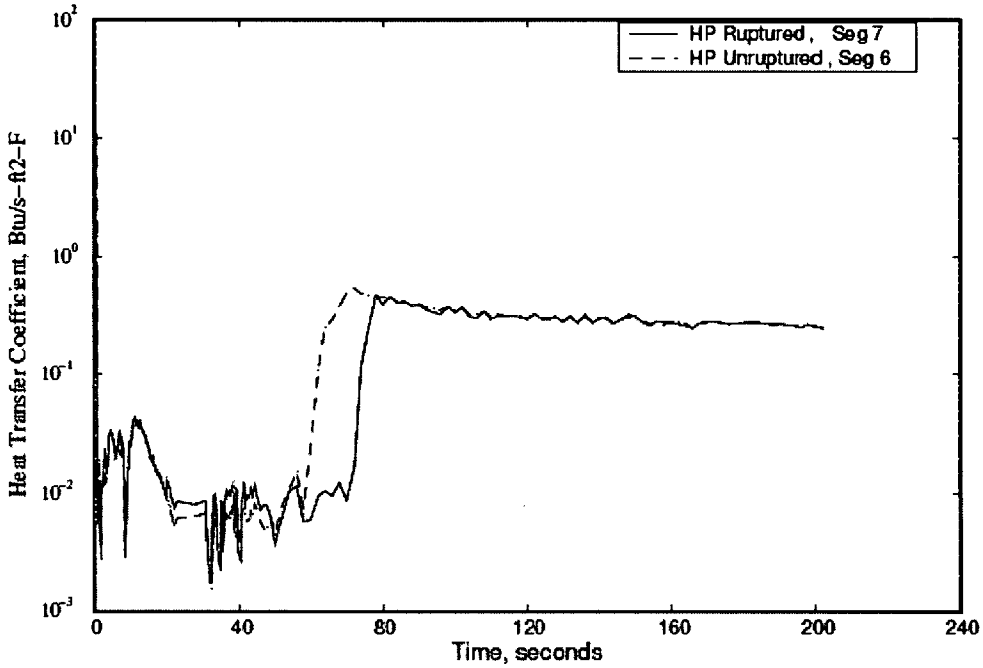
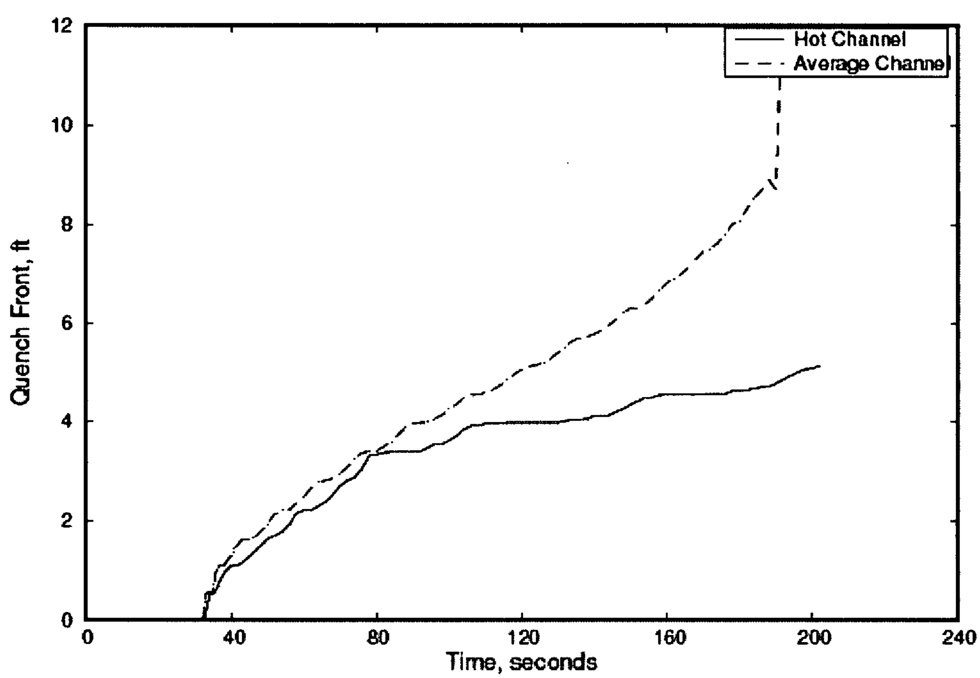


Figure 5-17: 2.506-ft, Mark-B-HTP MOL LOCA Limit Case – Quench Front Advancement



6.0 SBLOCA SENSITIVITY STUDIES AND ANALYSES

SBLOCA licensing analyses are completed with a model that is constructed based on Volume II of the NRC-approved BWNT LOCA Evaluation Model [1]. There are a variety of sensitivity studies that are performed to demonstrate model convergence and conservatism before the SBLOCA analyses are performed. Many of the studies are generic in nature and reported in the BWNT LOCA EM topical. Other studies are applicable to a specific plant-type (i.e., lowered-loop 177-FA plant category which includes the CR-3 plant). In some special circumstances there are plant-specific studies that are required because of unique design features of the plant. The SBLOCA generic and plant-type specific sensitivity studies are presented in Section 6.1. These develop the limiting inputs that were used in the transient results that are presented in Section 6.2.

6.1 SBLOCA Sensitivity Studies

SBLOCA analyses require that various sensitivity studies be performed with the evaluation model to demonstrate model convergence and to identify the most limiting set of boundary conditions or break locations that should be used in demonstrating compliance with the five criteria in 10 CFR 50.46. As part of the SBLOCA EM [1], AREVA performed numerous SBLOCA sensitivity studies to confirm modeling techniques and methods. Although the EM was based on a slightly different plant design, the safety evaluation report for BAW-10192P-A [1] supports the application of the EM to the 177-FA plants. As discussed in Section 6.1.1, AREVA has determined that the SBLOCA sensitivity studies performed in the EM are directly applicable to and appropriate for use in the CR-3 EPU analyses. Section 6.1.1 provides a discussion of the generic sensitivity studies from the reference EM report that have been applied. Sections 6.1.2 and 6.1.3 describe the plant type and plant-specific sensitivity studies.

6.1.1 EM Generic Studies

The majority of the SBLOCA sensitivity studies presented in the EM topical report [1, Volume II] are generic and apply to any SBLOCA analysis for the B&W-designed nuclear steam system. An example is the RELAP5/MOD2-B&W time-step study, which showed that the automatic time step selection in RELAP5/MOD2-B&W would produce converged results. This demonstration need not be repeated for plant-specific applications in which the modeling techniques used are represented by those in the EM studies. The following is a listing of the sensitivity studies considered to be generic, with a discussion of why the conclusions of the study are applicable to this SBLOCA applications report. For convenience, each discussion is referenced to the section in the EM topical report where the study is documented.

6.1.1.1 SBLOCA Time-Step Study

The study using the generic EM, documented in BAW-10192P-A [1], Volume II, Appendix A, Section A.2, verified that, for light water reactor geometry, the RELAP5 time-step controller governs the code solution sufficiently to assure convergent results. In RELAP5/MOD2-B&W, the user specifies a maximum time step that can be modified internally by the code in the event of convergence or Courant limitations. The SBLOCA EM time-step studies justified use of a 20-millisecond maximum time-step size as appropriate for B&W-plant SBLOCA analyses. The EM controls the plant input models such that no significant deviation in the number or size of the control volumes or heat structures, critical to the model results, will be made to the different plant designs. Since the SBLOCA analytical model is similar to the model used for the EM time-step study, and the maximum time-step size is 20 milliseconds in the SBLOCA analyses, then the RELAP5/MOD2 time-step controller will also adequately control the problem advancement for these applications. The EM study remains valid, therefore, and this study does not have to be repeated.

6.1.1.2 SBLOCA Pressurizer Location Study

Previous configuration studies performed with the SBLOCA EM (BAW-10192P-A [1], Volume II, Appendix A, Section A.3) showed that there is little difference in results when the pressurizer is connected to the broken loop instead of the intact loop. This result is expected since the SBLOCA transient is dominated by such factors as leak flow, decay heat generation rate, initial primary liquid inventory, and ECCS injection rates. Therefore, the pressurizer location study performed with the EM is applicable to the SBLOCA analyses and need not be repeated.

6.1.1.3 SBLOCA Core Crossflow Resistance Study

Core crossflow is incorporated in the base model through the use of RELAP5/MOD2-B&W crossflow junctions between the hot and average channels in the core region. The crossflow areas are calculated based upon the actual flow area between fuel rods in the three-by-four matrix of fuel assemblies in the hot channel, and the junction form loss factors are input based on the method discussed in the EM (BAW-10192P-A [1], Volume II, Appendix A, Section A.4). This scheme was found to increase the flow diversion out of the hot channel above the mixture level while restricting the flow of lower temperature steam from the average to the hot channel during core uncovering, thereby, maximizing the hot channel peak clad temperature prediction. The only variation between the cases used for the EM and the CR-3 EPU analyses is the implementation of void-dependent cross-flow logic. AREVA developed a new RELAP5/MOD2-B&W code option that used the EM cross-flow modeling philosophy to standardize the cross-flow modeling implementation by allowing the core cross flow to vary depending on the mixture level [13] as opposed to the fixed cross-flow resistances shown in Table A-3 of the SBLOCA EM [1]. This improvement (which was approved by the NRC) retains the prescribed core cross-flow conservatisms while removing the likelihood of PCT variation because of the fixed nature of the constant cross-flow model specification. This void-dependent cross-flow model improves the implementation of the conservatisms of the EM cross-flow resistances. It remains consistent with the current EM discussions. Therefore, the studies performed for the EM remain applicable and do not need to be repeated.

6.1.1.4 SBLOCA Core Channel Modeling Study

The core noding in the CR-3 model used 20 axial control volumes to model the heated fuel assembly region with twelve assemblies in the hot channel and the remaining assemblies lumped into the average channel. In addition, each channel included an unheated segment at the inlet and exit. The EM study (BAW-10192P-A [1], Volume II, Appendix A, Section A.5) used a similar model, which was shown to ensure calculation of a conservative peak clad temperature for those cases in which the mixture level descends into the heated core region. Therefore, this study does not have to be repeated for this application.

6.1.1.5 SBLOCA CFT Line Resistance Study

The core flooding system consists of two pressurized CFTs that are each connected to the reactor vessel downcomer by a surge line containing two check valves and a normally open isolation valve. During the SBLOCA, the primary system may depressurize to the CFT fill pressure, allowing flow from the tanks and lines to enter the RV downcomer at a variable rate, depending on the CFT line resistance and the pressure drop between the CFTs and the RV downcomer. The CFT line resistance study performed with the EM (BAW-10192P-A [1], Volume II, Appendix A, Section A.7) included analyses of the base 0.1-ft^2 break and a larger 1.0-ft^2 break. This study confirmed that a CFT line resistance of one-hundred times the nominal value is appropriately conservative and acceptable for use for all SBLOCA analyses, except for the CFT line break. The CFT line break analysis uses the nominal resistance as stated in Section A.7 of the SBLOCA EM [1]. Since the geometry, phenomena, and modeling of the reactor vessel downcomer region are similar between the current applications and the EM cases, the EM CFT line resistance study remains appropriate and applicable.

6.1.1.6 Break Discharge Coefficient Study

The break discharge coefficient study performed with the EM (BAW-10192P-A [1], Volume II, Appendix A, Section A.8) confirmed that all classical EM applications should be performed with the set of high break void discharge coefficients. In the CR-3 EPU analyses with ROTSGs, all break flow model discharge coefficients (C_D) were set equal to 1.0. The classical EM applications include the reactor coolant pump discharge location with the reactor coolant pumps tripped. The break discharge coefficient studies performed with the EM confirmed that, during the critical boiling pot phase of a CLPD SBLOCA, the break volume void fraction was approximately 98 to 99 percent. The data verify [1, Volume II, Section 4.3.2.4] that the C_D should be 1.0 at these high void fractions. The process, identified in BAW-10192P-A [1], Volume II, Section 4.3.2.4, states that the high break voiding discharge coefficient range should be used for all classical EM SBLOCA applications. It also includes provisions for reanalysis of the case if the SBLOCA transient evolves to, or spends the critical portion of the transient with the break inlet conditions within, the intermediate void fraction range. These conditions may be encountered in a hot leg SBLOCA or in a long-term scenario with pumps-on simulation of any other SBLOCA break location. The only special analyses that are performed for this application are the one-minute RCP trip cases for PSC 2-00. The break void fraction for these cases quickly transitioned to high void fractions. Therefore, the CR-3 results for the high void discharge coefficient method remains applicable.

6.1.2 EM Plant-Type Studies

Although a considerable portion of the analysis inputs are set or controlled by the evaluation model and its sensitivity studies, some parameters are dependent on inputs specific to a plant type and should be established by separate studies. This section presents the studies performed with the SBLOCA evaluation model for the 177-FA LL plant that helped to define the final plant model configuration used in the CR-3 EPU SBLOCA analyses.

6.1.2.1 RC Pump Two-Phase Degradation

PSC 2-00 identified that the calculated consequences for some SBLOCAs (in particular a CFT line break and larger CLPD breaks) could be worse if offsite power were available, and the operators delayed tripping the reactor coolant pumps (RCPs). When the RCP trip is delayed, the continued forced circulation in the RCS causes more liquid to flow out the break, thereby decreasing the liquid inventory that remains in the reactor vessel. The consequences of the pump power status will be explicitly analyzed in the larger break sizes as discussed in Section 6.2. However, the PSC raised questions regarding the validity of applying the RCP two-phase degradation model listed in the EM to pumps-powered applications for SBLOCA.

Table 9-1 of the SBLOCA volume of the BWNT LOCA EM [1] states that the "default curve" (Semiscale) for two-phase head degradation should be used for SBLOCA applications. This is a general use curve that typically falls between the upper bound M1 (maximum degradation) and lower bound M3-modified (minimum degradation) curves. This selection was made because the RCP head degradation is of little consequence for SBLOCA transients with RCP trip coincident with LOOP. With offsite power available, the selection of the RCP two-phase head degradation model becomes important to the PCT consequences. A series of 177-FA studies on the limiting RCP degradation for these SBLOCAs were reported in [48]; this reference also includes analyses performed specifically for CR-3. The results of the study show that the lower bound M3-modified curve will produce more severe calculated PCT consequences for the CFT line break as well as larger CLPD breaks with a RCP trip delayed by up to two minutes. The higher head resulting from the minimum degradation for any B&W-design plant will transport to the break location the largest fraction of ECCS liquid that enters the RCS, as well as liquid remaining within the reactor vessel and RCS. The liquid lost out of the break increases the overall severity for these transients. Therefore, all delayed RCP trip SBLOCA analyses used the minimum (M3-modified) head degradation curve.

6.1.3 EM Plant-Specific Studies

AREVA determined that additional sensitivity studies were required for CR-3 to determine the appropriate CFT initial conditions for use in the CFT line break analysis and the appropriate RC pump two-phase degradation model. An additional EFW sensitivity study has been performed in [3] at the EPU power conditions.

6.1.3.1 CFT Line Break CFT Initial Conditions Study

The CFT-line break prevents one CFT from injecting into the reactor vessel. A failure of one emergency diesel to start disables an LPI pump and an HPI train. The remaining ECCS available for core cooling consists of one HPI train, one CFT, and flow from one LPI pump flow split between the broken CFT line, the intact CFT line via flow through the new continuously open LPI cross-tie line, and the hot leg injection line (after the operators open it to control the post-LOCA boric acid concentration). Prior to the new continuously open cross-tie line, no credit was taken for the LPI cross-tie flow for a CFT line break with LOOP in previous CR-3 analyses. No credit was taken because the line was normally closed and had to be opened, plus there was no effective method for balancing the flow. Even if the operators opened the cross-tie line, most if not all the LPI would flow out of the broken CFT line. A plant modification of the LPI system is planned at CR-3. The modification includes a continuously open cross-tie line with downstream throttle valves to add resistance to balance the LPI flows in the event of the CFT line break, to assure that some LPI flow is available for core cooling during a CFT line break with the limiting single failure of one LPI pump. The CFT line break analyses at the EPU power level were performed to confirm which combination of initial CFT pressure and liquid inventory that produces the limiting results, given that the core flood tank initial pressure and liquid inventory were varied between the minimum and maximum values as shown below.

	CFT Inventory (ft^3)	CFT Pressure (psia)
Maximum	1070	653
Minimum	970	577

For the CFT line SBLOCA analyses discussed in Appendix I of [3], a minimum initial cover pressure (577 psia) with a minimum CFT liquid volume (970 ft^3) was utilized. With the new LPI cross-tie line and one-minute RCP trip for the offsite power available cases, the CFT line break cases did not uncover the core. Therefore, the selection of minimum CFT liquid volume is appropriate since it would minimize the CFT inventory thereby promoting minimum RV water inventory to increase the likelihood of core uncovering. Similarly, the selection of minimum CFT initial pressure further reduces and delays delivery of the CFT flow and therefore is appropriate. As such, the conclusions of the sensitivity studies discussed in Section 6.1.2.1 of [49] remain valid, and the minimum liquid volume (i.e., inventory) and minimum cover pressure configuration remains the most limiting for CFT line SBLOCA analyses.

6.1.3.2 CFT Initial Conditions for CLPD Breaks

The CFT initial pressure and liquid level conditions used in the CLPD SBLOCA analyses can influence the calculated PCTs if the PCT time is after the point in the transient that the CFTs could begin to discharge. When the PCT is produced before the CFT could discharge, the initial conditions are not a factor. If the PCT is produced during the CFT draining phase, the worst results are generally produced with a minimum pressure and maximum liquid level to reduce the CFT discharge rate as they empty. If the PCT results occur after the CFT has emptied, the minimum liquid inventory and maximum pressure are generally limiting. These trends related to a sensitivity study considering CFT initial liquid volume for CLPD breaks are summarized in Section 5.5 of [47, Rev. 0].

For the CR-3 SBLOCA analyses, the timing and results of each case are reviewed to ensure that the limiting CFT initial volume and pressure were modeled appropriately to produce the limiting calculated consequences.

6.1.4 EFW Flow Sensitivity Study

The EFIC system initiates EFW flow and controls the rate of SG refill to also control the rate of primary-to-secondary heat transfer. It is designed to open EFW valves as necessary based on the primary-to-secondary heat transfer to accomplish its mission. The rate of SG level increase driven by EFW flow is based on SG outlet pressure. If the pressure is high (≥1050 psig), the rate targets 8 inches per minute because there is indication of good primary-to-secondary heat transfer. If the pressure is lower (≤800 psig) then primary-to-secondary heat transfer is reduced and the rate is limited to 2 inches per minute in order to preclude overcooling the system. In the event the EFIC level rate controller is not controlling as designed, either a higher or lower flow may be obtained. The highest flow is obtained with full flow from two EFW pumps with full open control valves. If a single EFW pump is flowing, it can produce roughly 800 gpm of flow depending on the secondary side pressure and control valve positions. Two pumps can produce effectively double the EFW flow and it will be split somewhat evenly between the two SGs. If EFIC is not controlling the level rate, then a range of EFW flows is possible. The maximum is effectively 800 gpm per SG, and the minimum flow is that which is currently proceduralized in the EOPs as 200 gpm per SG.

6.1.4.1 EFW Study with FCS

When crediting either operator-initiated or automatic SG blowdown with the ADVs, the secondary side pressure will decrease and the EFIC fill rate will be limited to 2 inches per minute, corresponding to approximately 80 gpm per SG. EFIC EFW flows were limited to a maximum value of 300 gpm prior to use of the ADV depressurization (Appendix H of [3]).

As discussed in detail in Section 6.2.3, EFW interdependencies are break size dependent. As a result of taking credit of SG blowdown by automatic or manual operator action to open the ADVs, small break sizes up to Category 3 breaks take advantage of the primary-to-secondary heat removal and consequently do not uncover the core. Therefore, the Category 1 and 2, and to some extent Category 3 breaks that rely heavily on secondary side heat transfer and primary side condensation induced by EFW flow will not be affected by the EFIC fill rate limited system. Category 4 break sizes rely less on EFW flow since the break size is large enough to quickly depressurize the RCS to the CFT pressure and the Category 5 breaks depressurize even quicker and rely primarily on ECCS to mitigate the event.

An EFW sensitivity study was performed using only the limiting Category 4 break size, the 0.13 ft^2 CLPD SBLOCA case. This case constitutes the limiting PCT case for the CR-3 EPU SBLOCA spectrum. The results of the sensitivity study for this break size is expected to be representative for the entire range of Category 4 breaks since these break categories were formed based on ECCS and EFW interdependencies.

Based on the sensitivity study performed from full power with FCS, it is concluded that modeling of EFIC with a dynamic flow versus secondary pressure response gives the lowest overall EFW flow and the highest PCT. The EFIC EFW flow is appropriate to conservative for use in the CR-3 EPU SBLOCA analyses, particularly where secondary side depressurization is credited.

6.1.4.2 EFW Study without FCS

The pressure-dependent EFIC EFW level rate controller modeled in all CR3 SBLOCA analyses will provide higher EFW flows when FCS is not used because the secondary side pressure will be higher. However because of complexity of the EFIC control system, the EFW flow could be higher or lower than the values targeted by EFIC. The EOPs provide a lower bound flow of 200 gpm/SG when the plant analyzed core power was limited to 2619 MWt including uncertainties. The maximum flow rate could be as high as 807 gpm/SG, which coincides with the cavitating flow limit from the EFW cavitating venturis. Since there is such a large variation on the flow rates, there can be a significant effect on the result of analyses, especially for the range of break sizes wherein EFW flow and primary-to-secondary heat transfer are important. Therefore, the sensitivity studies were performed to evaluate the interrelationships with variations in the EFW flow for the range of break sizes without credit for the FCS. Both HPI and CLPD EFW sensitivity studies were performed in Reference [65] and [72]. The sensitivity studies in [65] considered two constant EFW flow rates (minimum flowrate of 200 gpm/SG and maximum flowrate of 807 gpm/SG) with different timing of resetting the SG level from the natural circulation to the LSCM control level of 26.3 ft.

There were two SBLOCA spectra without FCS, one from full power with two HPI pumps [72] and one from a partial power of 2619 MWt and one HPI pump [65]. The results of the studies shows that the effects on EFW flow on the transients are highly break size dependent. For Category 1, the variances of EFW flow do not have significant effects on the conclusions since breaks in this category do not exhibit core uncovering. The EFW flow variations change RCS pressure responses and minimum RCS liquid inventory, but the core will not uncover and heat up. Any EFW flow that exceeds 200 gpm/SG is capable of removing the core decay heat prior to 30 minutes after trip.

Category 2 and 3 breaks rely heavily on secondary side heat transfer and primary condensate created by EFW flow. The results of the analyses on the Category 2 and 3 breaks showed that the maximum EFW injection of 807 gpm/SG predicted the highest PCT because of shorter duration of high-elevation Boiler-Condenser Cooling (BCC) caused by shorter duration of EFW flow filling to the natural circulation level. The abbreviated period of BCC contributes less condensate to the RCS for core cooling. As such, the timing of the level reset from the NC setpoint to the LSCM setpoint influences the outcome of the event. The reset reinitiates EFW flow and slight PCT variations occur when the reset time is changed from when the NC level is reached (~6 minutes) up to the maximum operator action time of 20 minutes.

The reduced power one-HPI no FCS cases [65] considered this variation in EFW level reset while the full power two-HPI no FCS cases [72] credited an automatic reset at no later than 10 minutes. The results of the studies in [65] considering a 20 minute level reset can still be used because they are more conservative than results from cases with a 10 minute level reset.

Category 4 and 5 breaks rely less on EFW flow since the break size is large enough to quickly depressurize the RCS to the CFT pressure. The result of the Category 4 and 5 breaks showed that the limiting PCTs were predicted by the EFIC EFW fill rate since the secondary pressure is lower and EFIC has the lowest flow at these lower secondary pressures. The maximum EFW flow cases reach the CFT pressure earlier for larger Category 4 breaks than they do at EFIC EFW flow rates. The higher EFW flow is beneficial in depressurizing the secondary side which accelerates the RCS depressurization rate and gets CFT injection earlier because there is less SG reverse heat transfer.

Based on the EFW flow sensitivity study performed [65], it is concluded for the Category 2 and 3 breaks that unlike the larger break categories, modeling of maximum EFW flow can produce higher PCTs and predicts a larger range of breaks with core uncovering. The timing of the LSCM level reset also plays a role with an early reset being slightly more conservative for the Category 2 and smaller Category 3 break analyses. Larger Category 3 break sizes may be more limiting with a maximum LSCM level reset time. For larger break sizes (Category 4 and 5), modeling EFIC with a dynamic EFW flow versus secondary pressure response produces similar to slightly higher PCTs for Category 4 and 5 in the CR-3 EPU SBLOCA partial power analyses when no FCS is available.

The conclusions drawn from the reduced power without FCS cases [65] were also considered and extended to the EPU two-HPI without FCS cases in [72]. The original two-HPI cases (Rev. 0 of [72]) considered only EFIC rate control for the EFW. However, based on the results of the partial power cases, maximum EFW flow cases were performed for Category 2 and 3 break sizes. In addition, smaller Category 4 cases were studied. These studies credited the automatic 10 minute LSCM level reset.

6.2 SBLOCA Analyses

This section presents the results of the SBLOCA spectrum analyses performed for CR-3 at an initial analyzed core power level of 3026.1 MWt and also a reduced power level of 2619 MWt including the ROTSGs with up to five percent steam generator tube plugging in each SG. A total of three sets of SBLOCA analyses are described in this section:

1. The 100 percent EPU power level (3026 MWt with uncertainties) with credit for only one train of ECCS and automatic or manual FCS initiation at 10 minutes.
2. The 86.6 percent EPU power level (2619 MWt with uncertainties) with credit for only one train of ECCS and no FCS because it was declared unavailable.
3. The 100 percent EPU power level (3026 MWt with uncertainties) with credit for partial to full flow from two trains of HPI and no automatic or manual FCS.

The spectra consist of a number of break sizes analyzed in the CLPD and CFT piping using throttled HPI flow. In addition, at least a full area HPI line break with unthrottled HPI flow (and in some cases smaller HPI line breaks) was analyzed. The variations in the HPI flow, EFW flows, and time delays are discussed in the chronology given in Section 4.1.

The specific break areas, in square feet, analyzed at the CLPD location for the first set (1) at full power with FCS were: 0.005, 0.01, 0.03, 0.04, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, 0.20, 0.30, and 0.50. The specific break areas, in square feet, analyzed at the CLPD location for the second set (2) at reduced power without FCS were: 0.01, 0.04, 0.06, 0.07, 0.08, 0.10, 0.12, 0.14, 0.16, 0.20, 0.30, and 0.50. The specific break areas, in square feet, analyzed at the CLPD location for the third set (3) at full power without FCS were: 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, and 0.20.

All breaks for analysis sets (1), (2), and (3) were analyzed with LOOP coincident with reactor trip. Larger break sizes, up to and including the largest break that is included in the SBLOCA spectrum and the spectrum of CFT line breaks have been analyzed with and without offsite power for analyses sets (1) and (2). All break sizes for analyses (1), (2), and (3) have been analyzed with the new LPI plant modifications.

The base model used for the Mark-B-HTP spectrum is described in Section 6.2.1. A general discussion of SBLOCA phenomena and transient progression is provided in Section 6.2.2. Section 6.2.3 discusses the interdependencies of the ECCS and EFW systems in mitigating SBLOCAs for B&W plants. The results of the Mark-B-HTP spectrum analysis are presented in Section 6.2.4. Recent topics regarding SBLOCA are discussed in Section 6.2.5.

6.2.1 Base Model

The EM studies [1] determined that the most limiting SBLOCA break location is in the bottom of the cold leg piping between the reactor vessel inlet nozzle and the HPI nozzle. This location is limiting, because it bypasses the largest amount of HPI flow. Therefore, this break location is examined for the current SBLOCA break spectrum analysis. Additionally, an HPI line break and a spectrum of CFT line breaks were analyzed to ensure the most limiting case has been determined. For all cases, the following modeling choices were made. The high void discharge coefficient method ($C_D = 1$) is applied in the model. The maximum steam generator tube plugging is set to 5 percent in each ROTSG, with 1 percent of the plugged tubes resident in the EFW wetted region. The pressurizer is attached to the intact loop. The CR-3 plant model uses an entire core of Mark-B-HTP 15 X 15 fuel assemblies at an initial power level of 3026.1 MWt (1.004 times 3014 MWt) and an axial power shape with a 1.7 peak at the 11-ft elevation. An additional model was analyzed for a reduced power level of 2619 MWt (2609 MWt with uncertainties) to accommodate the unavailability of the FCS. The hot channel contains twelve assemblies with a peak linear heat rate of 17.3 kW/ft and a transient EDF of 1.0. The remaining 165 assemblies are grouped into the average channel. The tripped rod worth credited in the analysis is a conservatively low value that is assured to be available at all times in cycle. The entire range of core input parameters are covered by using a 0 pcm/F moderator temperature coefficient to define the moderator reactivity feedback curve, with a high beginning of cycle (BOC) beta-effective of 0.007102. The Doppler reactivity model uses a conservative EOC contribution to ensure bounding results for any TIL. The BOL initial fuel temperature, BOL cladding oxide thickness, and several hot pins with pin pressures ranging from BOL to EOL are modeled to evaluate the swelling and rupture effects at various fuel pin burnup conditions.

A plastic weighted heating ramp rate model is applied for the EM pin rupture model. Three supplemental pins are used to facilitate a quasi time-in-life study and examine the effects of rupture on the PCT. The hot channel is set to the pin pressure limit at EOL. This pin pressure maximizes the hoop stress and the likelihood of cladding rupture such that the rupture form loss is applied to the hot bundle coolant channel to maximize core flow diversion. In addition, if rupture occurs in the hot channel at the EOL pressure, the inside metal-water reaction energy release to the problem is maximized. The three supplemental pins use pin pressures consistent with BOL and two pressures roughly uniformly distributed between the BOL and EOL values. The BOL pin pressure will be the least likely pin to rupture with the other two simulating different times during the cycle. By using this supplemental pin approach the limiting PCT is evaluated for the entire time in life for the fuel pins.

Only one HPI pump and one LPI pump are modeled in the CR-3 analyses for (1) and (2) due to a single failure of a vital DC bus with a loss of offsite power. This results in the failure to start of one of the emergency diesel generators and the subsequent loss of one train of ECCS equipment (one HPI pump, one LPI pump, and one RB spray pump). With the makeup/HPI system cross tied, no manual operator actions are required to maximize the HPI flow delivery to the core. Table 4-2 provides the HPI flow distribution used in analyses of pump discharge breaks, HPI line break, and the CFT line break. A plant modification will unthrottle the HPI valves as described in Section 4.1. Higher flows are achieved for CLPD and CFT line breaks, but the analyses did not credit these higher flow rates. The unthrottled HPI flows are lower for HPI line breaks at higher RCS pressures so these were included in the HPI line break analyses. Table 4-3 provides the LPI flow distribution used in analyses of CLPD breaks, the HPI line break and the CFT line breaks. The CFT line break prevents one CFT from injecting ECC, while the single failure disables the other LPI pump and an HPI pump. Therefore, the flow from one LPI pump is split between the broken CFT line and the intact CFT line via flow through the new LPI cross-tie line. The hot leg injection line is maintained isolated until operator action to manually open it is credited for boron precipitation control during the sump recirculation portion of long-term core cooling phase. For cases that considered offsite power available, only the manual operator action to trip the RCPs was considered and the availability of additional ECCS or shorter delay times was not credited.

The reactor trips on a low primary system pressure of 1890 psia with a 0.6-second delay before control rod insertion begins. When a loss of offsite power (LOOP) is assumed to occur in the analyses, it is applied at the time of reactor trip, causing the reactor coolant pumps to coast down. For the cases that consider offsite power available, the RCPs are automatically or manually tripped at one minute following the LSCM. The main feedwater pumps also coast down on the LOOP (or reactor trip for offsite power available scenarios). ESAS is triggered when the primary system pressure drops below 1640 psia with a 67-second delay time before HPI flow begins.

At 40 seconds after reactor trip, EFW is actuated on loss of MFW. Thirty-five percent of the total credited EFW flow rate is bypassed between the holes and gaps between the 15th TSP and the shroud, while the remaining EFW flow is injected into the tube nest above the 15th TSP. The bypass due to the larger gap between the 15th TSP and the shroud in the ROTSGs is injected in the model into the top node of the SG downcomer. Injection at this location credits the condensation induced by EFW, but it does not provide any direct primary-to-secondary heat removal until the EFW falls into the pool and raises the secondary side water level. The level is automatically raised by EFIC to the natural circulation (NC) level of 50 percent on the operate range when the RCPs trip. The analyses also include an automatic or operator action to increase the ROTSG level to the loss of subcooling margin setpoint at a specific time to ensure SG heat removal is available for small break sizes before core uncovering begins. For the CR-3 SBLOCA analyses, at 10 minutes following a loss of subcooling margin, an operator or automatic action opens both safety-grade ADVs on the secondary side of the ROTSGs. On or before 20 minutes following a loss of subcooling margin, there is an automatic or manual operator reset of the secondary side setpoint from the NC level of 50 percent to the LSCM level of 73 percent on the operate range (26.3 feet).

The 73 percent level, which is roughly 2 feet above the RCP spillover elevation, represents the in-plant LSCM setpoint less instrumentation error. Once the secondary levels reach the LSCM setpoint, the EFW is throttled to maintain this level.

The EFIC system has been modeled in the SBLOCA analyses to appropriately consider its effects on the event. The EFIC system controls the rate of SG level increase by adjusting the EFW flow rate based on the SG outlet pressure. The EFIC control rate is given as 8 in/min (ipm) for SG pressures of 1050 psig and greater and 2 ipm for SG pressures of 800 psig or lower. The EFIC control rate is linearly ramped down from 8 ipm at 1050 psig to 2 ipm at 800 psig. Further, the EFIC EFW flow available is limited to a maximum of 300 gpm per SG, with thirty-five percent being bypassed into the SG downcomer as discussed previously. Sensitivity studies with different EFW flow rates and times to reset the LSCM steam generator level were also performed.

Another EFW-related issue considered in the SBLOCA analyses is the actuation of FOGG logic in the course of the FCS blowdown. As mentioned in Section 4.1, if the FOGG logic is not bypassed before the FCS is actuated, the secondary side depressurization can cause the existing EFIC FOGG circuitry to occasionally, but only briefly, interrupt EFW to whichever SG is below the FOGG pressure setpoint of 600 psig, or is at a pressure 125 psid lower than the other SG when both SG pressures are below 600 psig. The FOGG signal resets, restoring EFW, when the SG pressure is above 600 psig, or the pressure difference decreases below 125 psid at SG pressures below 600 psig. The net effect of the interrupted EFW was assessed for the categories of small breaks in Section 6.2.5, the section that best characterizes the accident progression with consideration for FOGG interactions.

For analyses of breaks in the reactor coolant pump discharge piping, including the HPI line breaks, each CFT has an initial maximum liquid inventory of 1070 ft^3 (nominal + uncertainty) and is pressurized to the minimum of 577 psia (nominal – uncertainty) as discussed in Section 6.1.3.2. The initial CFT pressure and liquid inventory used for the CFT line break analysis are discussed in Section 6.1.3.1. The LPI flow is also pressure-dependent, and the LPI pumps are activated either by a low primary system pressure with a delay of 35 seconds, ESAS RCS low-low trip with a delay of 10 seconds.

At reduced power levels without FCS the base case input parameters are defined in Table 4-1. Likewise, any plant parameter changes for the two-HPI pump case without FCS are described in Table 4-1. Differences in input data for all three SBLOCA spectra are identified.

The results of the LBLOCA analyses (Tables 2-3 through 2-7) confirmed that the reduction in LHR limits for Gadolinia compensates for the thermal conductivity and volumetric heat capacity differences. For SBLOCA analyses, the LHR limit reduction is larger than the volumetric heat capacity differences. Therefore, Gadolinia will not be limiting and was not explicitly included in the SBLOCA analyses.

The base analysis includes several of the key operator actions as listed in Table 4-7. All actions specified in the plant specific EOPs should be performed by automatic systems or manual actions to successfully aid in the mitigation of the LOCA consequences. Section 4.1 provides additional information on which analyses credited manual actions and which ones credited automatic actions that were added during or after when the analyses were being performed. In all cases, the automatic function performed the credited manual action at or before the required action was credited in the analyses.

The potential for clad rupture is increased in the SBLOCA analytical model by including an initial internal pin pressure typical of the end of fuel life. If clad rupture is calculated, it must be demonstrated that the calculated PCT will bound the fuel pin conditions at any time-in-life condition. This demonstration is achieved via use of the supplemental pin modeling that provides a representative time-in-life evaluation. The supplemental pins are used in the current analyses with a plastic-weighted heating ramp rate and multiple pins with internal pressures that are representative of all times in life. This new modeling technique does not require additional studies should cladding rupture be predicted.

6.2.2 SBLOCA Transient Progression without FCS

The transient progression for SBLOCAs that do not rely on credit for the secondary side cooldown with ADVs or turbine bypass system is summarized here to identify the key phenomena and controlling thermal-hydraulic behavior during each phase of the event. Section 6.2.3 further investigates the interdependencies of the ECCS and EFW systems when mitigating a LOCA without FCS. The discussions of the break spectrum results refer to this information to avoid repetition. When the steam generators are depressurized by operator action using the FCS, the transient progression is changed as discussed in Section 6.2.4.

A SBLOCA without ADV cooldown generally progresses through five phases: (1) subcooled depressurization (2) reactor coolant pump and loop flow coastdown and natural circulation, (3) loop draining, (4) boiling pot, and (5) refill and long-term cooling. The subcooled depressurization phase begins at the leak initiation. This phase is characterized by the period of time before the RCS begins to saturate and voids begin to form in the RV upper head and hot leg U-bends. During this period, the pressurizer will begin to empty, the RCS will depressurize to the low RCS pressure reactor trip setpoint, and the turbine will trip. Coincident with reactor trip, the MFW pumps will trip and EFW will be initiated following an appropriate delay.

Following the RCP coastdown, the RCS flow tends to evolve to a natural circulation flow condition. The energy generated by the core is transferred by convection to the steam generators during the flow phase. The continued loss of the RCS liquid inventory allows steam voids to form in the upper reactor vessel head and the upper hot leg U-bends. Natural circulation ends when the U-bend steam void displaces the hot leg mixture levels below the U-bend spillover elevation. Flow is usually interrupted first in the hot leg containing the pressurizer surge line connection, because of the additional flashing of the saturated pressurizer liquid that enters during the subcooled depressurization. Near the end of the flow phase, alternating periods of RCS repressurization can cause intermittent spillovers of hot-leg liquid into the steam generator primary region.

With the interruption of the RCS loop flow, the loop-draining phase begins. As the entire RCS approaches saturated conditions, the onset of subcooled and saturated nucleate boiling occurs in the core because of the high decay heat levels and the RCS depressurization. The flashing within the hot legs increases the size of the voids in the U-bends and eventually interrupts RCS flow and decreases the primary-to-secondary heat transfer. For the larger SBLOCAs, the RCS will continue to depressurize as the loops drain. For smaller breaks, however, the reduced heat transfer can interrupt the RCS depressurization. Also for these smaller breaks, the volumetric expansion of the RCS, due to continued steam formation, can exceed the volumetric discharge from the break, causing the RCS pressure to temporarily stabilize or even increase.

In the reactor vessel, the steam void in the upper head displaces enough liquid to uncover the reactor vessel internals vent valves (RVVVs), creating a manometric imbalance between the core and the downcomer. The imbalance forces the RVVVs to open and pass steam into the reactor vessel downcomer. The downcomer steam volume grows until the cold leg nozzle is exposed to steam. As soon as the downcomer liquid level decreases below the cold leg nozzle spillunder elevation, a steam venting path develops from the core through the RVVVs to the cold leg break, enhancing the RCS depressurization.

During the loop draining phase, the steam voids that develop in the U-bends can become large enough that the primary liquid level is displaced into the steam generator tube region below the EFW nozzles. If EFW is injecting, an improved primary-to-secondary heat transfer can then be restored, through condensation on the tubes wetted by the EFW. This heat transfer process within a once-through steam generator (OTSG) is referred to as boiler-condenser mode (BCM) cooling. When BCM cooling takes place near the location of the EFW nozzles, it is referred to as high-elevation BCM cooling. If high-elevation BCM cooling occurs, the RCS depressurization rate will be increased. Later in the loop draining phase, a different form of BCM cooling can occur if the RCS tube liquid level decreases below the secondary liquid level. This cooling process is referred to as pool BCM cooling, and will continue if, (1) RCS condensation and ECCS injection do not cause the RCS liquid level to increase above the secondary level and, (2) the secondary fluid temperature is maintained below the temperature of the steam on the primary side of the OTSG tubes. Further, if the secondary liquid level is several feet above the RCP spillover elevation then the condensate formed during this process can augment the ECCS flow to the core. For the smaller breaks, the combination of leak flow (with upper-RV venting through the RVVVs), BCM cooling, and HPI cooling will cause the RCS pressure to again decrease.

Also during the loop draining phase, the reactor vessel outlet annulus mixture level will decrease to the hot leg nozzle spillunder elevation. If the top of the hot leg nozzles void, steam will flow up the hot leg riser section, and liquid from the hot leg risers will drain back into the vessel. This hot leg draining allows the mixture level in the outlet annulus to remain near the top of the hot leg nozzle until the hot leg level drops into the RV exit nozzle horizontal piping.

After the hot legs empty, another path for the direct venting of steam to the break can be opened if the loop seals in the RCP suction piping are cleared. Depending on the break size, the RCS depressurization can be rapid enough to cause significant flashing in the suction piping, causing the liquid level to decrease below the suction piping spillunder elevation. The loop seals will then be clear, creating another steam relief path, in addition to the path through the RVVVs.

When loop draining ends, the break site void fraction will be based on core steam plus broken loop HPI flow. At that point, the only RCS liquid available for core cooling is the liquid remaining in the reactor vessel and the ECCS flow plus any SG condensate from the intact loops if the loop seal has not cleared. This portion of the transient is defined as the "boiling pot" phase. The increased void fraction at the break will further increase the RCS depressurization rate. The reactor vessel levels will continue to decrease, however, if the ECCS injection plus SG condensate cannot match the reactor vessel liquid loss from flashing, decay heat, and passive metal heat.

The EFW flow and secondary side pressure response plays a significant role in the mitigation of the smaller break sizes that do not readily decrease the RCS pressure below the secondary side pressure and get to the CFT fill pressure on pure break energy relief. If the secondary side pressure is controlled by the main steam safety valves (MSSVs), the smallest break sizes may not depressurize the RCS below the secondary side for considerable time periods that could be in the order of an hour or more. Operator initiated depressurization of the secondary side is effective in depressurizing the RCS when the primary and secondary conditions (levels, pressures, EFW flows, etc.) support good heat transfer coupling between these two systems. Lower RCS pressure increases the pumped ECCS injection delivery and it can also help the RCS reach the CFT fill pressure with increased CFT discharge rates. In addition, any subcooling of the liquid in the SG tubes or condensate generated on the primary side that flows over or displaces liquid over the RCP spillover elevation can augment the core cooling provided by the ECCS injection.

If the break energy relief coupled with any secondary side heat removal exceeds the core energy generation, then the RCS can depressurize. This depressurization can progress until either the CFT pressure is reached or the HPI flow rate exceeds the liquid loss rate, allowing the RCS to refill up to the break elevation. Before either of these conditions occur, the mixture levels may descend into the core heated region resulting in a heat up of the fuel cladding in the uncovered portion of the core.

The clad temperature increase calculated during a mixture level depression above the top of the core is maximized when a power shape skewed to the core exit is used. This power shape bounds the positive imbalance limits at the limits of normal operation. During the period of partial core uncovering, the clad may swell and possibly rupture if the clad temperatures exceed 1300 F. The limiting PCT is the maximum of the various base model fuel pins simulating internal rod pressures that bound the range of potential time-in-life rods pressures. If rupture was predicted in any of the pins it is reported in the summary tables, even though it may not be the limiting PCT pin.

A SBLOCA transient analysis is normally terminated at some point after the entire core is refilled and the cladding temperatures returned to within a few degrees of RCS saturation temperature. For the level to increase, core inflow (ECCS plus SG condensate) must exceed the liquid loss rate. Continued RCS depressurization permits higher ECCS injection rates that hastens core refill. The additional ECCS flow assures that the core can be kept covered. Once the core has been completely quenched (or rapidly approaching core quench with excess ECCS injection), the analytical results are checked to ensure a path to long-term cooling is established. For long-term cooling to be assured, the HPI flow and/or LPI flow should match or exceed the core boiling due to decay heat and wall metal heat plus flashing. When long-term cooling is assured, the LOCA analysis is terminated. The following section further develops the interdependencies of the ECCS and EFW in SBLOCA mitigation strategies.

6.2.3 Interdependencies of ECCS and EFW Used in SBLOCA Mitigation for B&W Plants without FCS

AREVA has demonstrated that the B&W-designed plants meet the 10 CFR 50.46 requirements by analyzing the limiting pipe break LOCAs with an NRC-approved EM [1]. The limiting breaks are generally those that result in the largest bypass of ECCS flow directly out of the break. The break size range includes any break that can exceed the makeup system flow up to and including that of a full, double-ended guillotine rupture of the cold leg or hot leg pipe. The mitigation of the break consequences is accomplished by a cooperative effort of makeup flow from HPI, CFT, and LPI, plus ultimate core decay heat removal via EFW, and long-term cooling via decay heat coolers with ECCS recirculation from the containment sump. These systems are activated and managed by both automatic trips and controls or manual operator actions identified in the plant emergency operating procedures (EOPs). This section clearly identifies the interrelationships of these systems in successful LOCA mitigation without credit for operator initiation of fast secondary side cooldown via ADVs. The use of the FCS is discussed separately in Sections 6.2.4 and 6.2.5.

The ECCS and EFW interdependencies are break-size dependent. Because of these dependencies, the relationships are best described according to approximate break size ranges. The break spectrum includes pipe break areas from twice the hot leg pipe cross-sectional area and less. Within this spectrum there are six categories of breaks. Each provides different challenges to both the ECCS and EFW injection systems. These six categories of breaks are given the following loose characterizations:

1. SBLOCAs too small to interrupt natural circulation.
2. SBLOCAs that may allow the reactor coolant system (RCS) to repressurize in a saturated condition.
3. SBLOCAs that allow the RCS pressure to stabilize at approximately the secondary side pressure.
4. SBLOCAs that depressurize the RCS to the CFT pressure.
5. SBLOCAs that depressurize the RCS nearly to the containment pressure.
6. LBLOCAs.

The following subsections describe in detail the characteristics of each of the break categories. While each section identifies a specific break size range, care should be taken in maintaining them as absolute. The HPI flow inputs (e.g., 1 or 2 pumps), decay heat (e.g., initial core power, Appendix K power), effectiveness of the EFW heat removal, and critical flow model selected can change the break sizes. The subsections of Section 6.2.3 discuss the transient evolutions without SG cooldown using the FCS (e.g., indicated required flow from 2 HPI pumps) while the subsections of Section 6.2.4 discusses the results of the specific small breaks analyzed for CR-3 with single failure (one HPI pump available) and credit for the FCS.

6.2.3.1 Category 1: SBLOCAs too Small to Interrupt Natural Circulation

A LOCA is defined as any break size that is in excess of the makeup system capacity. This minimum break size is not easily defined because it is dependent on break location, makeup and letdown flow rates, the critical flow model used in the analysis, and operator actions that are credited. These smallest break sizes are in excess of the makeup system flow delivery and will depressurize slowly and achieve a reactor trip within the first twenty minutes following break opening. After reactor trip, the system will lose core exit subcooling margin, and the RCPs will be manually tripped (per the EOPs) within one minute of LSCM if they are not lost due to a loss of offsite power (LOOP). These smaller break sizes will not quickly depressurize to the low RCS ESAS trip pressure. The operators will have time to diagnose the symptoms of a LOCA (either LSCM or leakage greater than allowed by Technical Specifications) and may manually activate ESAS. Once ESAS is initiated, HPI is actuated and letdown is isolated, such that the net ECCS inflow is increased.

After initiation of ESAS, the ECCS inflow will be capable of matching saturated liquid break flows for break sizes in the range of 0.002 to 0.005 ft^2 depending on the break location and number of HPI pumps operating. If the ECCS injection matches break flow and EFW flow is initiated either automatically or manually at a flow rate sufficient to remove the core decay heat not lost through break-HPI cooling, then the RCS will remain in single-phase natural circulation. The single-phase natural circulation flow provides a continuous core-to-steam generator energy transport mechanism that keeps the core from boiling and the RCS pressure well coupled to the secondary side pressure. As the system is depressurized with steam generator cooldown via the ADVs or condenser (if available) the HPI flow will be throttled to maintain the desired core exit subcooling margin. These LOCA break sizes are easily mitigated by the combination of HPI and EFW flow. The HPI makes up for break inventory loss, and the EFW provides core decay heat removal and system cooldown. Without HPI, the system inventory loss would cause natural circulation to be interrupted. This interruption in flow would result in initiation of core boiling and RCS repressurization. Without EFW and the steam generator heat transfer, the RCS could repressurize to the pressurizer safety valve open pressure. The steam generator cooldown allows the RCS to be cooled to the conditions at which the decay heat removal system can be initiated.

6.2.3.2 Category 2: SBLOCAs that May Allow RCS Repressurization in a Saturated Condition

If the break liquid discharge is slightly larger than the ECCS inflow, inventory loss will cause the RCS to depressurize until the fluid in the hot legs saturates and begins to flash. The steam accumulation in the U-bend region blocks natural circulation and interrupts the steam generator heat removal. For these LOCAs, with break areas ranging from roughly 0.005 to 0.035 ft^2, the steam generator removes core heat during the early portion of the transient, when the decay heat is high to prevent the RCS from repressurizing. When RCS liquid flow ceases, and the energy removal by the steam generator is interrupted, some repressurization will occur due to core boiling. The minimum RCS pressure reached prior to this repressurization will determine if the low RCS pressure ESAS trip is actuated. (If the trip is not achieved automatically, the operator is instructed by the EOPs to activate ESAS based on the loss of adequate subcooling margin.) The repressurization that occurs accelerates the rate of liquid loss out of the break if the break phase remains liquid only and reduces the HPI inflow if ESAS has been actuated and the system pressure is not too high. The repressurization is halted when the combination of break-HPI cooling and steam generator heat removal matches or exceeds the core energy addition rate.

The net loss of system liquid inventory will cause steam bubbles to form in the hot leg U-bends, which can expand into the steam generator tube region. This expansion is established either by flashing of hot leg liquid during the depressurization periods or by an intermittent steam venting up the hot leg when the break discharge plus HPI condensation cannot offset all the core generated steam. If EFW is flowing when the level descends into the tube region, and the primary pressure is greater than the secondary side pressure, high-elevation BCM will ensue. Condensation on the primary side will decrease RCS pressure. If the EFW is off because the secondary side has been refilled to the loss of subcooling margin level (above RCP spillover), then the BCM will be delayed until the primary level drops below the secondary side level. The pool BCM will reduce RCS pressure before the vessel level has decreased below the bottom of the hot leg nozzle. With either the high-elevation or pool BCM, the core-to-steam generator heat removal mechanism is re-established. The heat transfer condenses RCS steam. This steam sink in combination with the break and HPI reduce the RCS pressure to near that of the secondary side pressure. (It should be noted that if the ESAS trip setpoint has not been reached or the operators have not manually started HPI, this depressurization will initiate ECCS flow.) In some cases, the condensate can augment ECCS inflow by keeping the CLPS liquid full, such that liquid displaced by the condensate can flow over the pump into the reactor vessel. Operator-initiated depressurization of the secondary side below the MSSV setpoints can further enhance the core cooling from the SG heat removal and increase the HPI pumped injection rate.

Without any steam generator heat removal, the smallest Category 2 LOCAs could repressurize all the way to the pressurizer safety valve opening pressure, because the break energy removal is unable to relieve all the core-generated energy, through either liquid or steam discharge. At elevated RCS pressures, the HPI system may not be able to provide sufficient (or any) ECCS into the reactor vessel to make up for the core boil-off rate. With time, the RCS liquid inventory above the top of the core will be depleted and the core could uncover and heat up. This evolution, however, will not occur so long as EFW is preserved at a flow rate sufficient to remove the core decay heat, and the secondary side level is controlled to a level (the loss of subcooling margin level) that is above the RCP spillover elevation. In this configuration, a pool BCM will be established before the core uncovers. The pool BCM ensures that the RCS pressure can be controlled to a value slightly above the secondary side pressure. At these moderate RCS pressures, the HPI system can generally match core decay heat to prevent core uncovering. Should uncovering occur, HPI will limit the extent of the peak cladding temperature (PCT) increase.

The break location and HPI flow network determine the fraction of the total HPI flow that actually reaches the reactor vessel and is available for core cooling. The HPI line breaks directly discharge a significant portion of the HPI flow directly to containment and CLPD breaks located on the bottom of the pipe between the HPI nozzle and the reactor vessel inlet nozzle bypass a lower but still significant fraction of HPI flow. The lost HPI flow fraction makes breaks in the CLPD pipe limiting from a short term core cooling perspective.

The smaller Category 2 break sizes will not be able to depressurize the RCS below the secondary side pressure for many hours post-LOCA. The RCS pressure for these break sizes can be decreased via operator-initiated steam generator cooldown. This RCS cooldown could be interrupted if the RCS refills above the top of the tubes, thereby halting the high-elevation BCM. The cooldown can be continued when the RCS refills sufficiently to re-establish single-phase natural circulation, or when the subsequent RCS inventory loss causes the level to drop back into the tube region.

6.2.3.3 Category 3: SBLOCAs that Slowly Depressurize the RCS to CFT Pressure

As the break size increases, the break energy discharge to the reactor building replaces the steam generator as the primary core heat sink. For CLPD breaks in the range of 0.035 to 0.06 ft^2, the break energy discharge will exceed the core decay heat within a few seconds following reactor shutdown. The steam generator heat transfer via EFW is still important for these break sizes, because it can condense RCS steam and augments the break in depressurizing the RCS. The condensate combines with the ECCS flow to help limit the ECCS-to-core-boil-off deficit. Operator-initiated depressurization of the secondary side increases the condensate generation rate. In the event the secondary side is not depressurized, the EFW cooling of the secondary side limits the magnitude of the reverse heat transfer when the break depressurizes the RCS below the secondary side pressure.

These moderate break sizes limit the RCS depressurization rate. Generally it takes 25 to 60 minutes (depending on break size, decay heat power, and steam generator heat removal) for these break sizes to depressurize the RCS to the CFT pressure. Any secondary side depressurization initiated during this period helps shorten the time before the RCS reaches the CFT fill pressure. During this time period, the core decay heat boils off the HPI flow that reaches the core and some of the RCS liquid inventory that drains into the reactor vessel. The continuous HPI flow delivery to the vessel is most critical for these break sizes, because the RCS liquid inventory available to augment the ECCS is only capable of providing 5 to 10 minutes of core boil-off before the core uncovers.

6.2.3.4 Category 4: SBLOCAs that Quickly Depressurize the RCS to the CFT Pressure

Break sizes from 0.06 to 0.25 ft^2 will depressurize the RCS to the CFT pressure within five to twenty-five minutes after break opening. The severity of the results somewhat depends on the total HPI flow delivery early during the transient with CLPD breaks limiting the amount of flow that can reach the core. The CFT fill pressure is most important in the overall severity of results, because the CFT flow injects directly into the reactor vessel downcomer instead of bypassing out of CLPD breaks, so it halts the core mixture level decrease and initiates vessel refill. Lower CFT pressures (nominal less operational band and uncertainty) delay the CFT refill which minimizes the core mixture level and maximizes the predicted PCT should core uncovering occur.

The EFW fill logic, EFW flow rate, and operator-initiated secondary side depressurization are less important on these transients because of the larger break size. Nonetheless, higher EFW flow rates and secondary side cooldown can be beneficial in accelerating the RCS depressurization rate, holding up slightly more liquid in the hot leg and steam generator tubes, and reducing the steam generator reverse heat transfer.

6.2.3.5 Category 5: SBLOCAs that Depressurize the RCS Nearly to the Containment Pressure

Break sizes greater than 0.25 ft^2 (but less than the maximum break size that does not predict initial clad DNB during the first several seconds of the SBLOCA, 0.50 ft^2 for the Mark-B-HTP fuel design) are sufficiently large to depressurize the RCS to approximately that of the containment pressure. These breaks are not large enough to reverse core flow, which would cause the cladding to exceed the critical heat flux upon break initiation. The core is shut down via control rods and cooled during the blowdown transient, which maintains a two-phase mixture that keeps the fuel pin cladding within a few degrees of saturation so long as the mixture level remains above the top of the core. During the rapid depressurization to the CFT pressure, some of these break sizes may cause some core uncovering and cladding heatup. For breaks with the RC pumps running for the first minute after LSCM, this situation is exacerbated, because the pumps push addition ECCS and RCS liquid to the break site. The duration of the uncovering is short since CFT flow quickly refills the core and quenches the clad temperature. Depressurization to the LPI initiation pressure will occur within the first two to ten minutes post LOCA, therefore HPI inflow during these first several minutes is of little consequence for core cooling prior to the time of core refill so long as the LPI liquid reaches the vessel. After the CFTs are empty and the core is refilled, however, LPI and HPI flow provide both diversity of makeup injection sites and more than sufficient ECCS flow to match the core boil-off rates. (NOTE: The dependency on HPI is greater in the event of a CFT line break as the CFT flow from the broken line is directly lost into containment as is a substantial fraction of the cross connected LPI flow. In this special break configuration, the unbroken CFT, HPI flow, and intact CFT line LPI flow must be capable of accounting for the necessary core cooling.)

6.2.3.6 Category 6: LBLOCAs

Break sizes greater than 0.50 ft^2 for the Mark-B-HTP (up to a full double-ended break of any RCS pipe) are considered large break LOCAs. These break sizes are of sufficient size to cause the cladding to exceed the critical heat flux upon break initiation. If the break is on the cold leg side of the core, the core flow may reverse during the blowdown phase. Core cooling during the blowdown and refill phases of the LOCA is by high velocity steam or steam plus liquid droplets. The final cladding quench occurs when the core is reflooded by CFT and LPI flow within minutes after break opening. Although not considered as a separate category, the LBLOCA spectrum is divided into two break ranges, the minimum break area to 2.0 ft^2 and greater than 2.0 ft^2, for the purpose of EM methods. The smaller range is analyzed using the transition LOCA method. These breaks are typically much less limiting than the larger break sizes.

6.2.4 SBLOCA Evolution with Credit for SG Depressurization with the FCS

The SBLOCAs have traditionally been placed in five categories based on the characteristic of each break as discussed in the previous subsections without credit for operator initiated SG FCS via the new ADVs. The introduction of the FCS for CR-3 with the EPU results in a forced rapid depressurization of the secondary side to a pressure of 350 psig that is modulated thereafter. The resulting effect on the transient progression has challenged the previously defined traditional break categories described in Sections 6.2.3.1 through 6.2.3.4 because of the SG heat removal induced by the FCS. The SBLOCA spectrum with the FCS effectively results in the merging of the categories when the FSC is credited at 10 minutes following LSCM. This merging combines the four smaller categories of breaks into two groups, with the larger SBLOCA remaining distinct because its PCT consequences occur prior to initiation of the FCS. This merger results in three distinct characterizations based on the break size, which is consistent with the EM study (BAW-10192P-A [1], Volume II, Appendix A, Section A.7). These three categories are defined as small, intermediate and large SBLOCAs which when combined with the LBLOCA transition and LBLOCA break sizes encompass the entire range of break sizes that must be considered.

With the FCS, the small SBLOCAs consists of the traditional Category 1, Category 2 and most of the Category 3 breaks, intermediate SBLOCAs consist of the largest Category 3 and the Category 4 breaks, and large SBLOCAs consist of the Category 5 breaks. The characteristics for each of these new groups of SBLOCAs are discussed next based on the observed transient progression with the FCS.

Small SBLOCAs

The smallest range of breaks sizes extends from the smallest break that exceeds the normal makeup system capacity to the break sizes that can effectively remove the core decay heat energy within a few minutes after reactor trip. This range of breaks encompasses the full range of the traditional Category 1 and 2 breaks and most of the Category 3 break sizes. This small break range is approximately 0.002 ft^2 to 0.05 ft^2 at the CR-3 EPU core power level. The smallest to largest break size in this grouping varies by a factor of 25 and encompasses some considerable timing differences in system evolutions going from the minimum to maximum break size. The one key consideration for these breaks is that the rate of ECCS inventory loss is small and none of these breaks could uncover the core before the FCS is initiated. After the FCS is initiated and the secondary side depressurization lowers RCS pressure, the combination of the higher HPI flows, SG condensate from the EFW heat removal, along with some CFT discharge for the larger breaks in this group keep the minimum core mixture level continuously above the top of the core.

The smallest break size that exceeds the makeup flow only has a small net outflow of a few gpm. The break flow plus RCS outflow from letdown and leakage may only exceed the inflow of the normal makeup and RCP seal injection inleakage. Such a small leak of a few gpm will take hours to days to deplete the RCS to the point that the core could have insufficient liquid to keep it continuously covered with a two-phase mixture capable of removing the core decay heat. For these scenarios, the break cannot remove the core generated energy so the SG provides nearly all the core heat removal via use of the EFW flow. If the EFW flow is inadequate, the RCS will repressurize to the PORV and pressurizer safety valve lift pressure. While HPI may be initiated, the break flow does not really challenge the HPI delivery rate. The FCS, may not be very effective at depressurizing the RCS for the smallest break sizes because the loop flows could be interrupted and the SG tube levels may not be low enough to achieve boiler condenser cooling. Under these conditions, the RCS pressure will remain significantly above the secondary side pressure that is controlled to 350 psig. Break sizes smaller than roughly 0.02 ft^2 may not reach the CFT pressure before the HPI matches the core decay heat rate and begins to refill the RCS.

As the break size is increased above 0.02 ft^2, the break mass loss will be sufficient to cause the water level inside the SG tubes to drop below the EFW spray elevation and a continuous boiler condenser cooling (BCC) is maintained. This SG heat removal augments the break energy relief and allows these break sizes to depressurize below the CFT fill pressure. The credit for the EFW condensate, higher HPI flow, and some CFT flow also keeps the minimum core mixture level continuous above the top of the heated core region. Therefore, the credit for the FCS at 10 minutes ensures that none of these breaks will predict core uncovering.

Intermediate SBLOCAs

As the CLPD RCS break size gets larger than approximately 0.05 ft^2, the net outflow increases and the break energy relief increases such that the heat removal from the break and the ECCS can match the core decay heat early in the event relative to the small SBLOCAs. There is less reliance on the SG heat removal via EFW flow during the first few minutes after reactor trip. With higher RCS inventory loss rates the HPI flow capacity and flow split is insufficient if the system remained at higher RCS pressures. However, the FCS depressurizes the secondary side at 10 minutes after the LSCM to induce primary-to-secondary heat transfer that in turn depressurizes the RCS to increase the HPI flow and obtain some CFT flow. For these break sizes, EFW, HPI, and CFT work together to mitigate the consequences of the LOCA. The effects of EFW heat removal help to depressurize the RCS. These break sizes will not keep the CLPS piping full, so the condensate from the EFW BCC cooling will not drain into the reactor vessel and augment the HPI in supplying core boil-off. Use of the FCS at the EPU power level may keep some of the smaller break sizes in this category from uncovering, but there will be some with partial core uncovering and PCT escalations for the intermediate SBLOCA break sizes in this category.

The largest break size in this group is the one that is big enough to depressurize the RCS below the 350 psig before the FSC is initiated. This break size is roughly 0.25 ft^2. Therefore, the intermediate group of break sizes ranges from approximately 0.05-ft^2 to 0.25 ft^2, which encompasses the largest of the traditional Category 3 breaks and all of the Category 4 break sizes. These break sizes will likely produce the most severe PCT for the spectrum of SBLOCAs.

Large SBLOCAs

The larger SBLOCA break sizes are of sufficient size that they depressurize the RCS below the CFT fill pressure (~600 psig) and below the secondary side ADV modulation pressure (~350 psig) during the first 10 minutes of the event. These break sizes remove all the core decay heat via the break so EFW flow has little to no effect on the event. The HPI, CFT, and longer-term LPI flows manage the RCS inventory loss and refill the system to limit the duration and magnitude of the core uncovering period. The rate of RCS liquid inventory loss is severe for these cases so core uncovering is predicted, but its uncovering period is short and the CFT flow refills the core and abates the core heat up. Flow from one HPI train and one CFT augmented with partial flow from one LPI train (from the new LPI cross-tie modification) provided sufficient ECCS flow for the analyzed spectrum of larger CFT line breaks (0.30 ft^2 through 0.44 ft^2) to maintain a minimum mixture level above the top of the core without any core heatup. For the smallest analyzed 0.25-ft^2 CFLB, the RCS to containment pressure differential did not allow for the actuation of the LPI flow available through the cross-tie line. Nonetheless, there was no core heatup for this small break size since the ECCS flow from one HPI train and one CFT was sufficient to maintain the core covered. The large SBLOCAs with the FCS are no different than the traditional Category 5 breaks that range from approximately 0.25 to 0.50 ft^2.

6.2.5 Full Power Spectrum Analysis with FCS

The following subsections describe the results of the analyzed SBLOCA spectrum based on the characteristics of each of the break categories identified in Section 6.2.3.1 through Section 6.2.3.5. The entire break spectrum was analyzed to ensure that the limiting case was appropriately determined for the Mark-B-HTP fuel design at the EPU conditions with the ROTSGs. Note that in the discussion and results tables for SBLOCA spectrum of analyses is broken into the traditional categories of SBLOCAs. This categorization, originally established for cases with no credit for FCS, is retained for consistency with pre-EPU LOCA summaries of results. However, Sections 6.2.5.1 through 6.2.5.6 discuss the effect of the FCS on the spectrum of analysis results, and thus revisit the SBLOCA break categories based on the characteristics observed due to the system and transient response to the FCS. Included in these effects is the interaction of the FOGG logic described previously. The net effect of the interrupted EFW as a result of intermittent FOGG actuation is described in the subsections, with the exceptions of Categories 5 and 6, which are sufficiently large break sizes that their accident progressions are unaffected by EFW interruptions or FOGG-induced asymmetric depressurization. For Categories 1 through 4 however, the net effect of the interrupted EFW was found to have negligible effects on the transient progression of the CR-3 EPU SBLOCA analyses with FCS and did not adversely affect compliance with 10 CFR 50.46 acceptance criteria [75].

6.2.5.1 Category 1 Break Sizes (0.002 to 0.005 ft^2)

While the BWNT LOCA EM [1] SER Limitation 10 states that the minimum SBLOCA break size that should be considered is the 0.01-ft^2 break, a smaller break size is considered to demonstrate full compliance with 10 CFR 50.46. Generally, the Category 1 breaks are not analyzed because the consequences are bounded by the larger Category 2 break sizes. The Category 1 break sizes produce slower RCS inventory loss rate and are typically less challenging to the capacity of the ECCS to provide adequate core cooling. These break sizes are more reliant on EFW flow to remove a significant fraction of the core decay heat and maintain the RCS near the secondary side pressure until the HPI is capable of matching and exceeding the core decay heat energy addition. This matchup generally occurs well before sufficient RCS inventory loss causes a core uncovering to occur. Because of the long transient duration, there is ample time for SG heat removal provided by the actuation of FCS, which contributes to HPI-core decay heat matchup. As a demonstration case, a 0.005-ft^2 CLPD break was analyzed at EPU conditions. The results of this break are summarized in Table 6-1 and shown in Figures 6-1 through 6-4.

A 0.005-ft^2 CLPD SBLOCA was analyzed to demonstrate adequate core cooling is assured for the largest Category 1 break sizes. The RCS initially depressurized (Figure 6-1) and achieved a low pressure reactor trip of 1890 psia and low RCS pressure ES actuation of 1640 psia at 148 and 307 seconds, respectively (Table 6-1). Offsite power was lost at the time of reactor trip resulting in the loss of MFW and the RCPs. Adequate subcooling margin was lost five seconds after reactor trip. The RCS flow coasted down to natural circulation flow rates and the RV upper plenum and hot legs saturated. The void accumulation in the hot legs interrupted the natural circulation and the loss of RCS flow decreased the SG heat removal. The RCS break flow could not remove the core decay heat so the RCS began to repressurize after roughly 600 seconds. The ADVs were opened by the operators via the FCS system at roughly ten minutes after LSCM and the secondary side depressurized rapidly to the 350 psig modulation pressure (Figure 6-1). The primary side pressure did not respond because the high system levels kept the liquid level at or above the EFW spray injection elevation. Intermittent hot leg liquid spillovers and short duration high-elevation boiler condenser cooling (BCC) periods provided some sporadic SG heat removal that depressurized the RCS momentarily. However, the SG heat removal was not continuous, so the RCS remained at a pressure well above the secondary side control pressure.

The RCS minimum liquid inventory remained near to top of the hot legs for the entire event so there was no serious challenge to core uncovering as shown in Figure 6-2. The break flow, shown in Figure 6-3, cycled from liquid to steam during the event as the ECCS flow, shown in Figure 6-4, made up for most of the RCS mass loss. The combination of sporadic SG heat transfer and ECCS for this Category 1 break size provides adequate core cooling without any core uncovering during the transient. The limiting PCT is defined by the fuel pin cladding temperature of 712 F near the time of reactor trip. There was no local oxidation increase and no hydrogen generation during the transient.

Upon review of the EFW flow response for this category, it was found that the SG pressures approached the ADV modulation pressure, the pressure in SG B oscillated near 600 psig for a duration of about 100 seconds while the pressure in SG A continued to decrease to 350 psig (Figure C-1, Reference [3]). This resulted in a brief period of EFW cycling on and off to SG A due to the FOGG logic. As soon as both SGs reached the ADV modulation pressure however, EFW remained constant to both SGs for the remainder of the transient (Figure C-78, Reference [3]).

The primary side pressure did not immediately respond to the FCS depressurization at 10 minutes after LSCM because the high system levels kept the liquid level at or above the EFW spray injection elevation. Intermittent hot leg liquid spillovers and short duration high-elevation boiler condenser cooling (BCC) periods occurred after the ADV modulation pressure was reached, however, the SG heat removal was not continuous, so the RCS remained at a pressure well above the secondary side control pressure throughout the transient analysis period.

For the smaller break sizes in this category, there could be similar periods during which FOGG could turn off EFW to either SG during the FCS depressurization. As shown for the 0.005 ft2 break, however, these short periods of no EFW would be inconsequential to the results since the primary liquid levels would be at or above the EFW injection elevation so that EFW would have only a little effect on heat transfer during the FCS depressurization period. Furthermore, the short period of time the EFW is off in SG A does not produce a more significant drop in the secondary side level for SG A versus SG B as seen in the comparison of Figures C-4 and C-5 of Reference [3]. Consequently, no hot channel clad temperature excursions were observed in Figure C-31 of Reference [3].

6.2.5.2 Category 2 Break Sizes (0.005 to 0.035 ft^2)

Break sizes analyzed in this category include 0.01- and 0.03-ft^2 CLPD breaks and a break in the HPI line with an area of 0.02463-ft^2 with throttled and unthrottled HPI flow. The HPI line break location was modeled in the HPI line providing normal makeup just upstream of the HPI nozzle. For the full-area HPI line break, the thermal sleeve in the nozzle was assumed blown out coincident with the break opening. The cross-sectional area of the pipe without the thermal sleeve limits the break area to 0.02463-ft^2. The results of these breaks are summarized in Table 6-2 and shown in Figures 6-5 through 6-10.

These small LOCAs challenge the EFW and HPI systems in providing adequate steam generator heat removal and core injection flow. The Category 2 break sizes present a slightly greater challenge to the HPI system to replace lost liquid inventory to ensure the mixture level does not drop below the top of the core. Upon break opening the RCS depressurizes initially as shown in Figure 6-5 achieving low pressure reactor trips between 23 and 74 seconds (Table 6-2). The low RCS pressure automatic ESAS actuation occurred between 45 and 130 seconds for the analyzed break sizes in this category (Table 6-2). These break sizes are not big enough to remove all the core decay heat so the RCS begins to repressurize after natural circulation is interrupted. The RCS inventory is decreasing because the HPI flow, shown in Figure 6-9, is less than the break flow shown in Figure 6-8. The inventory loss causes the liquid levels to drop into the tubes and initiate high-elevation BCC that re-establishes the SG heat removal and depressurizes the RCS. The RCS pressures for larger break sizes analyzed in this category respond to the secondary side pressure decrease (Figure 6-6) from the initiation of the FCS at ten minutes following LSCM. They both reach the CFT fill pressure and this augments the HPI flow and condensate from the EFW heat removal. The HPI flow and CFT flow plus condensate or cooling from the EFW heat removal, and CFT for the larger break sizes was effective in preventing core uncovering for any of the Category 2 break sizes (Figure 6-7). The analyses were continued until the heat removal capacity from the HPI flow was sufficient to match the core decay heat (Table 6-7). After core decay heat matchup, the reactor vessel inventory began to increase (Figure 6-7). Once the RCS pressure reaches the CFT fill pressure additional ECCS flow augments this refill process (Figures 6-5, 6-9 and Table 6-2). While the smaller break sizes did not depressurize to the CFT injection pressure by the end of the transient, break sizes larger than approximately 0.02-ft^2 will achieve good primary to secondary heat transfer and they will depressurize to the CFT injection pressure before the ECCS heat removal matches the core decay heat rate and begins to refill the RV (Figure 6-5).

For the Category 2 break sizes, EFW flow is needed until the break can remove the energy produced by the core. HPI flow must be maintained while supplied by the BWST, and then via piggyback from the LPI pumps after the sump recirculation phase is entered. Based on the Category 2 cases, it is clear that the Category 2 break sizes have adequate core cooling without any core uncovering during the transient. The minimum system liquid fraction was greater than 40 percent for each of these cases (Figure 6-10). The limiting PCT is defined by the fuel pin cladding temperature of 712 F near the time of reactor trip. There was no local oxidation increase and no hydrogen generation during the transient.

A review of the SG pressure response for these break sizes shows that the SGs exhibit some small differences in secondary pressure prior to FCS being activated. When the ADVs are opened, however, the capacity of the ADVs to relieve pressure quickly allows the SG pressures to merge and begin blowing down symmetrically prior to reaching 600 psig when FOGG circuitry could be activated (Figures D-1, D-89, and D-177 of Reference [3]). Consequently, EFW is provided continuously to both SGs throughout the FCS depressurization period.

The steam relieving capacity of the ADVs, however, clearly demonstrates that any initial SG pressure asymmetry prior to FCS actuation is overwhelmed by the ADV depressurization. There is enough time prior to reaching 600 psig for the SG pressures to fall in line with each other and prevent FOGG actuation from occurring during the FCS depressurization period (e.g., Figures D-117 and D-118; D-205 and D-206 of Reference [3]).

If FOGG logic were to briefly interrupt EFW flow to one SG for these break sizes, the secondary SG level could drop lower in the affected SG. Additionally, potential EFW condensate created, via high elevation BCC in the "early" SG, would not be added to the primary liquid volume available to the core. A review of the three break sizes in this category however show similar behavior as Category 1 break sizes in that the primary levels do not drop significantly into the high elevation EFW flow region and definitely do not reach the secondary pool elevation where pool BCM could occur. There is significant inventory available to the core so that a reduction in EFW condensate would not be detrimental to maintaining a core mixture level above the core. Although the effects described here could potentially exist, it should be noted that the brief time that the EFW would be terminated to one SG would be expected to produce negligible changes in the overall transient results.

An additional SBLOCA HPI line break with modified HPI flow was analyzed to determine the effect of unthrottled HPI flow on the PCT of the 0.02463 ft^2 [69]. The HPI line break with unthrottled HPI flow exhibits behavior consistent with the HPI line break analyzed with throttled flow. The unthrottled HPI flow rates are lower at higher pressures, resulting in faster inventory loss in the ROTSGs and hot legs. Other notable differences between the cases include CFT starting about 175 seconds sooner for the unthrottled HPI flow case, and the low-low RCS pressure ESAS setpoint (LPI) was reached about 2 minutes earlier. The transient was terminated once HPI flow matched core decay heat, which occurred almost 800 seconds earlier than the throttled HPI flow case. The core remained covered for the duration of the transient, thus there was no clad heatup and PCT was equal to the initial steady-state cladding temperature of 712 F. In addition, there was no local oxidation increase and no hydrogen generation during the transient.

6.2.5.3 Category 3 Break Sizes (0.035 to 0.06 ft^2)

Two break sizes were analyzed in Category 3, the 0.04-ft^2 and the 0.06-ft^2 CLPD break. The results of these breaks are summarized in Table 6-3 and shown in Figures 6-11 through 6-16.

This category of break sizes have larger break areas than the Category 1 or 2 breaks, and as a result the reactor trips before 17 seconds and ESAS is initiated before 34 seconds for the analyzed break sizes (Table 6-3). NC is interrupted shortly after one minute and the loss of steam generator heat removal causes the RCS to repressurize for a short time interval. The break energy relief for these larger break sizes matches the core decay heat generation rate earlier in the transient, as shown by the RCS pressure responses in Figure 6-11. While this seems to imply that this break range is less reliant on EFW and secondary side heat removal and associated condensate, it still receives considerable benefit from the FCS depressurization with the ADVs and EFW cooling to depressurize the primary side. The depressurization drives the RCS pressure down to achieve CFT injection as shown in Figure 6-15.

For these break sizes, the SG pressures show some asymmetry prior to FCS being activated and the SG pressures are already decreasing below the MSSV control pressure as the break site is capable of removing more heat. As with Category 2, when the ADVs are opened, the capacity of the ADVs to relieve pressure quickly creates a symmetric blowdown prior to the SG pressures passing through 600 psig when FOGG could be activated. Consequently, EFW flow is continuous to both SGs throughout the FCS blowdown period for these break sizes (e.g., Figures E-29 and E-30; E-117 and E-118 of Reference [3]). It should be noted that for these breaks, there is a brief termination of EFW to both SGs when the SG levels reach the natural circulation setpoint prior to FCS actuation. When the FCS begins depressurizing the secondary side, the EFW flow is initiated again at the lower flow rate of 2 inches/minute for the rest of the event. The SG level control actions are not related to FOGG logic and the EFW flow interruption is brief and symmetric. The steam relieving capacity of the ADVs clearly demonstrates that any initial SG asymmetry prior to FCS actuation is overwhelmed by the ADV depressurization. There is enough time prior to reaching 600 psig for the SG pressures to fall in line with each other and prevent FOGG actuation from occurring during the FCS depressurization period.

If FOGG logic were to briefly interrupt EFW flow to one SG for the Category 3 break sizes, the slight reduction in SG heat transfer for a short period of time would be inconsequential to the SG levels and RCS pressure response. The EFW condensate that could potentially be available to the core would also be a small amount for the short period of EFW termination. Consequently, any small effect FOGG may have on the EFW flow would not change the overall transient progression nor shift the limiting cases to this category.

The break flow rates, shown in Figure 6-14, are well in excess of the HPI flow, shown in Figure 6-15, prior to CFT discharge. This mismatch leads to significant RCS liquid inventory loss from the break discharge, core boil-off, and flashing. The RCS liquid fraction (Figure 6-16) decreases below 40 percent for both of these Category 3 breaks. The minimum mixture level for the smaller 0.04 ft^2 CLPD break dropped just below the top of the heated core for a short period but there was no clad heatup observed for this case (Figures 6-12 and 6-13). The 0.06 ft^2 CLPD case, however, had additional RCS liquid loss and its minimum mixture level decreased to approximately 9.9 ft (Table 6-3 and Figure 6-13). The clad temperature reached a maximum of 1328 F as shown in Figure 6-12. The 0.06 ft^2 break was large enough to depressurize the RCS to approximately 350 psig, the pressure at which the secondary side is modulated with the ADVs.

The limiting PCT for the Category 3 break sizes that were analyzed was 1328 F (Table 6-3). Since the cladding temperatures were above 1000 F, there was some metal water reaction and the maximum local oxidation was less than 0.5 percent of the cladding thickness and the whole core hydrogen generation was less than 0.02 percent of the entire core. Since the RCS pressure remained above the LPI shutoff head, no LPI flow is supplied to the system for these break sizes. Therefore, the LPI cross-tie modification has no effect to the result of the Category 3 break sizes.

6.2.5.4 Category 4 Break Sizes (0.06 to 0.25 ft^2)

Category 4 break sizes analyzed include breaks in the RCP discharge piping with break areas of 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, and 0.20 ft^2. The results of these breaks are summarized in Table 6-4 and the results for a subset of these cases are shown in Figures 6-17 through 6-22.

These break sizes depressurize the RCS rapidly from the break flow (Figure 6-20) and achieve low pressure reactor trip and ESAS trips within 7 and 18 seconds, respectively (Table 6-4). The break energy discharge from these larger break sizes depressurizes the RCS fairly continuously, causing them to approach or drop below the secondary side MSSV controlled pressure before the operators initiate the FCS (Figure 6-17). The larger 0.15 ft^2 and 0.20 ft^2 cases were both sufficiently large that they achieved CFT actuation (Table 6-4 and Figure 6-21) and depressurized below 350 psig before the FCS was actuated at 10 minutes after LSCM (Table 6-4 and Figure 6-17). The smallest Category 4 break size of 0.07 ft^2 depressurized the RCS to the CFT fill pressure within 8 minutes of operator initiation of the FCS. The FCS depressurized the secondary side to the modulation pressure of ≤350 psig within the first ten minutes of the event. Even with the CFT flow augmenting the HPI flow, they could not provide enough ECCS to keep up with the RCS liquid loss and core boil-off rate such that the core mixture level dropped below the top of the core for all break sizes (Figure 6-19). As a result, the upper core cladding experienced heatup with maximum PCTs between 1210 and 1426 F (Table 6-4 and Figure 6-18).

Only two hot channel heated segments uncovered for all break sizes smaller than 0.14 ft^2 and as a result they all had comparable PCTs (Table 6-4). The larger break sizes in this category uncovered 4 and 5 segments. The 0.14- and 0.15-ft^2 cases had slightly lower PCTs than the adjacent cases because their minimum core mixture level occurred near the time of the FCS cooldown at 10 minutes post LSCM (Table 6-4). Smaller break sizes in this Category had core uncovering periods ranging from 2800 to 3800 seconds that resulted in higher clad temperatures (Table 6-4).

The highest PCT for this class of breaks was 1426.0 F for the 0.13 ft^2 break size, which is the limiting PCT for the entire SBLOCA spectrum (Table 6-4). This case also had the maximum local oxidation that was less than 0.7 percent of the cladding thickness and the whole core hydrogen generation was less than 0.02 percent of the entire core. By the end of the transient, the analyzed break sizes larger than 0.1 ft^2 had reached RCS pressures that allowed LPI delivery to begin. In each case the CFTs were still discharging when the analyses were stopped or a termination criterion indicating long-term core cooling had been initiated.

The break sizes for the Category 4 breaks are sufficiently large that EFW heat removal is beneficial early but it is only significant during the FCS cooldown period to the 350 psig modulation pressure. The combination of HPI, CFT, and LPI flow (for some of the larger cases) ultimately exceeded the break flow and limited the minimum RCS liquid inventory to between 20 to 35 percent of the initial RCS liquid volume (Figure 6-22). The initial RCS inventory loss was partially compensated for by the HPI injection. The CFT flow in combination with the HPI flow halted the inventory loss and they initiated a core refill to mitigate the consequences of these break sizes. The calculations were stopped after the core was quenched and the pumped injection heat removal exceeded the core decay heat rate.

For this break category as for the other categories, the SG pressures show some asymmetry prior to FCS being activated. The SGs are already depressurizing for these breaks when the ADVs are opened at 10 minutes after reactor trip and LSCM. The capacity of the ADVs to relieve pressure quickly creates a symmetric depressurization throughout the blowdown period, resulting in continuous EFW flow to both SGs throughout the FCS depressurization. Similar to Category 3 breaks, there is a brief termination of EFW to both SGs when the SG levels reach the natural circulation setpoint prior to FCS actuation (e.g. Figures F-29 and F-30 of Reference [3]). When the FCS begins depressurizing the secondary side, the EFW flow is initiated again at the lower flow rate of 2 inches/minute for the rest of the event. The SG level control actions are not related to FOGG logic and the EFW flow interruption is brief and symmetric.

The break sizes in Category 4 do not generate secondary side pressures high enough keep the MSSVs open after the initial lift, post-reactor trip. The SGs begin depressurizing prior to FCS actuation. Some pressure asymmetry is seen prior to FCS, but as for the other breaks, the steam relieving capacity of the ADVs bring the pressures back into symmetry before FOGG logic could be actuated. Consequently, there is no effect of initial SG pressure asymmetry on the FCS depressurization period for the Category 4 breaks.

If FOGG logic were to briefly interrupt EFW flow to one SG for the Category 4 break sizes, the slight reduction in SG heat transfer for a short period of time would be inconsequential to the SG levels and RCS pressure response. With respect to the lost potential for EFW condensate in the affected SG, these break sizes do not keep the cold leg pump suction piping full, so the condensate from the EFW BCC cooling would not drain into the RV. Therefore the small reduction in EFW condensate is inconsequential to this break category. These offsetting and negligible effects would not change the overall transient progression for the Category 4 breaks and all acceptance criteria would continue to be met for the limiting cases.

This break category included the limiting PCT for all SBLOCAs that were analyzed. There are additional plotted results for the limiting PCT case, which was the 0.13 ft^2 CLPD break, shown in Figures 6-35 through 6-48, and in Table 6-4. The primary, CFT, and secondary pressures, RV collapsed levels, break and ECCS flows, break volume void fraction, RCS and secondary side levels, RVVV flows, core mixture levels, and core cladding and steam temperatures are provided in these plots.

6.2.5.5 Category 5 Break Sizes (0.25 to 0.50 ft^2)

Category 5 break sizes analyzed include breaks in the RCP discharge piping with break areas between 0.25 ft^2 and 0.50 ft^2 with either RCP trip concurrent with low RCS pressure trip based on an assumed loss of offsite power (LOOP) or operator initiated RCP trip one minute after loss of subcooling margin with offsite power available. It also includes a spectrum of CFT line breaks with LOOP and 1-minute RCP trip. The results of these breaks are summarized in Table 6-5 and Table 6-6 and shown in Figures 6-23 through 6-34, 6-49 and 6-50.

The Category 5 break sizes are greater than 0.25 ft^2 but less than the maximum break size that does not predict initial clad DNB during the first several seconds of the SBLOCA from full power (0.50-ft^2 for the Mark-B-HTP fuel design) and are sufficiently large to depressurize the RCS to approximately that of the containment pressure (Figures 6-23, 6-29, 6-49). These break sizes depressurize the RCS rapidly (Figure 6-23 and 6-29) from the break flow (Figure 6-26 and 6-32) and achieve low pressure reactor trip and ESAS trips within 1 and 7 seconds, respectively (Table 6-5 and 6-6). The RCS pressure for these break sizes is below 350 psig before the operators initiate the FCS, so it is of no consequence to the severity of these cases.

These break sizes cause the RCS to depressurize continuously and achieve CFT actuation and LPI flow earlier in the transient than the Category 4 break sizes (Tables 6-5 and 6-6). During the rapid depressurization to the CFT pressure, some of these break sizes have some short lived core uncovering and cladding heatup (Figures 6-24 and 6-30). The 1-minute RCP trip cases were evaluated to determine if they were more limiting than the LOOP cases primarily due to the continued RCP operation changing the fluid conditions at the break, potentially resulting in more RCS liquid loss (Figures 6-28 and 6-34). While the break phase can change, the RV core and downcomer levels can also be altered by the RCP operation for up to 1 minute. The analyses confirm that the LOOP condition produces the most limiting PCT consequences for the Category 5 CLPD cases.

The highest PCT for this class of CLPD breaks was generated by the 0.30 ft^2 break size with LOOP. It had a PCT of 1224 F and it also had the maximum local oxidation that was less than 0.2 percent of the cladding thickness. The whole core hydrogen generation was less than 0.01 percent of the entire core (Table 6-5). By the end of the transient, all of the CLPD breaks analyzed in this category had reached pressures that allowed LPI delivery to begin (Table 6-5). In each case, the CFTs were still discharging when the analyses were stopped (Table 6-5). This was after the core was completely recovered and the PCT had occurred and the cladding temperatures were decreasing with the level increasing, indicating that the ECCS flow matched flashing plus core boil-off due to decay heat and wall metal heat contributions (Figures 6-25 and 6-31). Therefore, the analyses confirmed that, for Category 5 CLPD breaks, the HPI, CFT, and LPI combined ECCS flow capacity was sufficient to recover the core and to provide adequate to abundant long-term cooling for these Category 5 CLPD breaks.

Also analyzed in the Category 5 break spectrum is a series of CFT line break sizes. The CFT line break is unique because it results in the loss of flow from one CFT and its associated LPI line. The maximum break area for the CFT line breaks is limited to 0.44 ft^2 by the cross-sectional area of the nozzle insert. This break location represents a more severe degradation of the CFT and LPI ECCS flow capacity when compared to a CLPD break, however, the available HPI flow increases because all HPI flow reaches the RV downcomer and core region. The LPI system was modified with an always open cross-tie line to mitigate the CFT line breaks for CR-3 at the EPU power level. Without LPI flow for the biggest CFT line break, unacceptable core cooling results would have been obtained for the offsite power case with the 1-minute RCP trip. The LPI cross-tie line is designed to provide some portion of the LPI flow into the RCS before the core could uncover and heat up. Analysis of this limiting 0.44-ft^2 case with the LPI cross-tie line flow at the EPU power level showed that the minimum core mixture level remained above the top of the core without any core heat up (Figure 6-31). The partial flow from one LPI train, combined with full flow from one HPI train with one CFT, provided adequate to abundant core cooling for this limiting single failure. The limiting PCT for this case is defined by the fuel pin cladding temperature of 712 F near the time of reactor trip (Table 6-6). There was no local oxidation increase and no hydrogen generation during the transient.

The LPI cross-tie line flow is a function of the pressure difference between the RCS and the containment. A smaller break size will increase the RCS pressure and consequently the pressure difference between the RCS and containment. As a result LPI flow into the RCS will decrease with break size and for much smaller breaks no LPI flow will be obtained. However, as the break size is decreased, the quantity of RCS liquid lost from the break will also decrease. In addition, the flashing and passive metal and fuel stored energy boil-off contributions will reduce. To evaluate these competing effects, a spectrum of CFLB cases were analyzed representing five break sizes of 0.44, 0.40, 0.35, 0.30, and 0.25 $ft^2$with LOOP and offsite power available, and credit for the operators tripping the RC pumps within 1-minute of LSCM. These are relatively large break sizes that caused a rapid RCS depressurization to the CFT fill pressure and below the FCS modulation setpoint of 350 psig before FCS could be actuated (Figures 6-49 and 6-50). Therefore, while the FCS does not influence the results any of these break sizes, the minimum core mixture level remained above the top of the heated core (Table 6-6).

The analyses showed that some LPI flow was obtained for all cases except the 0.25-ft^2 CFLB (Table 6-6). For this smallest analyzed size, the RCS-to-containment pressure differential did not allow for the injection of the LPI flow available through the cross-tie line (Figure 6-49 and 6-50). The minimum core mixture level was obtained for the 0.35-ft^2 CFLB case with 1-minute RCP trip (Table 6-6). Any break smaller than 0.25 ft^2 would lose less RCS liquid and have lower flashing or metal heat contributions, and the minimum core mixture level would be obtained later in the event when the decay heat is lower. Therefore, the spectrum of CFLBs has been adequately considered and it has been shown that the LPI cross-tie modification precludes uncovering the core with the limiting PCT defined by the fuel pin cladding temperature of 712 F near the time of reactor trip. The results of these cases demonstrated that one CFT and one train of HPI combined with LPI through the cross-tie connection, when conditions permit, provide adequate to abundant ECCS flow to mitigate the consequence of any CFLB.

6.2.5.6 Category 6 Breaks

These breaks are large break LOCAs because they result in initial cladding DNB from the pressure and core flow changes. The limiting LBLOCAs are determined by the largest CLPD break sizes. As the break size decreases, the PCTs decrease. As a result, specific analysis of break sizes between the Category 5 Breaks and the limiting LBLOCA were not explicitly performed. See Section 5.0 for the discussions of the LBLOCAs.

6.2.6 Reduced Power Spectrum Analyses without FCS

The full spectrum of breaks consisted of a number of break sizes analyzed at the CLPD and HPI locations. The specific break areas, in square feet, analyzed at the CLPD location for the partial power spectrum were: 0.01, 0.03, 0.04, 0.055, 0.06, 0.07, 0.08, 0.10, 0.12, 0.14, 0.16, 0.20, 0.30, and 0.50. The specific break areas at the HPI location were 0.02, 0.022, and 0.02463 ft^2. All cases were run with LOOP conditions.

In addition to the base cases analyzed in Section 8.0 of Reference [65], which utilize EFIC level rate controlled EFW flows, additional sensitivity studies were performed in [65] to examine the effect of minimum and maximum EFW flow rates. In some cases, primarily among Categories 2 and 3, the EFW flow sensitivity studies produce more limiting PCT values. In the category discussions below, only the most limiting cases among the EFIC controlled and EFW sensitivity studies are summarized. However, a detailed compilation of PCTs versus break size can be seen in Table 6-11 and Figure 6-99.

6.2.6.1 Category 2 Break Sizes (0.005 to 0.035 ft^2)

Scenarios analyzed in this category include breaks in the RCP discharge piping with an area of 0.01 ft^2 and 0.03 ft^2 and the three HPI line breaks just upstream of the HPI nozzle. The results are summarized in Table 6-7 and select plots are shown in Figures 6-51 through 6-54.

For the breaks analyzed in this category, the RCS depressurization led to boiling and flashing in the core, and the steam flashed in the hot legs accumulated in the HL U-bend region. This voiding quickly interrupted natural circulation. With primary-to-secondary heat transfer momentarily interrupted due to the loss of flow, a distinct RCS repressurization was observed for these break sizes. Repressurization continued until the SG tube liquid levels dropped below the EFW nozzle elevation. When EFW is injecting on the outside of the tubes, the EFW film induces high-elevation boiler-condenser cooling (BCC) where steam condenses in the tubes and some of the EFW liquid boils off. Breaks in this category observe longer periods of high-elevation BCC since the break size is small and unable to depressurize the system without primary-to-secondary heat removal early in the event, when the decay heat is high. With SG heat removal, the primary system depressurizes and break flow decreases while HPI flow increases. Approximately 60 to 120 minutes after reactor trip, the decay heat decreased to the point where ECCS heat removal could match the core decay heat. Once the core is quenched and the ECCS pumped injection matches or exceeds the core decay heat, then the transient analyses are terminated because the short-term core cooling is assured.

Since the break sizes in this category rely heavily on EFW induced high-elevation BCC, a sensitivity study was performed to confirm which EFW flow conditions could result in the most severe results: the EFIC level rate EFW flow, a constant minimum EFW flow, or a maximum EFW flow from two EFW pumps. The most limiting results were generated by the maximum EFW flow with credit for the operator initiated LSCM level change prior to 5 minutes. While the traditional timing for credit in raising the secondary side level to the LSCM value is 20 minutes following LSCM, early fill at a maximum rate fills the SG prior to when the primary level decreases to the elevation where high-elevation BCC can occur. The loss of primary side condensate plus lower HPI flow due to the elevated RCS pressure, combined to give more limiting results. The maximum EFW flow caused the larger break sizes of this category to enter the boiling pot phase earlier and undergo more core uncovering. The maximum EFW flow will also increase the break size that predicts core uncovering. The 0.01-ft^2 break did not predict core covering for any EFW flow rate.

The HPI line breaks were significantly more limiting when analyzed with maximum EFW flow rate because the flow reaching the RCS is lower than it is for a CLPD break at the same pressure. This is because the asymmetric pressure difference causes loss of more HPI out of the broken HPI line. The limiting PCT for the category of breaks reached 1326.5 F for the largest (0.02463-ft^2) HPI line break. The largest HPI line break predicted the most limiting results with a 20 minute reset of the LSCM level.

6.2.6.2 Category 3 Break Sizes (0.035 to 0.06 ft^2)

Scenarios analyzed in this category include breaks in the RCP discharge piping with an area of 0.04, 0.055, and 0.06 ft^2. The results are summarized in Table 6-8 and select plots are shown in Figures 6-55 through 6-58.

These breaks sizes also underwent RCS repressurization after interruption of natural circulation like the Category 2 breaks; however, they resumed steady RCS depressurization once high-elevation BCC was established. These larger break sizes lose liquid inventory faster, thus shortening the time until the high-elevation BCC is established. The RCS reaches the CFT fill pressure for all of these break sizes and the CFT injection helps the HPI match core decay heat and begin to refill the core. The cladding temperatures reached a maximum at or within a few hundred seconds after CFT injection. The additional ECCS not needed to remove core decay heat refilled the core and the liquid levels continued to rise as pressure decreased. The transients were terminated after the core was quenched and the pumped injection matched or exceeded the core decay heat.

Similar to the Category 2 breaks, the smaller breaks in this range (0.04 and 0.055 ft^2) proved to be significantly affected by secondary side heat transfer. As a result, the maximum EFW cases with a minimum LSCM level reset time provided the most limiting PCTs because they reached the LSCM setpoint earlier, shortening the duration of high-elevation BCC. The highest Category 3 PCT of 1374.1 F was predicted for the 0.055 ft^2 CLPD break with maximum EFW flow.

6.2.6.3 Category 4 Break Sizes (0.06 to 0.25 ft^2)

Scenarios analyzed in this category include breaks in the RCP discharge piping with break areas of 0.07, 0.08, 0.1, 0.12, 0.14, 0.16, and 0.20 ft^2. The results are summarized in Table 6-9 and select plots are shown in Figures 6-59 through 6-62.

These break sizes caused the RCS to depressurize faster with a shorter lived high-elevation BCC prior to the RCS depressurizing to the secondary side pressure. The faster inventory loss caused these breaks to enter into the boiling pot mode earlier, than the Category 2 and 3 breaks. This category includes cases which underwent momentary repressurization as well as those at the larger end of the spectrum which continuously depressurized. All of the break sizes display an increased depressurization rate at the initiation of high elevation BCC, but the depressurization rate slowed when the SG pressure was reached.

Even though the RCS depressurized fairly quickly, allowing the CFT injection to begin relatively early in the event, partial core uncovering did occur for all breaks in this category. Clad heatup occurred in the upper core regions. The core mixture levels for the larger breaks in this category reached their initial minimum values at, or within a few seconds after, the start of CFT injection. The limiting Category 4 PCT was predicted by the 0.08 ft^2 CLPD break as 1406.9 F with EFIC level rate controlled EFW with a 20 minute LSCM level reset. This PCT was also the limiting value for the partial power SBLOCA spectrum for any EFW flow condition.

These breaks are large enough that the early transient primary-to-secondary heat transfer is much smaller and reverse heat transfer is predicted relatively quickly. The limiting PCT for all cases larger than 0.06 ft^2 was predicted by the EFIC EFW fill rate while the PCTs for the minimum or maximum EFW flows are similar to or less than the EFIC PCT. The EFW flow variations were observed to change the primary and secondary side depressurization rates. The primary difference was during the reverse heat transfer period, when higher EFW flows depressurize the secondary side faster. Since EFIC gives the lowest EFW flow rates during the depressurization phase, the higher primary pressure minimizes CFT flow rates and the results are similar to slightly worse.

These break sizes reached lower core mixture levels than the smaller break sizes therefore more of the core was uncovered. The duration of core uncovering was influenced by RCS depressurization rate as it reached the CFT sooner and achieved higher CFT and HPI discharge rates.

It is also noted that the maximum PCT case had a slightly larger value due to an artificially elevated secondary peak in cladding temperature after the core began to refill. The secondary peak is attributed to a high cross flow from the hot channel to the average channel during refill. The flow used in the core heat transfer model does not account for the cross flow and because of this, the heat transfer decreased and resulted in a secondary peak that is slightly higher than the peak that coincides with the minimum core mixture level. However, in the interest of conservatism, the artificial secondary cladding temperature peak is reported. It is approximately 50 F greater than the initial peak from before the level began to increase (Figure 6-72).

For most Category 4 breaks, the core was recovered and refilled before the RCS depressurized sufficiently to allow LPI flow to enter the reactor vessel. In each case, the CFTs were still discharging when the analyses were stopped due to core quench and pumped injection decay heat matchup. Successful short term core cooling was confirmed for Category 4 breaks, and the path to adequate long-term cooling is evident.

6.2.6.4 Category 5 Break Sizes (0.25 to 0.50 ft^2)

Scenarios analyzed in this category include breaks in the RCP discharge piping with an area of 0.30 and 0.50 ft^2. The results are summarized in Table 6-10 and select plots are shown in Figures 6-63 through 6-66.

The break sizes in this category depressurize continuously throughout the transient. There is no repressurization of the primary system because the break alone is capable of removing the decay heat. Like the Category 4 breaks, EFW heat removal has only a small effect and the limiting PCTs are produced by a minimum EFW flow that is provided via the EFIC EFW controlled cases. For these large break sizes, the maximum EFW flow rate is the most beneficial for reducing the SG reverse heat transfer.

For both Category 5 cases, the low-pressure reactor trip setpoint was reached within the first second after break opening, and ESAS Low Pressure was actuated within the first four seconds. The transients progressed relatively quickly through the SBLOCA phases. In comparison with smaller breaks, the HPI, CFT and LPI delivery during the large SBLOCAs was enhanced by the lower transient RCS pressures, i.e. the actuation times were earlier and the flow rates were higher. CFT injection started shortly after the onset of core uncovering.

The rapid depressurization rates produced significant core voiding and level swell. The improved ECCS flow, combined with the increased level swell, significantly shortened the duration of core uncovering. Although more of the core uncovered, the calculated PCTs for these breaks were well below the value calculated for the limiting break size because of the short core uncovering period. The LPI flow was initiated for all cases, but well after the HPI and CFT flow had begun to refill the core and turn over the clad temperature increase. Although EFW does not have much effect on these break sizes, the EFIC level rate controlled EFW flow with a 20 minute LSCM level reset was most limiting.

The disablement of the FCS had no effect on this category of breaks because the PCT occurred before the FCS would have been credited. This is reflected by the similar PCT trend between FCS and no FCS analyses shown in Table 2-8.

6.2.7 Full Power Spectrum Analyses without FCS

The subsections of 0 describe the results and evaluation of the SBLOCA spectrum analyzed with the flow from two HPI pumps when the CR-3 plant has been operating at full power. When two HPI pumps are in service, the uncertainty adjusted total indicated HPI flow should exceed the one HPI pump flow by at least 30 percent and this additional ECCS is sufficient such that the FCS is not required. When the FCS is not used, these analyses [72] showed that 30 percent additional HPI flow for the one HPI pump flow rate is sufficient to keep the limiting CLPD PCT below the EPU FCS one-HPI results from Reference [3]. These analyses considered both throttled and unthrottled HPI flow as described in Section 4.1, plus they also include the results of the limiting EFW flow rates and timing for reset of the LSCM level. The specific break areas, in square feet, analyzed at the CLPD location were: 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, and 0.20. The largest HPI line break of 0.02463 ft^2 was also analyzed. Table 2-8 and Figure 2-9 provide the most limiting PCTs among the EFIC controlled and EFW sensitivity studies. A more detailed compilation of PCTs versus break size can be seen in Table 6-15 and Figure 6-100.

6.2.7.1 Category 1 Breaks (0.002 to 0.005 ft^2)

Category 1 break sizes are not typically analyzed because breaks in this range produce a slower RCS inventory loss rate and they are less challenging to the capacity of the HPI pumps to provide adequate core cooling. These break sizes are heavily dependent on EFW flow to remove a significant fraction of the core decay heat and maintain the RCS near the secondary side pressure until the HPI is capable of matching or exceeding the core decay heat energy addition. This matchup typically occurs with a minimum RCS liquid inventory that is well above the value at which core uncovering can occur.

The Category 1 break sizes do not need to be analyzed with 130% of the single-train unthrottled HPI flow and no credit for FCS actuation because no core uncovering will occur. This conclusion is derived from the analysis of the 0.005-ft2 Category 1 EPU FCS case with one HPI pump [3]. In the EPU FCS case, the RCS pressure remained above the MSSV lift pressure for the first four hours of the event. While the secondary side was depressurized via the FCS, the depressurization was unable to couple the primary and secondary heat transfer because the water level was near the top of the SG tubes and continuous BCC could not be maintained. With the 30 percent increase in HPI flow, this category of break sizes may stay in single phase natural circulation in at least one loop. Consequently, no core uncovering occurs and the acceptance criteria were not challenged. Therefore, an explicit analysis of the Category 1 break sizes is not performed.

6.2.7.2 Category 2 Break Sizes (0.005 to 0.035 ft^2)

Category 2 break sizes range roughly from 0.005 ft2 to 0.035 ft2. Section 6.2.5 describes the breaks evaluated in this category with only one train of HPI and credit for FCS actuation. The results show that in all three FCS cases the core remains covered and cooled such that the acceptance criteria are not challenged. The 0.01-ft^2 case behaved similarly to the 0.005-ft^2 CLPD Category 2 break in that the minimum water level was near the top of the SG tubes. The 0.02463-ft^2 HPI line break ([3] with throttled HPI control valves and [69] with unthrottled HPI control valves) and the 0.03-ft^2 CLPD break did loose sufficient RCS liquid inventory that the FCS depressurized these cases to the CFT fill pressure.

From the EPU FCS cases it is demonstrated that the 0.01-ft^2 case does not need to be analyzed with 30% more HPI from a second HPI pump because no core uncovering would occur with or without FCS. Two 0.02463-ft^2 HPI line breaks were analyzed in [3] without FCS and two different HPI flow rates. The first case credited full flow from one HPI pump with throttled HPI control valves and predicted core uncovering. The second was a simple increase in flow to 140% of the one HPI pump flow based on the expected flow from two HPI pumps. This case had no core uncovering. Therefore, it is uncertain if the full HPI line break with 130% flow from a throttled HPI control valve would have core uncovering, so it was analyzed and no core uncovering was predicted. However, when the HPI valves are unthrottled, the HPI flow lost out of the break increases and the total flow reaching the core is lower at pressures above 900 psia. The HPI line breaks also are in the range of break sizes that the maximum EFW flow is more limiting. Therefore, the largest HPI line was analyzed with unthrottled HPI flows and maximum EFW flow.

The unthrottled 0.02463-ft^2 HPI line break case was analyzed with estimated flows that were reduced from the throttled 130% HPI line break flows to approximately 125% of the HPI line break flows. The estimated flow was established based on ratios to hydraulic analysis flow rates in an effort to consider the uncertainty adjusted flow at which the FCS system would not be actuated. The maximum EFW flow with minimum LSCM level reset was used because it results in more limiting results based. With these boundary conditions the HPI line break predicted some core uncovering with a PCT of 855.7 F. None of the smaller HPI line breaks or any of the CLPD breaks in this category predict core uncovering.

The results of these cases are summarized in Table 6-12 and in Figures 6-77 through 6-80.

6.2.7.3 Category 3 Break Sizes (0.035 to 0.06 ft^2)

Five CLPD break sizes were analyzed in Category 3 with break sizes of 0.04, 0.045, 0.05, 0.055, and 0.06 ft^2. The results of these cases are summarized in Table 6-13 and Figures 6-81 through 6-84. Break sizes of 0.05 ft^2 and smaller were limiting when the maximum EFW flow and early LSCM level setpoint reset were assumed. The two larger break sizes in this category were more limiting with the maximum EFW flow and a longer time delay to reset the LSCM level setpoint. An automatic reset of the LSCM level setpoint was credited at 10 minutes for these cases. The limiting PCT of 1397.9 F was predicted by the 0.06-ft^2 CLPD break [72]. This is the limiting PCT for any of the two-HPI pump full power SBLOCA cases without FCS. This PCT remains less than the overall maximum peak of 1426 F for a 0.13 ft^2 break using a single train of HPI flow and credit for FCS actuation [3].

CLPD break sizes of 0.04 ft^2 and less did not predict core uncovering, but all the other sizes analyzed did predict core uncovering. It is noted that EFW filling of the steam generators with maximum EFW flow provided the shortest time for BCC and the least favorable overall RCS pressure response. As a result, the maximum EFW flow results were worse than the EFIC rate limited results.

6.2.7.4 Category 4 Break Sizes (0.06 to 0.25 ft^2)

A total of eleven Category 4 break sizes were analyzed with two trains of HPI and no FCS actuation. The HPI flow was set to 130% of the single train throttled HPI flow for the analysis of CLPD break areas of 0.065, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, and 0.20 ft2. A relatively fine break size distribution was analyzed because the lower eight break sizes predicted PCTs within 100 F of the maximum PCT case. The results of these cases are summarized in Table 6-14 and Figures 6-85 through 6-88.

The Category 4 break sizes depressurize the RCS continuously, dropping below the secondary side pressure and achieving CFT actuation earlier in the transient than the Category 3 break sizes. The reverse heat transfer in the SGs is an additional heat source to the RCS that is maximized when the lowest EFW flow is used for break sizes of 0.65 ft^2 and larger. When the HPI is not augmented by the secondary side heat removal, it cannot keep up with the core boiloff rate and the plant rapidly enters the boiling pot mode and undergoes core uncovering.

The highest PCT for the Category 4 breaks with 130% of the single train HPI flow and no FCS actuation is 1394.9 F for the 0.10-ft2 CLPD break. This PCT is within 5 F of the limiting PCT for this SBLOCA spectrum. It is noted that for break sizes larger than 0.1 ft^2, the additional flow from two-HPIs is more favorable in terms of keeping the PCTs lower than the one-HPI pump FCS cases.

One additional sensitivity study was performed for the 0.10-ft^2 CLPD with 125% of the single train HPI flow and no FCS actuation. It was determined that the PCT would be higher than 1426 F [3]. Therefore, the HPI flow must be at least 130% of the single train throttled HPI flow in order to ensure that the results are not worse than the results with a single train of HPI and credit for FCS actuation.

6.2.7.5 Category 5 Breaks (0.25 to 0.50 ft^2)

Category 5 breaks consist of CLPD breaks between 0.25 ft2 and 0.50 ft2. Category 5 breaks consider either RCP trip concurrent with LOOP as a result of the low RCS pressure trip based on or automatic or manual action to trip the RCPs one minute after LSCM. Category 5 breaks in [3] also included a spectrum of CFT line breaks with LOOP and 1-minute RCP trip. Category 5 breaks are sufficiently large to depressurize the RCS to approximately that of the containment pressure. These break sizes cause the RCS to depressurize continuously and achieve CFT actuation and LPI flow earlier in the transient than Category 4 break sizes. During the rapid depressurization to the CFT pressure, some of the break sizes may cause some short lived core uncovering and cladding heatup.

Table 6-5 and Table 6-6 of Reference [3] document the CLPD Category 5 breaks with LOOP and with 1-minute RCP trip assuming one train of HPI and LPI and credit for FCS actuation. Although the FCS actuation was available, in each of the cases analyzed the transient analysis ended before the ADV blowdown occurred. Therefore, the FCS system does not influence the results of these cases and an analysis with 130% of the single train HPI flow would produce similar to slightly better results for all of the Category 5 breaks. Therefore, cases with additional HPI flow and no FCS actuation were not analyzed and the limiting PCTs were estimated as equal to the FCS actuation results. Table 2-8 and Figure 2-9 show these estimated PCTs.

6.2.7.6 Category 6 Breaks

These breaks are considered large break LOCAs and EFW and HPI are not explicitly credited in the core cooling analyses. Therefore this category of breaks is unaffected by the FCS, EFW, or number of trains of HPI and it was not evaluated.

6.2.8 Discussion of SBLOCA EM Input and Changes

Several items affecting generic SBLOCA analysis inputs have been addressed and incorporated in the current analyses consistent with the methodology described in Section 3.0. These changes are consistent with what is included in BAW-10192P, Rev. 02 [70]. Items related to the energy deposition factor and methods for addressing changes in actinide decay heat for low enrichment fuel are discussed in Section 6.2.8.1 and 6.2.8.2, respectively. Items related to the CHF predictions for SBLOCA are discussed in Section 6.2.8.3. Discussions of changes incorporated to address PSCs to ensure the results are in compliance with 10 CFR 50 Appendix K are presented in Sections 6.2.8.4.

6.2.8.1 Energy Deposition Factor

The energy deposition factor (EDF) is defined as the energy absorbed (thermal source) in the fuel pellet and clad divided by the energy produced by the pellet (nuclear source).

$$EDF = P_{\text{thermal source}} / P_{\text{nuclear source}}$$

The BWNT LOCA EM specifies a steady-state and transient EDF of 0.973 for SBLOCA analyses. New methods and predictions for the EDFs appropriate for use in LOCA analyses at various times in life have recently been evaluated by AREVA [40]. These calculations do not totally support 0.973 for high burnup, low power fuel or fuel that may be surrounded by higher power fuel. As a result, the LOCA evaluations may use different EDFs. For the EPU analyses a LHR limit of 17.3 kW/ft with a transient EDF of 1.0 was modeled.

6.2.8.2 Actinide DH for Low Enrichment

Section 5.2.7.3 of the LBLOCA section describes how the actinide decay heat changes with enrichment and burnup. The SBLOCA analyses performed with the BWNT LOCA EM typically consider batch fuel pin enrichments in the range of 3 to approximately 5 percent. The more conservative RELAP5 default actinide model [66] was used in the SBLOCA analyses to minimize future reload licensing efforts. This model was used in the

SBLOCA analyses [3, 65, 69, 72] to conservatively cover the entire licensed TIL (0 to 62 GWd/mtU) and enrichment (3 to 5 $^{w}/_{o}$) range for the hot pin, hot bundle, and average core actinide contributions.

6.2.8.3 CHF Predictions for SBLOCA

The BWNT LOCA EM [1, Volume II, p. 4-1] states that a "break is considered to be a small break when the DNB does not occur within the first few seconds after break opening" and concludes that "breaks with cross-sectional areas less than 0.75 ft^2 should not show initial clad DNB." Previous Mark-B10 fuel LOCA analyses for CR-3 [49], which used the BWC CHF correlation, did not predict DNB for any break sizes of 0.75 ft^2 or less. The Mark-B-HTP fuel, which uses the BHTP CHF correlation implemented into RELAP5/MOD2-B&W, predicted DNB during the first second of the Category 5 break sizes larger than 0.5 ft^2. Therefore, break sizes between 0.50 and 2 ft^2 are considered transition LBLOCAs. These break sizes are well bounded by the limiting LBLOCA.

6.2.8.4 Preliminary Safety Concerns

Since the EM described in BAW-10192P-A [1] has been approved, several preliminary safety concerns (PSCs) have been generated. The results of these PSCs must be incorporated into the LOCA analyses. This section summarizes the SBLOCA PSCs and indicates how they have been dispositioned with respect to the CR-3 specific LOCA analyses.

PSC 5-94 Uncertainties on CFT and PZR

The EM states that initial inventories and pressures are to be set by nominal operation levels. The PZR has active methods to control to the nominal value, therefore maintaining a nominal level for analyses is appropriate. However, the CFT does not have an active method for controlling to nominal conditions. PSC 5-94 identified that the CFT initial conditions would affect the transient results as applied to the CRAFT2-based SBLOCA evaluation model. Therefore, the B&W plant SBLOCA analyses performed with the RELAP5-based evaluation model evaluate the combination of minimum and maximum CFT initial volumes and pressures for each plant type. A discussion of these studies for CR-3 is presented in Sections 6.1.3.1 and 6.1.3.2.

PSC 2-00 – SBLOCA Two-Phase RCP Degradation (R5 versus M3)

The EM states that the "default" two-phase RCP degradation multiplier should be used for SBLOCAs. This statement implied that the values provided in the RELAP5 topical are the "default" values that would be used. Sensitivity studies show that the results of a SBLOCA with RCPs tripped at loss of off-site power near the time of reactor trip are not affected by the choice in RCP degradation [34]. However, with RCPs powered until they are manually tripped, the choice of RCP degradation is important. The M3-modified curve was shown to provide limiting results for the SBLOCA with RCPs running up to two-minutes after LSCM [48]. A discussion of these studies for CR-3 is presented in Section 6.1.2.1. The NRC was notified that the M3-modified curve would be utilized to reanalyze the limiting SBLOCAs with RCPs running in resolution of PSC 2-00. An SER was issued on PSC 2-00 [25] which imposed a limitation that required that the two-phase degradation model used in the SBLOCA analyses be demonstrated to be conservative with respect to the plant specific RCPs. AREVA submitted information to the NRC to justify application of the pump model to the B&W plants [26]. In response to this information, the NRC revised the SER to remove this limitation [27]. Therefore, the results of PSC 2-00 and associated SER are generically applicable to the B&W plants. The CR-3 specific analyses to support the PSC 2-00 resolutions are discussed in detail in [48]. In addition, new EPU analyses were performed with offsite power available and the RCPs running for up to 1 minute following LSCM. They are summarized in Tables 6-5 and 6-6.

Table 6-1: Summary of Full Power with FCS Mark-B-HTP Category 1 Break Results (Reference [3])

Parameter	0.005 ft^2
Break Location	CLPD
Break opens (sec)	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	147.9
Loss of Subcooling Margin (sec)	152.3
RCP Trip (sec)	147.3
EFW Actuation (sec)	187.3
ESAS Low RCS Pressure (HPI) Actuation (sec)	307.0
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	NA
HPI/LPI Actuation (sec)	374.1 / 752.3
HPI/LPI Flow Starts (sec)	374.1 / No Flow
Hot legs drained, loop A/B (sec)	HL Not Drained / HL Not Drained
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered
CFT injection starts / ends (sec)	NA / NA
HPI & LPI Core Power Match	11821.4
Transient analysis ends (sec)	14400
ADV Blowdown (sec)	716.9
MSIV Isolation SG-1 / SG-2 (sec)	852.4 / 864.2
Minimum mixture level (ft @ sec) (Note 3)	~18.2 @ ~13400
AC PCT (F) [Segment Number]	692.06 [20]
PCT time (sec)	0.0021
Heated Segments (#) (Note 4)	None
Maximum Local Oxidation (%)	0.079940
Average Oxidation (%)	0.079927
HC PCT (F) [Segment/Channel Number]	711.95 [19/1,3,4,5]
PCT time (sec)	0.0031
Heated Segments (#) (Note 4)	None
Rupture Time (sec)	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079964 [5]
Average Oxidation (%)[Channel Number]	0.079950 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-2: Summary of Full Power with FCS Mark-B-HTP Category 2 Break Results (Reference [3] and [69])

Parameter	0.01 ft^2	0.02463 ft^2	0.03 ft^2
Break Location	CLPD	HPI Line	CLPD
Break opens (sec)	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	73.5	28.96	23.3
Loss of Subcooling Margin (sec)	77.9	33.34	27.7
RCP Trip (sec)	72.8	28.34	22.7
EFW Actuation (sec)	112.9	68.34	62.7
ESAS Low RCS Pressure (HPI) Actuation (sec)	129.8	54.58	45.4
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	NA	4859.76	3584.1
HPI/LPI Actuation (sec)	196.8 / 677.9	121.60 / 633.36	112.5/627.7
HPI/LPI Flow Starts (sec)	196.8 / No Flow	121.64 / > EOT	112.5/No Flow
Hot legs drained, loop A/B (sec)	HLs Not Drained	2312.08 / 1789.74	1513.7 / 1940.3
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	Core Remains Covered	Core Remains Covered
CFT injection starts / ends (sec)	NA / NA	4186.96 / > EOT	3232.6 / >EOT
HPI & LPI Core Power Match	7043.1	5183.28	4917.0
Transient analysis ends (sec)	14400	5183.3	4917.0
ADV Blowdown (sec)	656.6	633.36	616.2
MSIV Isolation SG-1 / SG-2 (sec)	799.9 / 808.6	757.96 / 753.54	732.9 / 735.3
Minimum mixture level (ft @ sec) (Note 3)	~18.4 @ ~12800	N/A	~13.8 @ ~3200
AC PCT (F) [Segment Number]	692.06 [20]	692.06 [20]	692.06 [20]
PCT time (sec)	0.0021	0.0021	0.0021
Heated Segments (#) (Note 4)	None	0	None
Maximum Local Oxidation (%)	0.079940	0.079926	0.079920
Average Oxidation (%)	0.079927	0.079913	0.079908
HC PCT (F) [Segment Number/Channel Number]	711.95 [19/1,3,4,5]	711.95 [19 / 1, 3, 4, 5]	711.95 [19/1,3,4,5]
PCT time (sec)	0.0031	0.0031	0.0031
Heated Segments (#) (Note 4)	None	0	None
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079965 [5]	0.079961 [5]	0.079958 [5]
Average Oxidation (%)[Channel Number]	0.079951 [5]	0.079946 [5]	0.079943 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218	0.0799167 / 0.0799218	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	< 0.01	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-3: Summary of Full Power with FCS Mark-B-HTP Category 3 Break Results (Reference [3])

Parameter	**0.04 ft^2**	**0.06 ft^2**
Break Location	CLPD	CLPD
Break opens (sec)	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	16.6	9.5
Loss of Subcooling Margin (sec)	21.0	13.9
RCP Trip (sec)	16.0	8.9
EFW Actuation (sec)	56.0	48.9
ESAS Low RCS Pressure (HPI) Actuation (sec)	33.4	21.0
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	2620.5	1503.0
HPI/LPI Actuation (sec)	100.4 / 621.0	88.1 / 614.0
HPI/LPI Flow Starts (sec)	100.4 / No Flow	88.1 / No Flow
Hot legs drained, loop A/B (sec)	1103.3 / 1239.1	946.4 / 943.5
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	2500 / 5400
CFT injection starts / ends (sec)	2365.2 / >EOT	1346.9 / >EOT
HPI & LPI Core Power Match	4869.1	4674.2
Transient analysis ends (sec)	5011.0	7230.5
ADV Blowdown (sec)	610.7	604.9
MSIV Isolation SG-1 / SG-2 (sec)	729.1 / 725.8	727.2 / 722.4
Minimum mixture level (ft @ sec) (Note 3)	~12 @ ~2300	~9.9 @ ~3500
AC PCT (F) [Segment Number]	692.06 [20]	1072.5 [20]
PCT time (sec)	0.0021	3611.8
Heated Segments (#) (Note 4)	None	2
Maximum Local Oxidation (%)	0.079919	0.11494
Average Oxidation (%)	0.079907	0.08222
HC PCT (F) [Segment/Channel Number]	711.95 [19/1,3,4,5]	1328.1 [20/1]
PCT time (sec)	0.0031	4124.0
Heated Segments (#) (Note 4)	None	2
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079957 [5]	0.43791 [1]
Average Oxidation (%)[Channel Number]	0.079942 [5]	0.10896 [1]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.02

Notes related to this table are provided on the page following Table 6-6.

Table 6-4: Summary of Full Power with FCS Mark-B-HTP Category 4 Break Results (Reference [3])

Parameter	0.07 ft^2	0.08 ft^2	0.09 ft^2	0.10 ft^2
Break Location	CLPD	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	7.2	5.6	4.4	3.5
Loss of Subcooling Margin (sec)	11.6	10.0	8.8	7.9
RCP Trip (sec)	6.6	5.0	3.8	2.9
EFW Actuation (sec)	46.6	45.0	43.8	42.9
ESAS Low RCS Pressure (HPI) Actuation (sec)	17.5	15.2	13.4	12.0
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	1208.5	882.8	818.1	779.9
HPI/LPI Actuation (sec)	84.5 / 611.6	82.2 / 610.0	80.4 / 608.8	79.0 / 608.0
HPI/LPI Flow Starts (sec)	84.6 / No Flow	82.2 / No Flow	80.5 / No Flow	79.1 / No Flow
Hot legs drained, loop A/B (sec)	856.1 / 883.2	612.4 / 751.3	524.2 / 498.4	441.7 / 447.9
Core starts to uncover/entire core quenched (sec) (Note 2)	~2100 / ~5900	~1900 / ~5600	~1800 / ~4300	~1500 / ~4200
CFT injection starts / ends (sec)	1041.66 / >EOT	830.36 / >EOT	775.0 / >EOT	739.6 / >EOT
HPI & LPI Core Power Match	4583.7	4522.3	4484.9	4446.8
Transient analysis ends (sec)	8489.8	8312.0	6105.0	5686.9
ADV Blowdown (sec)	603.4	602.3	601.6	601.2
MSIV Isolation SG-1 / SG-2 (sec)	729.1 / 728.3	742.3 / 741.5	707.4 / 709.8	686.1 / 689.1
Minimum mixture level (ft @ sec) (Note 3)	~9.7 @ ~4200	~9.6 @ ~3900	~9.9 @ ~2200	~9.8 @ ~1900
AC PCT (F) [Segment Number]	1104.8 [20]	1131.9 [20]	1101.9 [20]	1117.3 [20]
PCT time (sec)	3175.1	2881.5	2360.4	2097.9
Heated Segments (#) (Note 4)	3	3	2	2
Maximum Local Oxidation (%)	0.139100	0.159910	0.121370	0.127150
Average Oxidation (%)	0.083822	0.085716	0.082636	0.083015
HC PCT (F) [Segment Number/Channel Number]	1319.5 [20/5]	1333.4 [20/5]	1381.0 [21/1]	1379.5 [20/3]
PCT time (sec)	2878.7	2428.5	2733.0	2440.1
Heated Segments (#) (Note 4)	2	2	2	2
Rupture Time (sec)	Not Ruptured	Not Ruptured	2733.0	2407.4
Maximum Local Oxidation (%)[Channel Number]	0.54957 [1]	0.62046 [1]	0.56354 [3]	0.57649 [3]
Average Oxidation (%)[Channel Number]	0.11988 [1]	0.12635 [1]	0.11702 [3]	0.11788 [3]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.02	<0.03	<0.02	<0.02

Notes related to this table are provided on the page following Table 6-6.

Table 6-4 (Cont'd): Summary of Full Power with FCS Mark-B-HTP Category 4 Break Results (Reference [3])

Parameter	0.11 ft^2	0.12 ft^2	0.13 ft^2	0.14 ft^2
Break Location	CLPD	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	2.8	2.3	2.0	1.8
Loss of Subcooling Margin (sec)	7.3	6.8	6.4	6.2
RCP Trip (sec)	2.2	1.7	1.4	1.2
EFW Actuation (sec)	42.2	41.7	41.4	41.2
ESAS Low RCS Pressure (HPI) Actuation (sec)	11.0	10.1	9.4	9.0
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	749.5	721.0	695.9	671.4
HPI/LPI Actuation (sec)	78.0 / 607.3	77.1 / 606.8	76.4 / 606.4	76.0 / 606.2
HPI/LPI Flow Starts (sec)	78.0 / 4699.8	77.1 / 4084.0	76.5 / 3613.1	76.0 / 3174.6
Hot legs drained, loop A/B (sec)	402.9 / 399.4	365.0 / 369.0	331.4 / 328.8	293.7 / 297.8
Core starts to uncover/entire core quenched (sec) (Note 2)	~1200 / ~4000	~900 / ~3800	~900 / ~3800	~550 / ~3300
CFT injection starts / ends (sec)	710.6 / >EOT	684.5 / >EOT	662.4 / >EOT	633.2 / >EOT
HPI & LPI Core Power Match	4415.4	4085.7	3757.6	3364.3
Transient analysis ends (sec)	4745.7	4155.4	3842.5	3446.7
ADV Blowdown (sec)	600.9	600.8	600.7	600.6
MSIV Isolation SG-1 / SG-2 (sec)	665.9 / 667.94	650.4 / 650.6	633.5 / 634.3	622.7 / 623.1
Minimum mixture level (ft @ sec) (Note 3)	~10.1 @ ~3300	~10.2 @ ~3600	~10.1 @ ~2200	~9.3 @ ~600
AC PCT (F) [Segment Number]	1104.9 [20]	1087.9 [20]	1092.4 [20]	1015.2 [20]
PCT time (sec)	1832.5	1809.9	1807.7	2240.1
Heated Segments (#) (Note 4)	2	2	2	4
Maximum Local Oxidation (%)	0.121120	0.115710	0.12788	0.085941
Average Oxidation (%)	0.082615	0.082258	0.083060	0.080277
HC PCT (F) [Segment/Channel Number]	1395.7 [20/3]	1410.4 [20/3]	1426.0 [20/3]	1344.5 [20/1]
PCT time (sec)	2175.7	1894.5	2175.8	2282.8
Heated Segments (#) (Note 4)	2	2	2	4
Rupture Time (sec)	2075.9	1796.9	2175.8	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.59518 [3]	0.60844 [3]	0.66407 [4]	0.60421 [1]
Average Oxidation (%)[Channel Number]	0.11670 [3]	0.11683 [3]	0.12072 [4]	0.11484 [1]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.799167 / 0.0799218	0.0799167/0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.02	<0.02	<0.02	<0.02

Notes related to this table are provided on the page following Table 6-6.

Table 6-4 (Cont'd). Summary of Full Power with FCS Mark-B-HTP Category 4 Break Results (Reference [3])

Parameter	0.15 ft^2	0.20 ft^2
Break Location	CLPD	CLPD
Break opens (sec)	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	1.6	1.1
Loss of Subcooling Margin (sec)	6.0	5.5
RCP Trip (sec)	0.9	0.5
EFW Actuation (sec)	41.0	40.5
ESAS Low RCS Pressure (HPI) Actuation (sec)	8.5	7.0
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	641.9	435.1
HPI/LPI Actuation (sec)	75.5 / 606.0	74.0 / 445.1
HPI/LPI Flow Starts (sec)	75.6 / 2626.7	74.1 / 1218.7
Hot legs drained, loop A/B (sec)	280.8 / 277.7	145.9 / 168.9
Core starts to uncover/entire core quenched (sec) (Note 2)	~550 / ~800	~320 / ~790
CFT injection starts / ends (sec)	585.0 / >EOT	400.2 / >EOT
HPI & LPI Core Power Match	2631.2	1224.1
Transient analysis ends (sec)	2702.4	1224.1
ADV Blowdown (sec)	600.54	600.4
MSIV Isolation SG-1 / SG-2 (sec)	619.1 / 621.0	607.5 / 612.9
Minimum mixture level (ft @ sec) (Note 3)	~9.4 @ ~650	~8.6 @ ~400
AC PCT (F) [Segment Number]	963.13 [20]	1074.6 [20]
PCT time (sec)	661.49	543.75
Heated Segments (#) (Note 4)	4	5
Maximum Local Oxidation (%)	0.080106	0.086335
Average Oxidation (%)	0.079893	0.080329
HC PCT (F) [Segment/Channel Number]	1209.5 [20/4&5]	1364.7 [20/5]
PCT time (sec)	663.42	541.9
Heated Segments (#) (Note 4)	3	5
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.099426 [5]	0.250840 [1]
Average Oxidation (%)[Channel Number]	0.081235 [5]	0.095812 [4]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-5: Summary of Full Power with FCS Mark-B-HTP Category 5 Break Results (LOOP Results, Reference [3])

Break Size	0.30 ft^2	0.50 ft^2
Break Location	CLPD	CLPD
Break opens (sec)	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	0.9	0.8
Loss of Subcooling Margin (sec)	5.3	5.2
RCP Trip (sec)	0.3	0.2
EFW Actuation (sec)	40.3	40.2
ESAS Low RCS Pressure (HPI) Actuation (sec)	5.3	3.7
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	265.3	141.7
HPI/LPI Actuation (sec)	72.3 / 275.3	70.7 / 151.7
HPI/LPI Flow Starts (sec)	72.4 / 563.1	70.7 / 264.6
Hot legs drained, loop A/B (sec)	95.8 / 104.8	62.9 / 68.6
Core starts to uncover/entire core quenched (sec) (Note 2)	~200 / ~380	~120 / ~200
CFT injection starts / ends (sec)	243.3 / >EOT	130.9 / >EOT
HPI & LPI Core Power Match	565.9	265.9
Transient analysis ends (sec)	565.9	277.2
ADV Blowdown (sec)	NA	NA
MSIV Isolation SG-1 / SG-2 (sec)	NA / NA	NA / NA
Minimum mixture level (ft @ sec) (Note 3)	~8.7 @ ~260	~8.2 @ ~140
AC PCT (F) [Segment Number]	955.74 [20]	845.21 [20]
PCT time (sec)	332.48	169.56
Heated Segments (#) (Note 4)	5	6
Maximum Local Oxidation (%)	0.079894	0.079892
Average Oxidation (%)	0.079882	0.079880
HC PCT (F) [Segment Number/Channel Number]	1223.7 [20/5]	1070.2 [20/5]
PCT time (sec)	332.0	169.76
Heated Segments (#) (Note 4)	4	4
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.106350 [5]	0.080974 [1]
Average Oxidation (%)[Channel Number]	0.081834 [5]	0.079982 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-5 (Cont'd): Summary of Full Power with FCS Mark-B-HTP Category 5 Break Results (1-min RCP Trip Results, Reference [3])

Break Size	**0.30 ft²**	**0.50 ft²**
Break Location	CLPD	CLPD
Break opens (sec)	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	0.9	0.8
Loss of Subcooling Margin (sec)	5.3	5.2
RCP Trip (sec)	65.3	65.2
EFW Actuation (sec)	40.3	40.2
ESAS Low RCS Pressure (HPI) Actuation (sec)	3.2	0.7
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	250.4	414.7
HPI/LPI Actuation (sec)	70.2 / 260.5	67.7 / 151.7
HPI/LPI Flow Starts (sec)	70.3 / 487.4	67.7 / 224.9
Hot legs drained, loop A/B (sec)	118.5 / 122.0	HL Not Drained / HL Not Drained
Core starts to uncover/entire core quenched (sec) (Note 2)	~210 / ~300	Core Remains Covered
CFT injection starts / ends (sec)	231.9 / >EOT	133.3 / >EOT
HPI & LPI Core Power Match	489.6	226.3
Transient analysis ends (sec)	489.6	242.5
ADV Blowdown (sec)	NA	NA
MSIV Isolation SG-1 / SG-2 (sec)	NA / NA	NA / NA
Minimum mixture level (ft @ sec) (Note 3)	~10.3 @ ~240	~17.7 @ ~130
AC PCT (F) [Segment Number]	757.04 [20]	692.06 [20]
PCT time (sec)	277.69	0.0021
Heated Segments (#) (Note 4)	3	None
Maximum Local Oxidation (%)	0.079894	0.079890
Average Oxidation (%)	0.079882	0.079878
HC PCT (F) [Segment Number/Channel Number]	848.42 [20/5]	711.95 [19/1,3,4,5]
PCT time (sec)	255.39	0.0031
Heated Segments (#) (Note 4)	2	None
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079940 [5]	0.079937 [5]
Average Oxidation (%)[Channel Number]	0.079925 [5]	0.079922 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-6: Summary of Full Power with FCS Mark-B-HTP CFT Line Break Results (LOOP Results, Reference [3])

Break Size	0.44 ft^2	0.40 ft^2	0.35 ft^2	0.30 ft^2	0.25 ft^2
Break Location	CFT	CFT	CFT	CFT	CFT
Break opens (sec)	0	0	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	0.8	0.8	0.9	0.9	1.0
Loss of Subcooling Margin (sec)	5.2	5.2	5.3	5.3	5.4
RCP Trip (sec)	0.2	0.2	0.3	0.3	0.4
EFW Actuation (sec)	40.2	40.2	40.3	40.3	40.4
ESAS Low RCS Pressure (HPI) Actuation (sec)	4.1	4.4	4.9	5.4	6.14
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	170.2	192.4	225.7	273.7	340.4
HPI/LPI Actuation (sec)	71.1 / 180.2	71.4 / 202.4	71.9 / 235.7	72.4 / 283.7	73.1 / 350.4
HPI/LPI Flow Starts (sec)	71.1 / 884.6	71.4 / 1209.0	71.9 / 1796.2	72.5 / 2683.3	73.2 / No Flow
Hot legs drained, loop A/B (sec)	72.1 / 75.7	79.1 / 84.7	90.7 / 95.5	109.4 / 112.6	128.8 / 146.0
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	Core Remains Covered	Core Remains Covered	Core Remains Covered	Core Remains Covered
CFT injection starts, ends (sec)	155.7 / 373.0	174.2 / 429.2	204.1 / 528.6	247.0 / 735.4	306.0 / 1014.7
HPI & LPI Core Power Match	~850	~1200	~1450	~1500	~1500
Transient analysis ends (sec)	3600.0	1600.0	2200.8	2975.2	3600.0
ADV Blowdown (sec)	600.1	600.2	600.2	600.2	600.3
MSIV Isolation SG-1 / SG-2 (sec)	606.0 / 608.7	605.3 / 607.1	605.5 / 606.4 2	605.4 / 607.02	610.5 / 610.9
Minimum mixture level (ft @ sec) (Note 3)	~13.5 @ ~160	~13.5 @ ~1200	~13.0 @ ~1750	~13.5 @ ~2200	~14.2 @ ~370
AC PCT (F) [Segment Number]	692.06 [20]	692.06 [20]	692.06 [20]	692.06 [20]	692.06 [20]
PCT time (sec)	0.0021	0.0021	0.0021	0.0021	0.0021
Heated Segments (#) (Note 4)	0	0	0	0	0
Maximum Local Oxidation (%)	0.079852	0.079866	0.079867	0.079868	0.079874
Average Oxidation (%)	0.079843	0.079854	0.079854	0.079856	0.079862
HC PCT (F) [Segment/Channel Number]	711.95 [19/1]	711.95 [19/1]	711.95[19/1]	711.95 [19/1]	711.95 [19/1]
PCT time (sec)	0.0031	0.0031	0.0031	0.0031	0.0031
Heated Segments (#) (Note 4)	0	0	0	0	0
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079904 [5]	0.079919 [5]	0.079919 [5]	0.079920 [5]	0.079925 [5]
Average Oxidation (%)[Channel Number]	0.079895 [5]	0.079904 [5]	0.079904 [5]	0.079905 [5]	0.079910 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218	0.0799167/0.0799218	0.0799167/0.0799218	0.0798523/0.0798428	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.01	<0.01	<0.01	<0.01

Notes related to this table are provided on the page following Table 6-6.

Table 6-6 (Cont'd). Summary of Full Power with FCS Mark-B-HTP CFT Line Break Results (1-min RCP Trip Results, Reference [3])

Break Size	0.44 ft^2	0.40 ft^2	0.35 ft^2	0.30 ft^2	0.25 ft^2
Break Location	CFT 1-min RCP Trip	CFT 1-min RCP Trip	CFT 1-min RCP Trip	CFT 1-min RCP Trip	CFT 1-min RCP Trip
Break opens (sec)	0	0	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	0.8	0.8	0.9	0.9	1.0
Loss of Subcooling Margin (sec)	5.2	5.2	5.3	5.3	5.4
RCP Trip (sec)	65.2	65.2	65.3	65.3	65.4
EFW Actuation (sec)	40.2	40.2	40.3	40.3	40.4
ESAS Low RCS Pressure (HPI) Actuation (sec)	1.6	1.7	2.7	3.3	4.14
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	154.0	168.4	200.2	249.4	326.4
HPI/LPI Actuation (sec)	68.6 / 164.0	68.7 / 178.4	69.8 / 210.2	70.3 / 259.4	71.2 / 336.4
HPI/LPI Flow Starts (sec)	68.6 / 828.1	68.7 / 1116.7	69.8 / 1796.2	70.3 / 2683.3	71.2 / No Flow
Hot legs drained, loop A/B (sec)	141.4 / 101.0	102.9 / 104.1	110.0 / 111.8	121.3 / 124.4	141.5 / 144.1
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	Core Remains Covered	Core Remains Covered	Core Remains Covered	Core Remains Covered
CFT injection starts, ends (sec)	144.6 / 298.2	157.1 / 346.4	185.6 / 432.2	227.6 / 581.3	293.6 / 926.9
HPI & LPI Core Power Match	~830	~1150	~1450	~1500	~1500
Transient analysis ends (sec)	1428.7	1556.3	2160.8	2967.7	3600.0
ADV Blowdown (sec)	600.1	600.2	600.2	600.2	600.3
MSIV Isolation SG-1 / SG-2 (sec)	636.4 / 648.9	645.6 / 649.6	643.5 / 645.6	620.1 / 622.4	605.0 / 613.0
Minimum mixture level (ft @ sec) (Note 3)	~13.3 @ ~850	~13.3 @ ~1150	~12.9 @ ~1700	~13.5 @ ~2100	~14.2 @ ~350
AC PCT (F) [Segment Number]	692.06 [20]	692.06 [20]	692.06 [20]	692.06 [20]	692.06 [20]
PCT time (sec)	0.0021	0.0021	0.0021	0.0021	0.0021
Heated Segments (#) (Note 4)	0	0	0	0	0
Maximum Local Oxidation (%)	0.079865	0.079866	0.079875	0.079880	0.079886
Average Oxidation (%)	0.079852	0.079854	0.079862	0.079868	0.079874
HC PCT (F) [Segment/Channel Number]	711.95 [19/1]	711.95 [19/1]	711.95 [19/1]	711.95 [19/1]	711.95 [19/1]
PCT time (sec)	0.0031	0.0031	0.0031	0.0031	0.0031
Heated Segments (#) (Note 4)	0	0	0	0	0
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079918 [5]	0.079919 [5]	0.079925 [5]	0.079929 [5]	0.079934 [5]
Average Oxidation (%)[Channel Number]	0.079902 [5]	0.079903 [5]	0.079910 [5]	0.079914 [5]	0.079919 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218	0.0799167/0.0799218	0.0799167/0.0799218	0.0799167/0.0799218	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	<0.01	<0.01	<0.01	<0.01	<0.01

Notes related to this table are provided on the following page.

Notes for Table 6-1 through Table 6-6:

1. This is the time rod insertion begins (i.e., trip time + delay time).
2. The time at which the core begins to uncover and when the entire core is quenched are characterized as the time when the clad segments begin to superheat, and when the temperatures of all superheated clad segments reach the saturation temperature of the surrounding liquid.
3. The minimum mixture level is referenced from the bottom of the heated fuel in Reference [3].
4. The number of heated segments is taken from the number of superheated fuel nodes in the indicated channel.
5. The whole core hydrogen generation is calculated using the simplified equation provided in Reference [22]. $H_2\% = 0.63 \times \left(AC\%_{oxide}^{ave} - AC\%_{oxide}^{initial}\right) + 0.37 \times \left(HC\%_{oxide}^{ave} - HC\%_{oxide}^{initial}\right)$. The initial oxidation fraction is taken from the zero edit of the run and multiplied by 100 to provide an initial oxidation percentage for both the hot and average channels.
6. EOT denotes End of Transient, and NA denotes Not Applicable/Available/Actuated.
7. The nomenclature for loops may be described as either Loop A/B or Loop 1/2 but are describing the same parameter. For example, SG-1 is the same as SG-A and SG-2 is the same as SG-B.

Table 6-7: Summary of Reduced Power without FCS Mark-B-HTP Category 2 Break Results (Reference [65])

Parameter	0.01 ft^2	0.02 ft^2	0.022 ft^2
Break Location	CLPD	HPI Line	HPI Line
Break opens (sec)	0	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	20	5	5
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	79.64	39.02	35.24
Loss of Subcooling Margin (sec)	84.04	43.42	39.64
RCP Trip (sec)	79.02	38.42	34.64
EFW Actuation (sec)	119.04	78.42	74.64
ESAS Low RCS Pressure (HPI) Actuation (sec)	132.98	69.40	63.48
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	> EOT	> EOT	> EOT
HPI/LPI Actuation (sec)	199.98 / 684.06	136.42 / 643.44	130.50 / 639.66
HPI/LPI Flow Starts (sec)	200.02 / > EOT	136.46 / > EOT	130.54 / > EOT
Hot legs drained, loop A/B (sec)	> EOT / > EOT	2956.84 / 2787.38	2963.16 / 2770.02
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	~6300 / ~9600	~5300 / ~8800
CFT injection starts / ends (sec)	> EOT / > EOT	> EOT / > EOT	> EOT / > EOT
HPI & LPI Core Power Match	6590.20	7669.98	6815.96
Transient analysis ends (sec)	6590.2	10000	10000
MSIV Isolation SG-1 / SG-2 (sec)	> EOT / > EOT	> EOT / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	~ 18.0 @ ~ 880	~ 10.4 @ ~7000	~ 10.0 @ ~6500
AC PCT (F) [Segment Number]	680.85 [20]	832.58 [20]	918.5 [20]
PCT time (sec)	1.14	7709.1	6553.4
Heated Segments (#) (Note 4)	0	2	2
Maximum Local Oxidation (%)	0.07994	0.07994	0.079938
Average Oxidation (%)	0.07993	0.079927	0.079925
HC PCT (F) [Segment Number/Channel Number]	713.48 [19 / 1, 3, 4, 5]	921.81 [21 / 1, 3, 4, 5]	1110.5 [21 / 3, 4, 5]
PCT time (sec)	0.0101	7491.3	6827.7
Heated Segments (#) (Note 4)	0	1	1
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.07996 [5]	0.079965 [5]	0.11669 [1]
Average Oxidation (%)[Channel Number]	0.079947 [5]	0.079951 [5]	0.082359 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 6-10.

Table 6-7 (Cont'd): Summary of Reduced Power without FCS Mark-B-HTP Category 2 Break Results (Reference [65])

Parameter	0.02463 ft^2	0.03 ft^2
Break Location	HPI Line	CLPD
Break opens (sec)	0	0
EFW Flow Rate (gpm/SG)	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	20	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	31.26	25.18
Loss of Subcooling Margin (sec)	35.64	29.58
RCP Trip (sec)	30.64	24.56
EFW Actuation (sec)	70.64	24.56
ESAS Low RCS Pressure (HPI) Actuation (sec)	56.14	48.4
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	> EOT	> EOT
HPI/LPI Actuation (sec)	123.16 / 635.66	115.4 / 629.6
HPI/LPI Flow Starts (sec)	123.20 / > EOT	115.42 / > EOT
Hot legs drained, loop A/B (sec)	2532.18 / 2302.98	1929.94 / 2214.75
Core starts to uncover/entire core quenched (sec) (Note 2)	~4200 / ~8200	~4800 / ~6300
CFT injection starts / ends (sec)	> EOT / > EOT	7170.78 / > EOT
HPI & LPI Core Power Match	6068.26	4070.48
Transient analysis ends (sec)	10000	7171.48
MSIV Isolation SG-1 / SG-2 (sec)	> EOT / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	~ 9.8 @ ~ 4820	~ 11.2 @ ~ 4980
AC PCT (F) [Segment Number]	1058.4 [20]	710.64 [21]
PCT time (sec)	5520.3	5208
Heated Segments (#) (Note 4)	3	1
Maximum Local Oxidation (%)	0.10332	0.079932
Average Oxidation (%)	0.081466	0.079919
HC PCT (F) [Segment Number/Channel Number]	1326.5 [20 / 4, 5]	713.48 [19 / 1, 3, 4, 5]
PCT time (sec)	6576.3	0.0101
Heated Segments (#) (Note 4)	2	0
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.3578 [1]	0.079962 [5]
Average Oxidation (%)[Channel Number]	0.10306 [1]	0.079948 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 8-15.

Table 6-8: Summary of Reduced Power without FCS Mark-B-HTP Category 3 Break Results (Reference [65])

Parameter	0.04 ft^2	0.055 ft^2	0.06 ft^2
Break Location	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0
EFW Flow Rate (gpm/SG)	807	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	0	0	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	17.90	11.78	10.28
Loss of Subcooling Margin (sec)	22.30	16.18	14.68
RCP Trip (sec)	17.28	11.16	9.66
EFW Actuation (sec)	17.28	11.16	49.66
ESAS Low RCS Pressure (HPI) Actuation (sec)	36.22	25.92	21.90
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	5223.18	2794.62	2333.59
HPI/LPI Actuation (sec)	103.22 / 622.32	92.92 / 616.20	88.90 / 614.70
HPI/LPI Flow Starts (sec)	103.24 / > EOT	92.94 / > EOT	88.92 / > EOT
Hot legs drained, loop A/B (sec)	1408.98 / 1521.62	1116.08 / 1099.70	700.80 / 958.56
Core starts to uncover/entire core quenched (sec) (Note 2)	~3200 / ~5200	~2200 / ~4000	~2000 / ~3800
CFT injection starts / ends (sec)	4246.08 / > EOT	2451.62 / > EOT	1995.42 / > EOT
HPI & LPI Core Power Match	3655.74	3281.67	3208.88
Transient analysis ends (sec)	5637.0	4814.7	5032.9
MSIV Isolation SG-1 / SG-2 (sec)	5523.62 / > EOT	> EOT / > EOT	2445.16 / 2466.73
Minimum mixture level (ft @ sec) (Note 3)	~ 9.9 @ ~ 3990	~ 9.4 @ ~ 2450	~ 9.8 @ ~ 3710
AC PCT (F) [Segment Number]	989.37 [20]	1022.3 [20]	965.16 [20]
PCT time (sec)	4165.4	2647.1	2626.6
Heated Segments (#) (Note 4)	2	3	2
Maximum Local Oxidation (%)	0.080114	0.086004	0.080109
Average Oxidation (%)	0.079927	0.080306	0.079915
HC PCT (F) [Segment/Channel Number]	1290.2 [20 / 4, 5]	1374.1 [20 / 1]	1055.4 [21 / 3, 4, 5]
PCT time (sec)	4316.1	3040.7	2507.5
Heated Segments (#) (Note 4)	2	2	1
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.24145 [1]	0.45529 [1]	0.093543 [1]
Average Oxidation (%)[Channel Number]	0.093087 [1]	0.10728 [1]	0.080819 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.02	< 0.01

Notes related to this table are provided on the page following Table 6-10.

Table 6-9: Summary of Reduced Power without FCS Mark-B-HTP Category 4 Break Results (Reference [65])

Parameter	0.07 ft^2	0.08 ft^2	0.10 ft^2	0.12 ft^2
Break Location	CLPD	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	7.86	6.14	3.88	2.56
Loss of Subcooling Margin (sec)	12.26	10.54	8.30	6.98
RCP Trip (sec)	7.24	5.52	3.28	1.96
EFW Actuation (sec)	47.24	45.52	43.28	41.96
ESAS Low RCS Pressure (HPI) Actuation (sec)	18.32	15.64	12.12	10.00
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	1841.79	1477.84	1041.71	817.93
HPI/LPI Actuation (sec)	85.32 / 612.28	82.64 / 610.56	79.12 / 608.32	77.00 / 606.99
HPI/LPI Flow Starts (sec)	85.36 / > EOT	82.68 / > EOT	79.16 / > EOT	77.04 / > EOT
Hot legs drained, loop A/B (sec)	789.52 / 775.34	639.86 / 642.46	441.58 / 449.30	349.58 / 354.40
Core starts to uncover/entire core quenched (sec) (Note 2)	~1500 / ~3600	~1200 / ~2800	~800 / ~2250	~ 700 / ~ 1400
CFT injection starts / ends (sec)	1637.20 / > EOT	1314.25 / > EOT	935.46 / > EOT	731.86 / > EOT
HPI & LPI Core Power Match	3094.38	3023.38	2924.87	2876.00
Transient analysis ends (sec)	4537.8	3761.6	3036.0	2876.0
MSIV Isolation SG-1 / SG-2 (sec)	1619.36 / 1628.82	1343.22 / 1385.02	1180.30 / 1155.88	963.83 / 1030.36
Minimum mixture level (ft @ sec) (Note 3)	~ 9.8 @ ~ 1630	~ 9.2 @ ~1410	~ 9.7 @ ~ 2000	~ 9.8 @ ~ 820
AC PCT (F) [Segment Number]	1062.8 [20]	1126.5 [20]	1037.1 [20]	966.34 [20]
PCT time (sec)	1977.9	1633.2	1253.5	956.24
Heated Segments (#) (Note 4)	3	4	3	2
Maximum Local Oxidation (%)	0.097918	0.11211	0.088644	0.08011
Average Oxidation (%)	0.081095	0.08222	0.080477	0.079898
HC PCT (F) [Segment/Channel Number]	1374.6 [20 / 5]	1406.9 [20 / 1]	1399.2 [20 / 5]	1295.2 [20 / 5]
PCT time (sec)	2318.4	1850.6	1263.6	977.4
Heated Segments (#) (Note 4)	2	3	2	2
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.53667 [1]	0.58192 [1]	0.53114 [1]	0.23886 [1]
Average Oxidation (%)[Channel Number]	0.11515 [1]	0.1303 [1]	0.11151 [1]	0.09042 [1]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.02	< 0.03	< 0.02	< 0.01

Notes related to this table are provided on the page following Table 6-10.

Table 6-9 (Cont'd): Summary of Reduced Power without FCS Mark-B-HTP Category 4 Break Results (Reference [65])

Parameter	0.14 ft^2	0.16 ft^2	0.20 ft^2
Break Location	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	1.92	1.54	1.18
Loss of Subcooling Margin (sec)	6.34	5.96	5.60
RCP Trip (sec)	1.32	0.94	0.58
EFW Actuation (sec)	41.32	40.94	40.58
ESAS Low RCS Pressure (HPI) Actuation (sec)	8.44	7.40	6.02
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	675.37	561.93	429.50
HPI/LPI Actuation (sec)	75.44 / 606.35	74.40 / 571.94	73.02 / 439.51
HPI/LPI Flow Starts (sec)	75.48 / 2565.46	74.44 / 1800.12	73.06 / 1030.12
Hot legs drained, loop A/B (sec)	288.20 / 292.08	225.36 / 229.10	143.74 / 160.48
Core starts to uncover/entire core quenched (sec) (Note 2)	550 / 1050	~400 / ~900	~ 310 / ~ 620
CFT injection starts / ends (sec)	607.45 / > EOT	508.48 / > EOT	389.25 / > EOT
HPI & LPI Core Power Match	2566.35	1806.76	1030.16
Transient analysis ends (sec)	2566.4	1806.8	1030.2
MSIV Isolation SG-1 / SG-2 (sec)	757.67 / 879.01	584.99 / 693.11	447.02 / 528.63
Minimum mixture level (ft @ sec) (Note 3)	~ 9.8 @ ~ 605	~ 8.7 @ ~ 510	~ 8.3 @ ~ 390
AC PCT (F) [Segment Number]	924.74 [20]	1022.1 [20]	967.97 [20]
PCT time (sec)	906.08	611.28	468.36
Heated Segments (#) (Note 4)	2	5	5
Maximum Local Oxidation (%)	0.079895	0.081592	0.080111
Average Oxidation (%)	0.079882	0.080006	0.079898
HC PCT (F) [Segment/Channel Number]	1240.2 [20 / 4, 5]	1361.8 [20 / 5]	1295.0 [20 / 4, 5]
PCT time (sec)	835.32	634.9	464.73
Heated Segments (#) (Note 4)	2	4	4
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.14266 [5]	0.23846 [5]	0.1411 [4]
Average Oxidation (%)[Channel Number]	0.084068 [5]	0.092783 [5]	0.084507 [4]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 8-15.

Table 6-10: Summary of Reduced Power without FCS Mark-B-HTP Category 5 Break Results (Reference [65])

Break Size	0.30 ft^2	0.50 ft^2
Break Location	CLPD	CLPD
Break opens (sec)	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	0.96	0.78
Loss of Subcooling Margin (sec)	5.36	5.18
RCP Trip (sec)	0.34	0.68
EFW Actuation (sec)	40.36	40.18
ESAS Low RCS Pressure (HPI) Actuation (sec)	3.30	0.55
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	263.59	142.08
HPI/LPI Actuation (sec)	70.30 / 273.60	67.56 / 152.09
HPI/LPI Flow Starts (sec)	70.34 / 516.08	67.60 / 251.82
Hot legs drained, loop A/B (sec)	95.92 / 106.92	64.16 / 70.28
Core starts to uncover/entire core quenched (sec) (Note 2)	~ 200 / ~ 325	~ 110 / ~ 180
CFT injection starts / ends (sec)	240.77 / > EOT	131.61 / > EOT
HPI & LPI Core Power Match	518.52	252.84
Transient analysis ends (sec)	518.5	263.72
MSIV Isolation SG-1 / SG-2 (sec)	4319.11 / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	~ 8.6 @ ~ 240	~ 7.5 @ ~ 133
AC PCT (F) [Segment Number]	861.6 [20]	788.77 [20]
PCT time (sec)	289.75	161.23
Heated Segments (#) (Note 4)	5	6
Maximum Local Oxidation (%)	0.079896	0.079893
Average Oxidation (%)	0.079883	0.079881
HC PCT (F) [Segment Number/Channel Number]	1150.9 [20 / 4, 5]	1065.4 [20 / 4, 5]
PCT time (sec)	309.77	168.4
Heated Segments (#) (Note 4)	3	4
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.086792 [3]	0.080655 [1]
Average Oxidation (%)[Channel Number]	0.080416 [5]	0.079959 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 6-10.

Notes for Tables 6-7 through 6-10:

1. This is the time rod insertion begins (i.e. trip time + delay time).
2. Core heatup is characterized as the time when cladding temperature begins to rise above the saturation temperature (from HC clad temperature plot). Core quench is characterized as the time when the temperatures of all superheated clad nodes reach the saturation temperature of the surrounding liquid (from HC and AC clad temperature plots).
3. The minimum mixture level is referenced from the bottom of the heated fuel and is taken from the _62 plot (the core mixture level plot).
4. The number of heated segments is taken from the number of superheated clad nodes (from the cladding temperature plot) in the indicated channel.
5. The whole-core hydrogen generation for Mk-B-HTP analysis is calculated using the simplified equation from Table 7 of Reference [22].
   $H_2\% = 0.63 \times \left(AC\%_{oxide}^{average} - AC\%_{oxide}^{initial}\right) + 0.37 \times \left(HC\%_{oxide}^{average} - HC\%_{oxide}^{initial}\right).$

   The initial oxidation fraction is taken from the zero edit of the run and multiplied by 100 to provide an initial oxidation percentage for both the hot and average channels.
6. EOT denotes End of Transient, and NA denotes Not Applicable/Available/Actuated.

Table 6-11: Reduced Power without FCS PCT versus Break Size

Offsite Power	Break Location	Break Size (ft^2)	EFIC PCT (F)	Min EFW 20 min SG level reset PCT (F)	Max EFW 20 min SG level reset PCT (F)	Max EFW 0 to 5 min SG level reset PCT (F)
LOOP	CLPD	0.01	713	-	-	-
		0.03	-	-	-	713
		0.04	713	-	-	1290.2
		0.055	-	-	1367.5	1374.1
		0.06	955.9	1003.4	1055.4	-
		0.07	1374.6	-	-	-
		0.08	1406.9	1387.0	999.58	-
		0.10	1399.2	-	-	-
		0.12	1295.2	-	-	-
		0.14	1240.2	-	-	-
		0.16	1361.8	-	-	-
		0.20	1295.2	1279.0	1139.3	-
		0.30	1150.9	-	-	-
		0.50	1065.4	1043.2	1004.4	-
	HPI	0.015	-	-	-	713 [1]
		0.02	713	-	-	921.8
		0.022	713	-	945.3	1110.5
		0.02463	906.3	713	1326.5	1308.5
	CFT	0.25	713 [1]	-	-	-
		0.30	713 [1]	-	-	-
		0.35	713 [1]	-	-	-
		0.40	713 [1]	-	-	-
		0.44	713 [1]	-	-	-
1-min RCP Trip	CLPD	0.30	780 [1]	-	-	-
		0.50	713 [1]	-	-	-
	CFT	0.25	713 [1]	-	-	-
		0.30	713 [1]	-	-	-
		0.35	713 [1]	-	-	-
		0.40	713 [1]	-	-	-
		0.44	713 [1]	-	-	-

Note [1]: The PCT reported is an estimated value.

Table 6-12: Summary of Full Power without FCS Mark-B-HTP Category 2 Break Results (Reference [72])

Parameter	0.022 ft^2	0.02463 ft^2
Break Location	HPI	HPI
Break opens (sec)	0	0
EFW Flow Rate (gpm/SG)	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	31.98	28.34
Loss of Subcooling Margin (sec)	36.98	33.34
RCP Trip (sec)	31.98	28.34
EFW Actuation (sec)	71.98	68.34
ESAS Low RCS Pressure (HPI) Actuation (sec)	60.46	54.58
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	> EOT	> EOT
HPI/LPI Actuation (sec)	127.46 / 636.99	121.58 / 633.35
HPI/LPI Flow Starts (sec)	127.48 / > EOT	121.60 / > EOT
Hot legs drained, loop A/B (sec)	3521.93 / 2887.03	2508.33 / 2376.06
Core starts to uncover/entire core quenched (sec) (Note 2)	Core Remains Covered	~5400 / ~7200
CFT injection starts / ends (sec)	> EOT / > EOT	> EOT / > EOT
HPI & LPI Core Power Match	6644.30	6024.66
Transient analysis ends (sec)	10800	10800
MSIV Isolation SG-1 / SG-2 (sec)	> EOT / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	13.5 @ ~ 7100	~ 10.6 @ ~ 6200
AC PCT (F) [Segment Number]	692.06 [20]	757.96 [21]
PCT time (sec)	0.0021	6321.2
Heated Segments (#) (Note 4)	None	1
Maximum Local Oxidation (%)	0.079937	0.079935
Average Oxidation (%)	0.079925	0.079922
HC PCT (F) [Segment/Channel Number]	711.95 [19/1,3,4,5]	855.71 [21/1,3,4,5]
PCT time (sec)	0.0031	6384.4
Heated Segments (#) (Note 4)	None	1
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079966 [5]	0.079966 [5]
Average Oxidation (%)[Channel Number]	0.079951 [5]	0.079950 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167/0.0799218	0.0799167/0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 6-14.

Table 6-13: Summary of Full Power without FCS Mark-B-HTP Category 3 Break Results (Reference [72])

Parameter	0.04 ft^2	0.045 ft^2	0.05 ft^2
Break Location	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0
EFW Flow Rate (gpm/SG)	807	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	0	0	0
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	16.62	14.36	12.54
Loss of Subcooling Margin (sec)	21.00	18.76	16.94
RCP Trip (sec)	16.00	13.74	11.92
EFW Actuation (sec)	16.00	13.74	11.92
ESAS Low RCS Pressure (HPI) Actuation (sec)	35.16	31.24	28.02
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	> EOT	4466.15	3803.17
HPI/LPI Actuation (sec)	102.16 / 621.02	98.26 / 618.78	95.04 / 616.96
HPI/LPI Flow Starts (sec)	102.18 / > EOT	98.30 / > EOT	95.08 / > EOT
Hot legs drained, loop A/B (sec)	1399.63 / 1729.15	1248.11 / 1148.88	947.12 / 1180.26
Core starts to uncover/entire core quenched (sec) (Note 2)	No Core Uncovery	~2800 / ~4200	~2450 / ~3800
CFT injection starts / ends (sec)	4789.81 / > EOT	3824.29 / > EOT	3172.89 / > EOT
HPI & LPI Core Power Match	2885.69	2751.88	2634.40
Transient analysis ends (sec)	4790.16	4648.93	4408.84
MSIV Isolation SG-1 / SG-2 (sec)	> EOT / > EOT	> EOT / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	~ 12.9 @ ~ 4100	~ 10.4 @ ~ 3250	~ 10.1 @ ~ 3000
AC PCT (F) [Segment Number]	692.06 [20]	919.66 [20]	1003.9 [20]
PCT time (sec)	0.0021	3783.4	3156.7
Heated Segments (#) (Note 4)	0	2	2
Maximum Local Oxidation (%)	7.99E-02	7.99E-02	8.15E-02
Average Oxidation (%)	7.99E-02	7.99E-02	8.00E-02
HC PCT (F) [Segment/Channel Number]	711.95 [19 / 1, 3, 4, 5]	992.85 [21 / 5]	1236.2 [20 / 5]
PCT time (sec)	0.0031	3628.1	3301.5
Heated Segments (#) (Note 4)	0	1	2
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079964 [5]	0.079962 [5]	0.1677 [5]
Average Oxidation (%)[Channel Number]	0.079948 [5]	0.079946 [5]	0.086656 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 6-14.

Table 6-13 Cont'd: Summary of Full Power without FCS Mark-B-HTP Category 3 Break Results (Reference [72])

Parameter	0.055 ft^2	0.06 ft^2	0.065 ft^2
Break Location	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0
EFW Flow Rate (gpm/SG)	807	807	807
Automatic or Manual Operator Action to Reset SG Level (min)	10	10	10
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	10.98	9.54	8.28
Loss of Subcooling Margin (sec)	15.38	13.94	12.68
RCP Trip (sec)	10.36	8.92	7.66
EFW Actuation (sec)	50.36	48.92	47.66
ESAS Low RCS Pressure (HPI) Actuation (sec)	23.34	21.04	19.08
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	3156.47	2603.48	2281.09
HPI/LPI Actuation (sec)	90.36 / 615.40	88.06 / 613.96	86.08 / 612.70
HPI/LPI Flow Starts (sec)	90.40 / > EOT	88.10 / > EOT	86.12 / > EOT
Hot legs drained, loop A/B (sec)	874.20 / 887.60	772.84 / 796.90	711.16 / 789.66
Core starts to uncover/entire core quenched (sec) (Note 2)	~1800 / ~3500	~1600 / ~3400	~1600 / ~3200
CFT injection starts / ends (sec)	2572.32 / > EOT	2165.60 / > EOT	1930.12 / > EOT
HPI & LPI Core Power Match	2489.89	2411.41	2352.48
Transient analysis ends (sec)	4139.8	3972.1	3753.9
MSIV Isolation SG-1 / SG-2 (sec)	> EOT / > EOT	> EOT / > EOT	> EOT / > EOT
Minimum mixture level (ft @ sec) (Note 3)	~ 9.4 @ ~ 2500	~ 9.0 @ ~ 2200	~ 9.2 @ ~ 1800
AC PCT (F) [Segment Number]	1163.5 [20]	1210.8 [20]	1171.2 [20]
PCT time (sec)	2570.6	2218.6	2104.7
Heated Segments (#) (Note 4)	3	4	4
Maximum Local Oxidation (%)	1.44E-01	1.79E-01	1.41E-01
Average Oxidation (%)	8.52E-02	8.93E-02	8.49E-02
HC PCT (F) [Segment/Channel Number]	1357.7 [20 / 1]	1397.9 [20 / 1]	1382.2 [20 / 5]
PCT time (sec)	2528.9	2169.6	2046.8
Heated Segments (#) (Note 4)	3	3	3
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.47483 [1]	0.57616 [1]	0.49945 [1]
Average Oxidation (%)[Channel Number]	0.12065 [1]	0.13645 [1]	0.12403 [1]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.02	< 0.03	< 0.02

Notes related to this table are provided on the page following Table 6-14.

Table 6-14: Summary of Full Power without FCS Mark-B-HTP Category 4 Break Results (Reference [72])

Parameter	0.07 ft^2	0.08 ft^2	0.09 ft^2	0.10 ft^2
Break Location	CLPD	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	7.20	5.58	4.36	3.52
Loss of Subcooling Margin (sec)	11.60	9.98	8.76	7.94
RCP Trip (sec)	6.58	4.96	3.75	2.92
EFW Actuation (sec)	46.58	44.96	43.76	42.92
ESAS Low RCS Pressure (HPI) Actuation (sec)	17.54	15.18	13.38	12.02
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	2079.85	1686.87	1372.56	1155.68
HPI/LPI Actuation (sec)	84.54 / 611.62	82.18 / 610.00	80.38 / 608.78	79.02 / 607.96
HPI/LPI Flow Starts (sec)	84.58 / > EOT	82.22 / > EOT	80.40 / > EOT	79.06 / > EOT
Hot legs drained, loop A/B (sec)	797.68 / 798.90	668.76 / 625.00	545.92 / 549.90	461.96 / 465.60
Core starts to uncover/entire core quenched (sec) (Note 2)	~1600 / ~2900	~1300 / ~2700	~1100 / ~2400	~900 / ~2100
CFT injection starts / ends (sec)	1842.54 / > EOT	1505.27 / > EOT	1214.81 / > EOT	1024.52 / > EOT
HPI & LPI Core Power Match	2315.31	2245.24	2169.69	2128.34
Transient analysis ends (sec)	3836.72	3479.32	3246.72	2953.11
MSIV Isolation SG-1 / SG-2 (sec)	1979.25 / 1998.53	1708.75 / 1723.75	1490.23 / 1521.91	1328.38 / 1371.55
Minimum mixture level (ft @ sec) (Note 3)	~ 9.4 @ ~ 1800	~ 9.3 @ ~ 1500	~ 9.3 @ ~ 1200	~ 9.4 @ ~ 1000
AC PCT (F) [Segment Number]	1099.4 [20]	1124.6 [20]	1147.4 [20]	1114.1 [20]
PCT time (sec)	1969.4	1688.2	1412.8	1209.3
Heated Segments (#) (Note 4)	3	3	3	3
Maximum Local Oxidation (%)	0.10122	0.10826	0.115	0.10503
Average Oxidation (%)	0.081318	0.081867	0.082529	0.081729
HC PCT (F) [Segment/Channel Number]	1323.4 [20 / 1]	1354.3 [20 / 1]	1380.1 [20 / 1]	1394.9 [20 / 5]
PCT time (sec)	2157.8	1863.4	1611.5	1365.5
Heated Segments (#) (Note 4)	3	3	3	3
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.33788 [1]	0.40654 [1]	0.49634 [1]	0.49246 [1]
Average Oxidation (%)[Channel Number]	0.10281 [1]	0.10876 [1]	0.11906 [1]	0.11574 [1]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.02	< 0.02	< 0.02

Notes related to this table are provided on the page following Table 6-14.

Table 6-14 Cont'd: Summary of Full Power without FCS Mark-B-HTP Category 4 Break Results (Reference [72])

Parameter	0.11 ft^2	0.12 ft^2	0.13 ft^2	0.14 ft^2
Break Location	CLPD	CLPD	CLPD	CLPD
Break opens (sec)	0	0	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	2.84	2.34	2.00	1.76
Loss of Subcooling Margin (sec)	7.26	6.76	6.42	6.18
RCP Trip (sec)	2.24	1.74	1.40	1.16
EFW Actuation (sec)	42.24	41.74	41.40	41.16
ESAS Low RCS Pressure (HPI) Actuation (sec)	10.98	10.08	9.44	8.96
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	996.34	878.82	782.32	708.70
HPI/LPI Actuation (sec)	77.98 / 607.28	77.08 / 606.78	76.44 / 606.44	75.96 / 606.20
HPI/LPI Flow Starts (sec)	78.02 / > EOT	77.12 / > EOT	76.48 / > EOT	76.00 / > EOT
Hot legs drained, loop A/B (sec)	405.22 / 401.36	376.46 / 373.54	334.10 / 331.62	299.48 / 303.42
Core starts to uncover/entire core quenched (sec) (Note 2)	~800 / ~1900	~800 / ~1600	~600 / ~1400	~600 / ~1200
CFT injection starts / ends (sec)	885.30 / > EOT	784.84 / > EOT	701.40 / > EOT	634.22 / > EOT
HPI & LPI Core Power Match	2080.15	2050.17	2021.23	2010.45
Transient analysis ends (sec)	2552.09	2284.94	2021.24	2010.46
MSIV Isolation SG-1 / SG-2 (sec)	1142.92 / 1257.63	1066.42 / 1215.92	956.22 / 1010.36	955.11 / 980.60
Minimum mixture level (ft @ sec) (Note 3)	~ 9.7 @ ~ 900	~ 10.1 @ ~ 800	~ 10.3 @ ~ 700	~ 10.4 @ ~ 800
AC PCT (F) [Segment Number]	1091.3 [20]	1036.1 [20]	1030.4 [20]	785.62 [21]
PCT time (sec)	1103.9	1078.6	1046.8	978.61
Heated Segments (#) (Note 4)	3	2	2	1
Maximum Local Oxidation (%)	0.096474	0.086805	0.084812	0.079899
Average Oxidation (%)	0.081091	0.080346	0.080214	0.079887
HC PCT (F) [Segment/Channel Number]	1349.4 [20 / 5]	1339.4 [20 / 5]	1371.9 [20 / 5]	967.44 [21 / 1, 3, 4, 5]
PCT time (sec)	1196.3	1155.2	1040.0	978.54
Heated Segments (#) (Note 4)	3	2	2	1
Rupture Time (sec)	Not Ruptured	Not Ruptured	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.37256 [1]	0.32299 [1]	0.32232 [1]	0.079944 [5]
Average Oxidation (%)[Channel Number]	0.10063 [1]	0.096362 [1]	0.096097 [1]	0.079929 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01	< 0.01	< 0.01

Notes related to this table are provided on the page following Table 6-14.

Table 6-14 Cont'd: Summary of Full Power without FCS Mark-B-HTP Category 4 Break Results (Reference [72])

Parameter	0.15 ft^2	0.20 ft^2
Break Location	CLPD	CLPD
Break opens (sec)	0	0
EFW Flow Rate (gpm/SG)	EFIC Controlled	EFIC Controlled
Automatic or Manual Operator Action to Reset SG Level (min)	20	20
Low RCS Pressure Reactor Trip Rod Insertion (sec) (Note 1)	1.56	1.14
Loss of Subcooling Margin (sec)	5.96	5.54
RCP Trip (sec)	0.94	0.54
EFW Actuation (sec)	40.96	40.54
ESAS Low RCS Pressure (HPI) Actuation (sec)	8.54	7.04
ESAS Low-Low RCS Pressure (LPI) Actuation (sec)	648.22	435.80
HPI/LPI Actuation (sec)	75.54 / 605.98	74.04 / 445.82
HPI/LPI Flow Starts (sec)	75.58 / > EOT	74.08 / 1549.45
Hot legs drained, loop A/B (sec)	281.44 / 286.22	149.16 / 172.56
Core starts to uncover/entire core quenched (sec) (Note 2)	~600 / ~900	~400 / ~700
CFT injection starts / ends (sec)	581.90 / > EOT	398.94 / > EOT
HPI & LPI Core Power Match	1998.43	1550.27
Transient analysis ends (sec)	1998.44	1550.28
MSIV Isolation SG-1 / SG-2 (sec)	926.04 / 895.15	737.27 / 824.28
Minimum mixture level (ft @ sec) (Note 3)	~ 11.0 @ ~ 600	~ 9.2 @ ~ 400
AC PCT (F) [Segment Number]	727.42 [21]	977.99 [20]
PCT time (sec)	751.19	470.16
Heated Segments (#) (Note 4)	1	4
Maximum Local Oxidation (%)	0.079897	0.080110
Average Oxidation (%)	0.079885	0.079897
HC PCT (F) [Segment/Channel Number]	711.95 [19/1,3,4,5]	1262.1 [20 / 5]
PCT time (sec)	0.0031	567.98
Heated Segments (#) (Note 4)	0	4
Rupture Time (sec)	Not Ruptured	Not Ruptured
Maximum Local Oxidation (%)[Channel Number]	0.079942 [5]	0.13441 [5]
Average Oxidation (%)[Channel Number]	0.079927 [5]	0.084269 [5]
Initial Oxide Fraction AC/HC (%)	0.0799167 / 0.0799218	0.0799167 / 0.0799218
Whole Core H_2 Generation (%) (Note 5)	< 0.01	< 0.01

Notes for Tables 6-12 through 6-14:

1. This is the time rod insertion begins (i.e. trip time + delay time).
2. Core heatup is characterized as the time when cladding temperature begins to rise above the saturation temperature (from HC clad temperature plot). Core quench is characterized as the time when the temperatures of all superheated clad nodes reach the saturation temperature of the surrounding liquid (from HC and AC clad temperature plots).
3. The minimum mixture level is referenced from the bottom of the heated fuel and is taken from the _62 plot (the core mixture level plot).
4. The number of heated segments is taken from the number of superheated clad nodes (from the cladding temperature plot) in the indicated channel.
5. The whole-core hydrogen generation for Mk-B-HTP analysis is calculated using the simplified equation from Table 7 of Reference [22].
   $$H_2\% = 0.63\times\left(AC\%_{\text{oxide}}^{\text{average}} - AC\%_{\text{oxide}}^{\text{initial}}\right) + 0.37\times\left(HC\%_{\text{oxide}}^{\text{average}} - HC\%_{\text{oxide}}^{\text{initial}}\right).$$
   The initial oxidation fraction is taken from the zero edit of the run and multiplied by 100 to provide an initial oxidation percentage for both the hot and average channels.
6. EOT denotes End of Transient, and NA denotes Not Applicable/Available/Actuated.

Table 6-15: Full Power without FCS PCT versus Break Size

Offsite Power	Break Location	Break Size (ft^2)	EFIC PCT (F)	Maximum EFW flow (807 gpm/SG) PCT (F) (0 minute delay)	Maximum EFW flow (807 gpm/SG) PCT (F) (10 minute delay)	Maximum EFW flow PCT (F) (807 gpm/SG) (20 minute delay)
LOOP	CLPD	0.005	712 [1]	-	-	-
		0.01	712 [1]	-	-	-
		0.03	712 [1]	-	-	-
		0.04	712 [1]	712.0	-	-
		0.045	-	992.9	857.6	-
		0.05	903.1	1236.2	-	-
		0.055	-	-	1357.7	-
		0.06	1304.7	1304.1	1397.9	-
		0.065	-	-	1382.2	-
		0.07	1323.4	1272.6	1317.0	-
		0.08	1354.3	-	-	-
		0.09	1380.1	-	-	-
		0.10	1394.9	-	-	-
		0.11	1349.4	-	-	-
		0.12	1339.4	-	-	-
		0.13	1371.9	-	-	-
		0.14	967.4	-	-	-
		0.15	727.4	-	-	-
		0.20	1262.1	-	-	-
		0.30	1224 [1]	-	-	-
		0.50	1070 [1]	-	-	-
	HPI	0.022	-	-	-	712
		0.02463	712.0	849.9	-	855.7
	CFT	0.25	712 [1]	-	-	-
		0.30	712 [1]	-	-	-
		0.35	712 [1]	-	-	-
		0.40	712 [1]	-	-	-
		0.44	712 [1]	-	-	-

Offsite Power	**Break Location**	**Break Size (ft^2)**	**EFIC PCT (F)**	**Maximum EFW flow (807 gpm/SG) PCT (F) (0 minute delay)**	**Maximum EFW flow (807 gpm/SG) PCT (F) (10 minute delay)**	**Maximum EFW flow PCT (F) (807 gpm/SG) (20 minute delay)**
1-min RCP Trip	CLPD	0.30	848 [1]	-	-	-
		0.50	712 [1]	-	-	-
	CFT	0.25	712 [1]	-	-	-
		0.30	712 [1]	-	-	-
		0.35	712 [1]	-	-	-
		0.40	712 [1]	-	-	-
		0.44	712 [1]	-	-	-

Note [1]: The PCT reported is an estimated value.

FIGURE 6-1: Category 1 0.005 ft² CLPD Break, Full Power with FCS Primary and Secondary Pressures

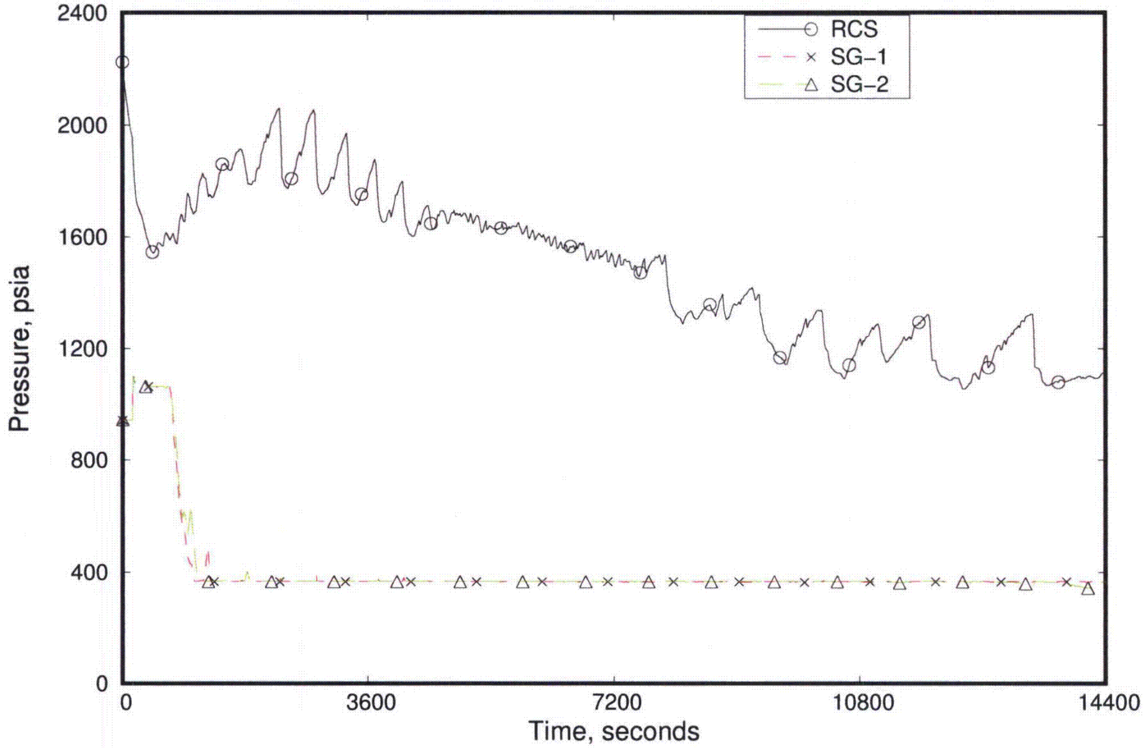


FIGURE 6-2: Category 1 0.005 ft² CLPD Break, Full Power with FCS RV Mixture Level

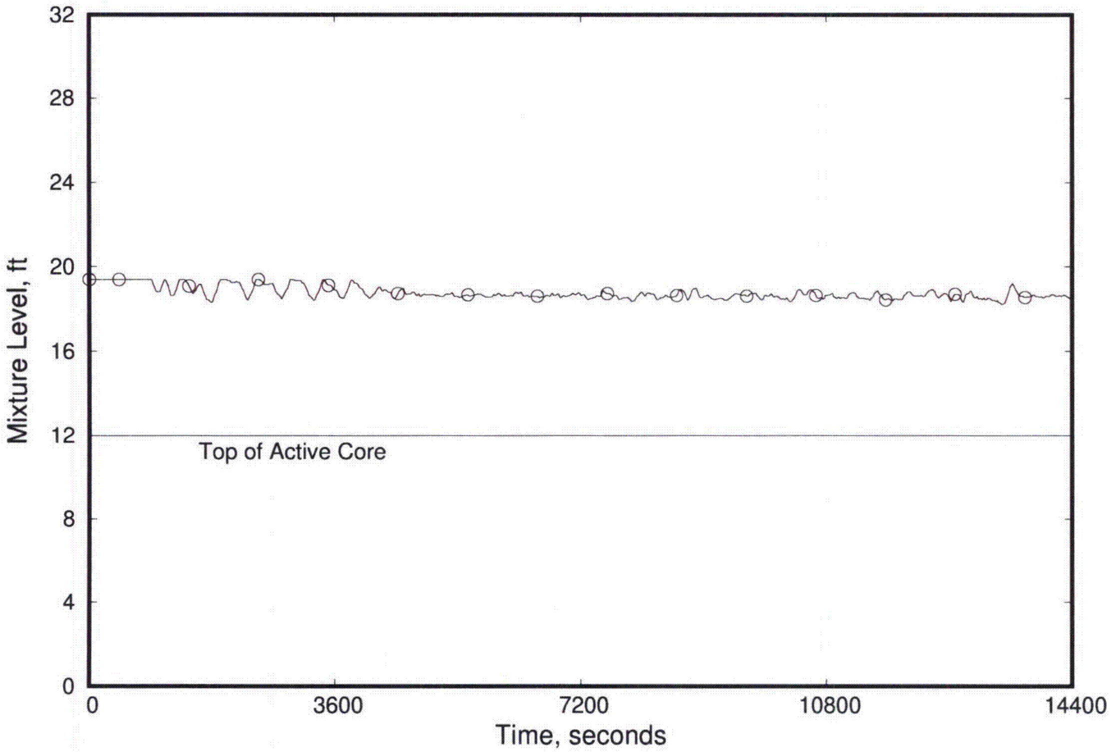


FIGURE 6–3: Category 1 0.005 ft^2 CLPD Break, Full Power with FCS Break Mass Flow Rate

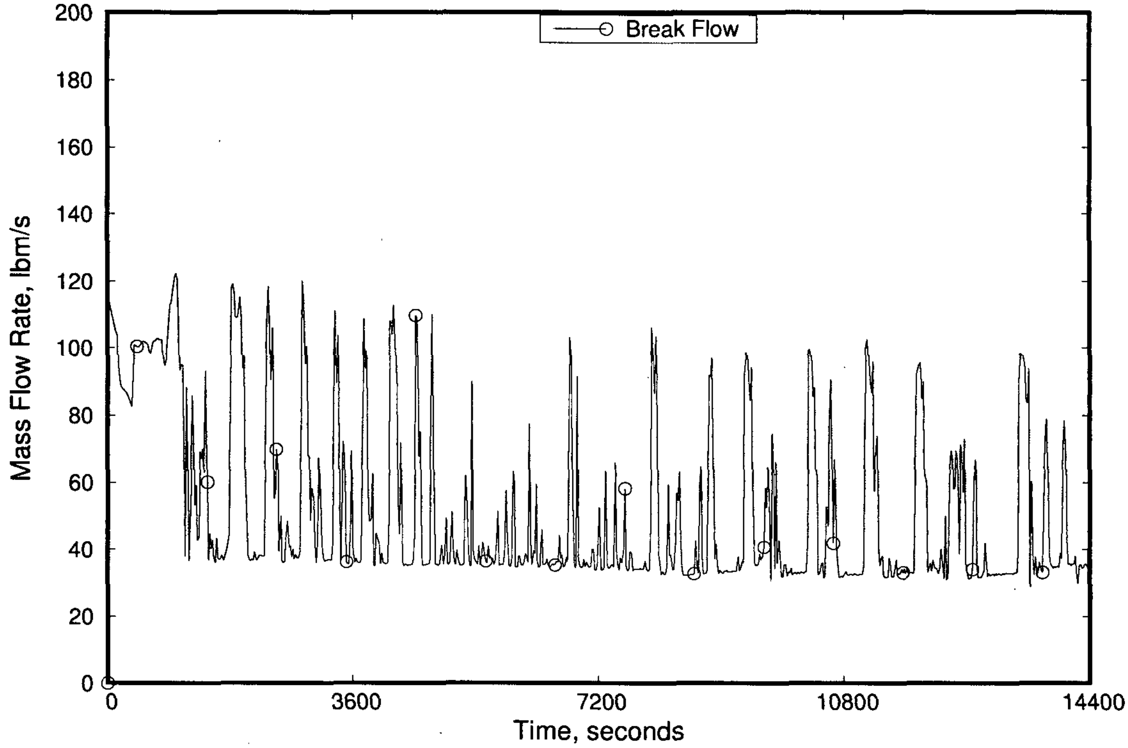


FIGURE 6–4: Category 1 0.005 ft^2 CLPD Break, Full Power with FCS ECCS Flow (Intact loop HPI, CFT and LPI)

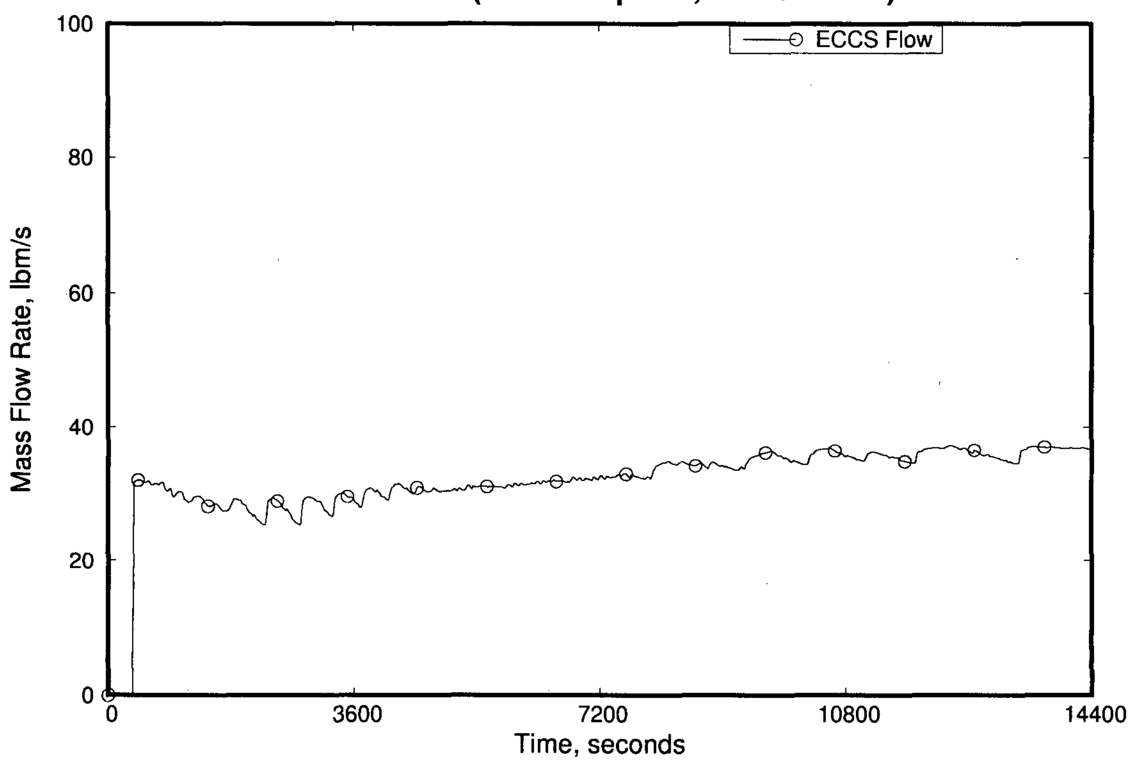


FIGURE 6-5: Category 2 CLPD Breaks, Full Power with FCS Comparison of Primary Pressures

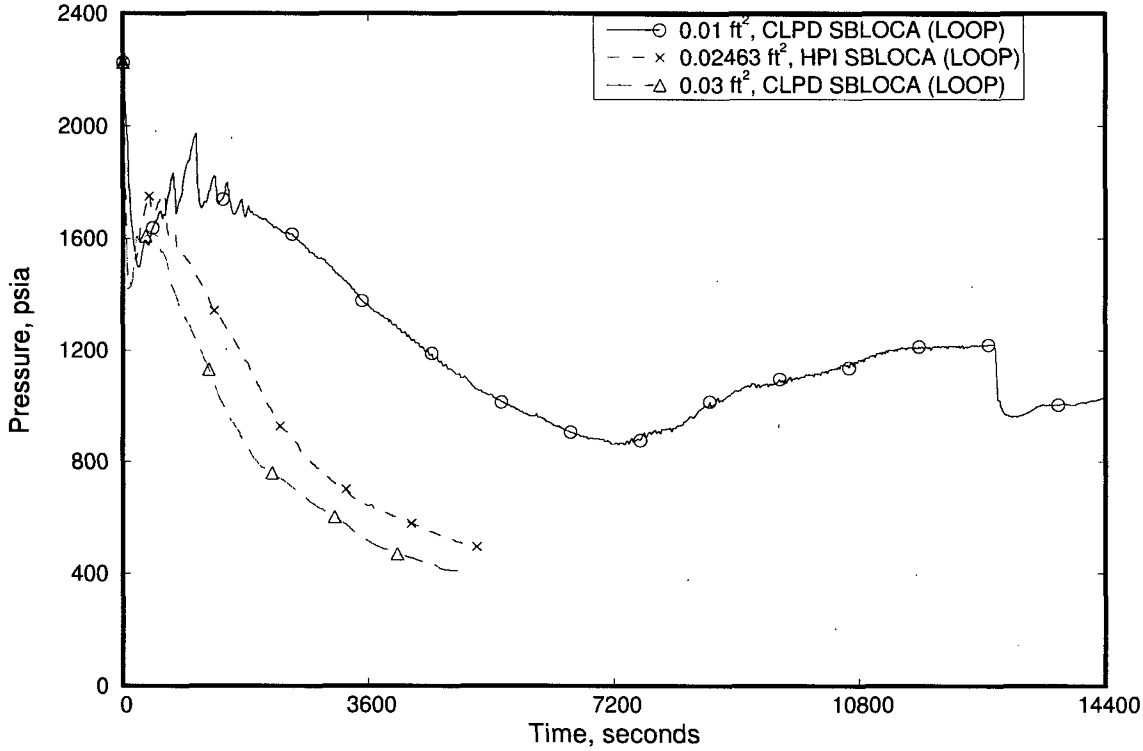


FIGURE 6-6: Category 2 CLPD Breaks, Full Power with FCS Comparison of Secondary Pressures

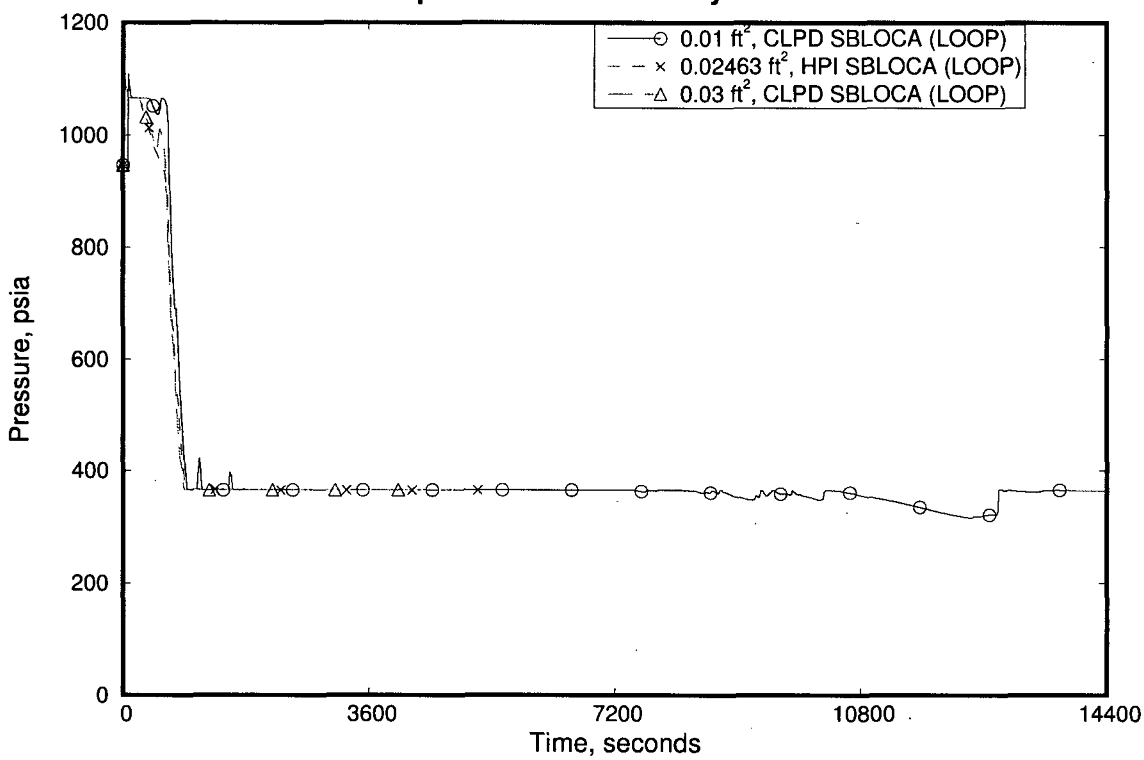


FIGURE 6-7: Category 2 CLPD Breaks, Full Power with FCS Comparison of RV Mixture Levels

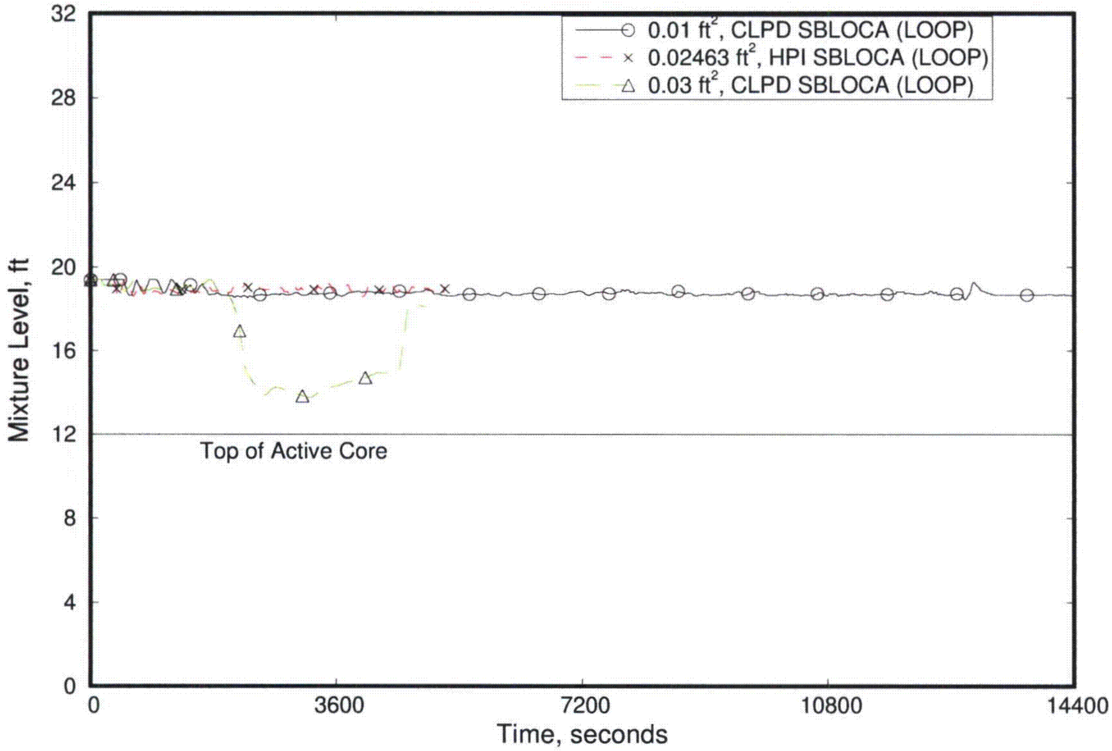


FIGURE 6-8: Category 2 CLPD Breaks, Full Power with FCS Comparison of Break Mass Flow Rates

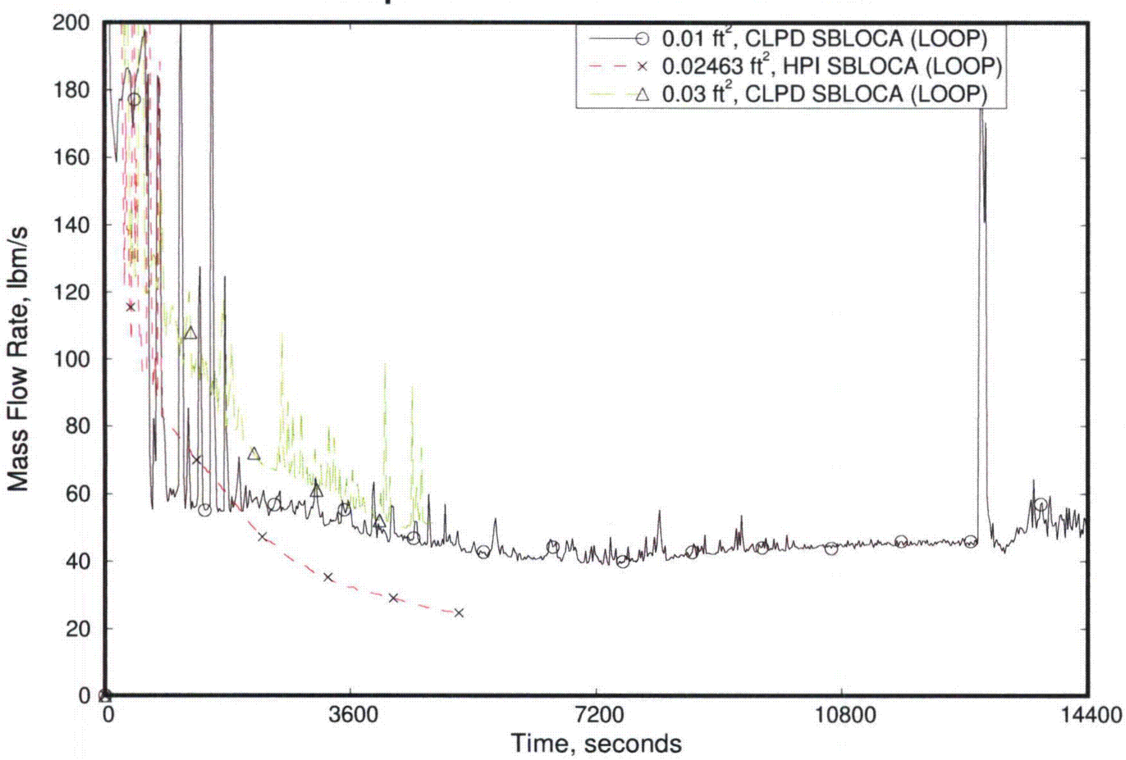


FIGURE 6–9: Category 2 CLPD Breaks, Full Power with FCS Comparison of ECCS Flows

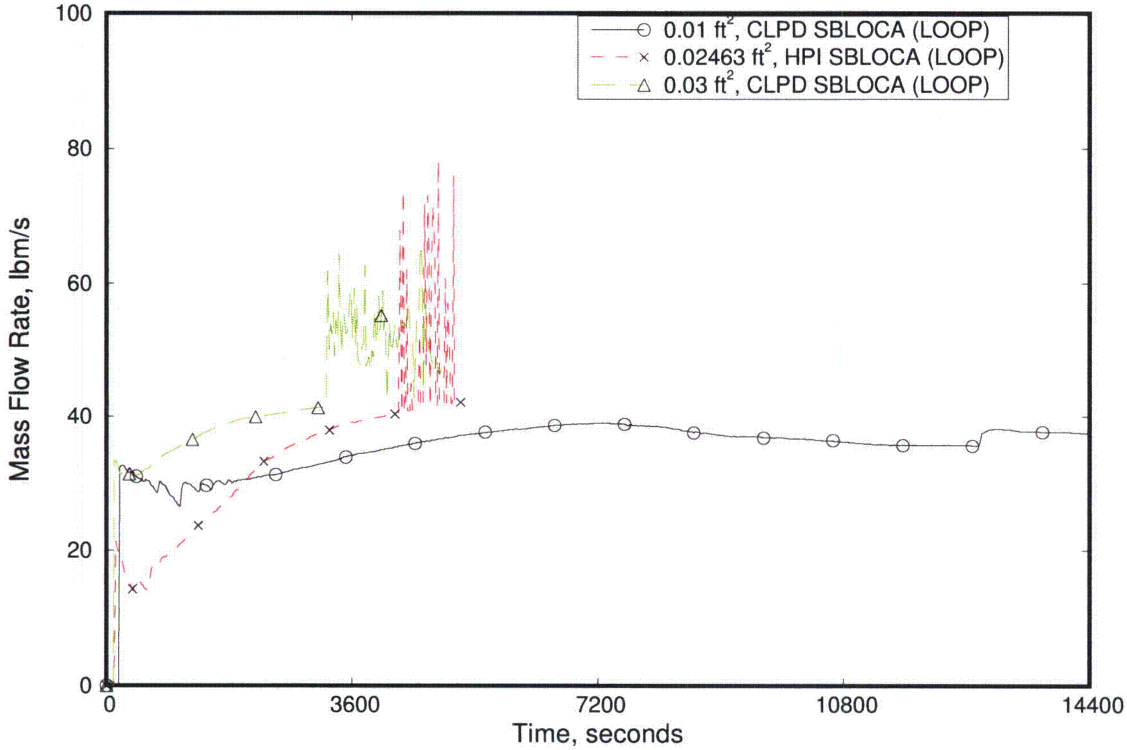


FIGURE 6–10: Category 2 CLPD Breaks, Full Power with FCS Comparison of RCS Liquid Fractions

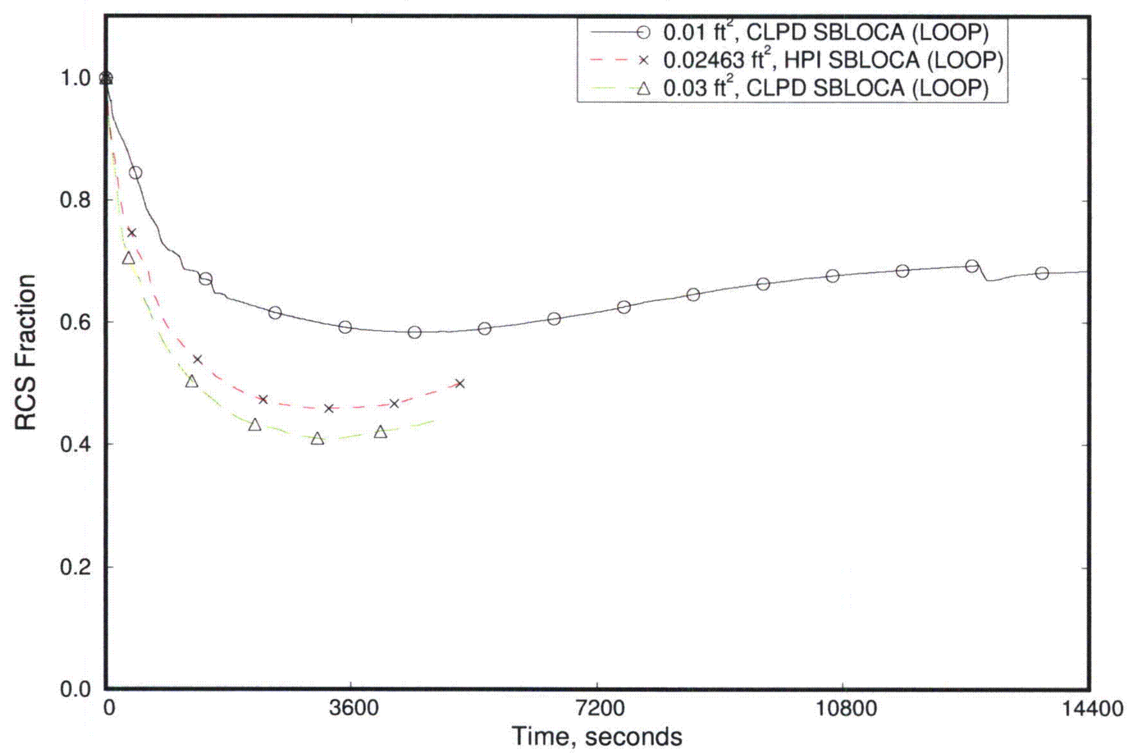


FIGURE 6-11: Category 3 CLPD Breaks, Full Power with FCS
Comparison of Primary Pressures

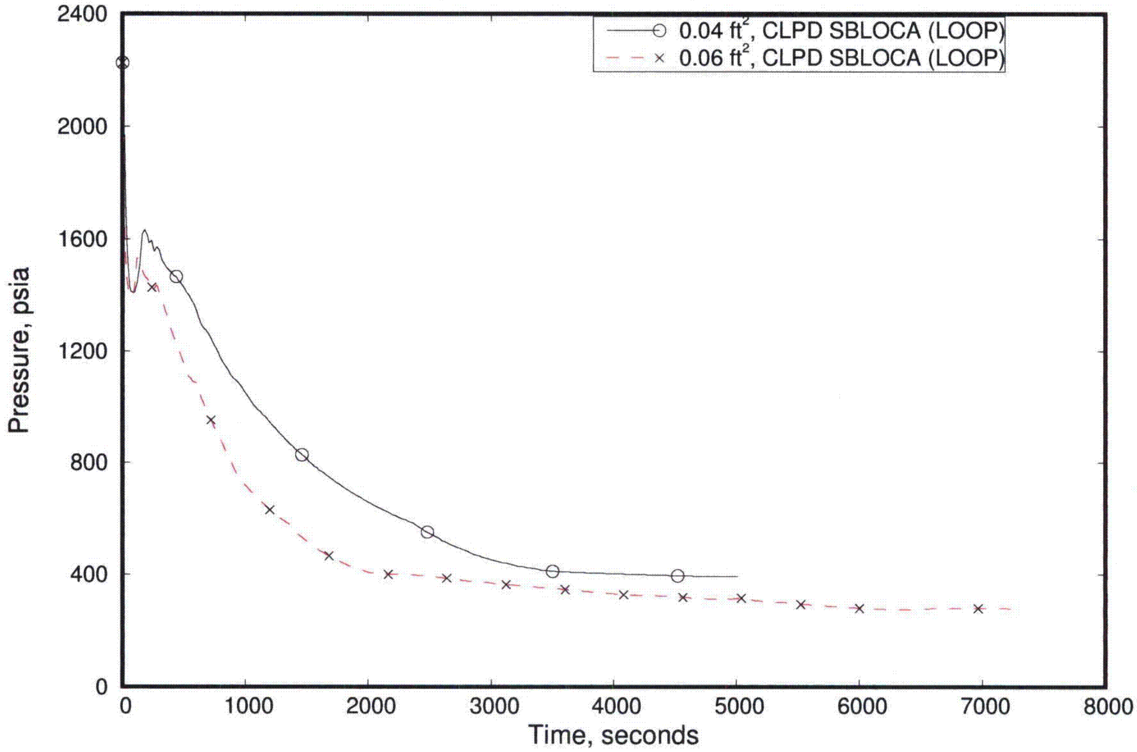


FIGURE 6-12: Category 3 CLPD Breaks, Full Power with FCS
Comparison of Peak Clad Temperatures

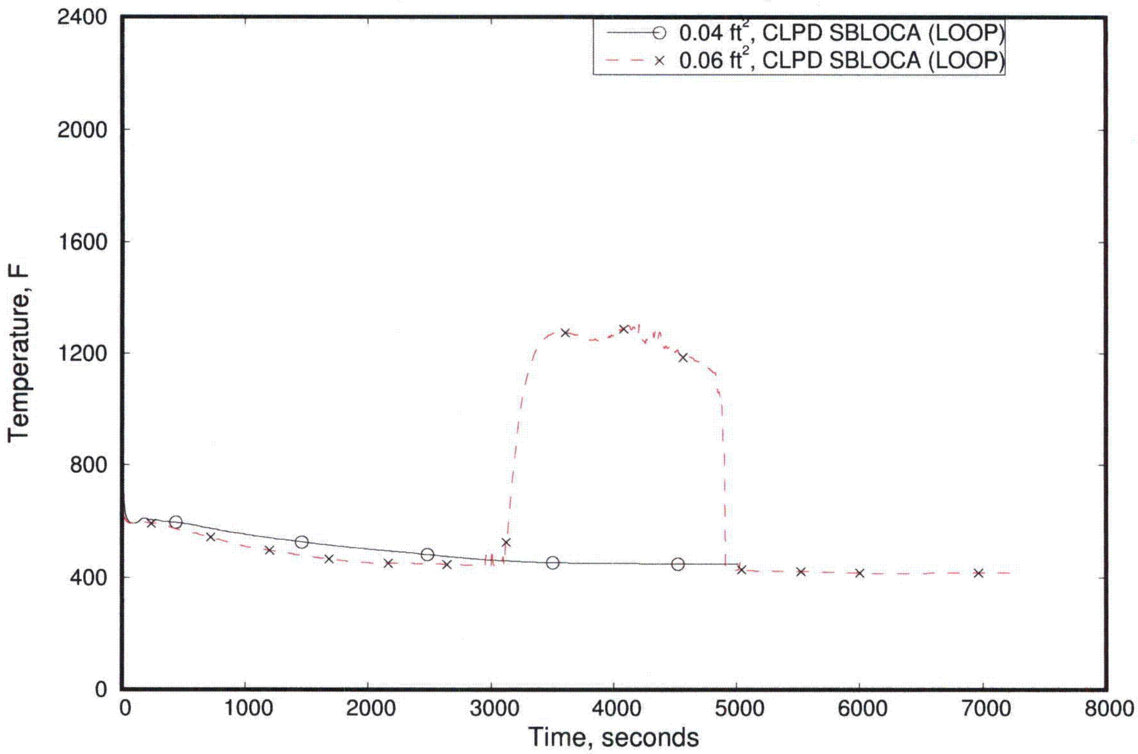


FIGURE 6–13: Category 3 CLPD Breaks, Full Power with FCS Comparison of HC Mixture Levels

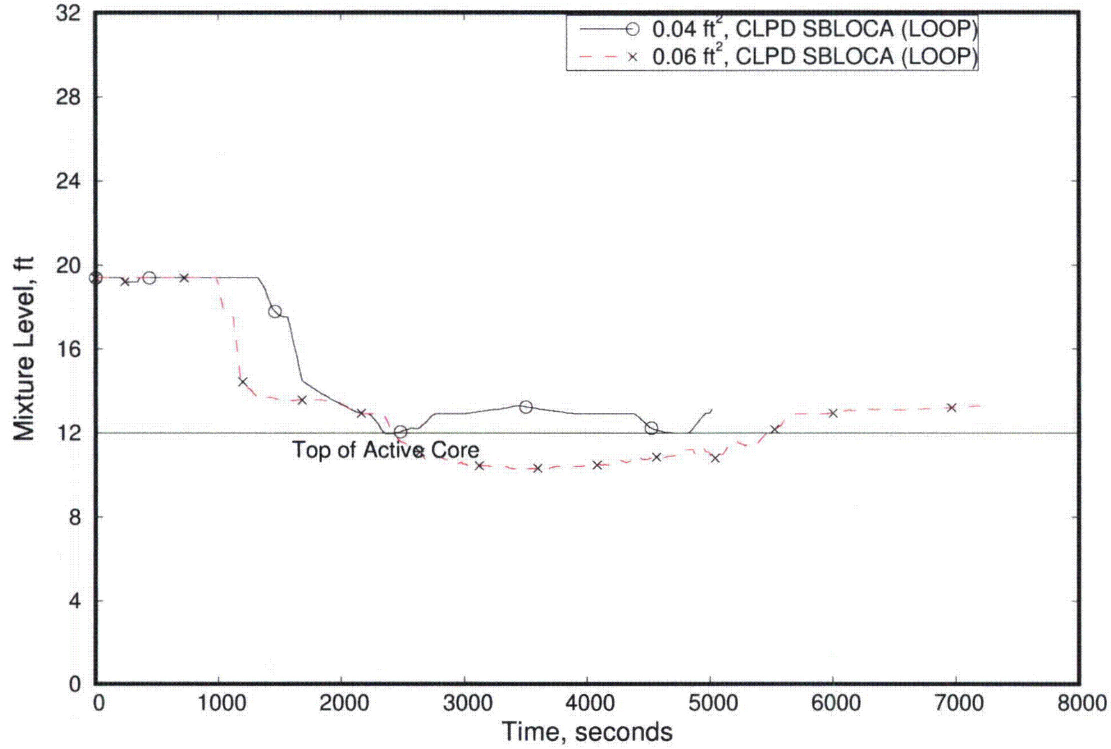


FIGURE 6–14: Category 3 CLPD Breaks, Full Power with FCS Comparison of Break Mass Flow Rates

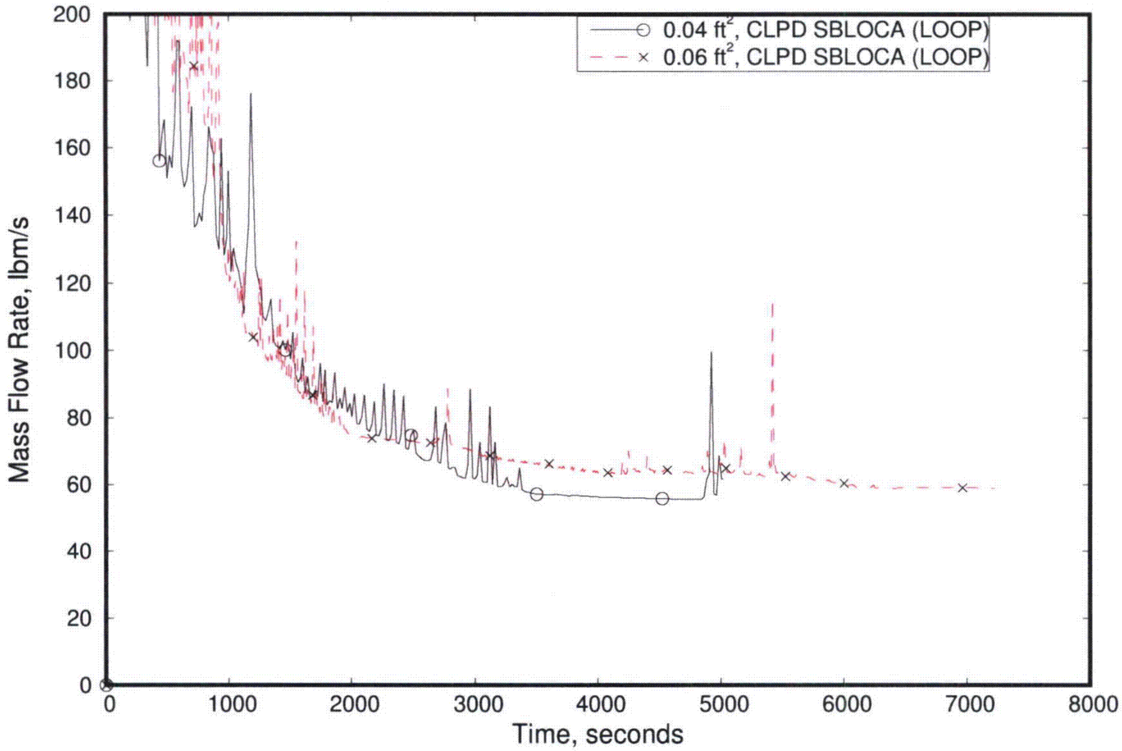


FIGURE 6–15: Category 3 CLPD Breaks, Full Power with FCS Comparison of ECCS Flows

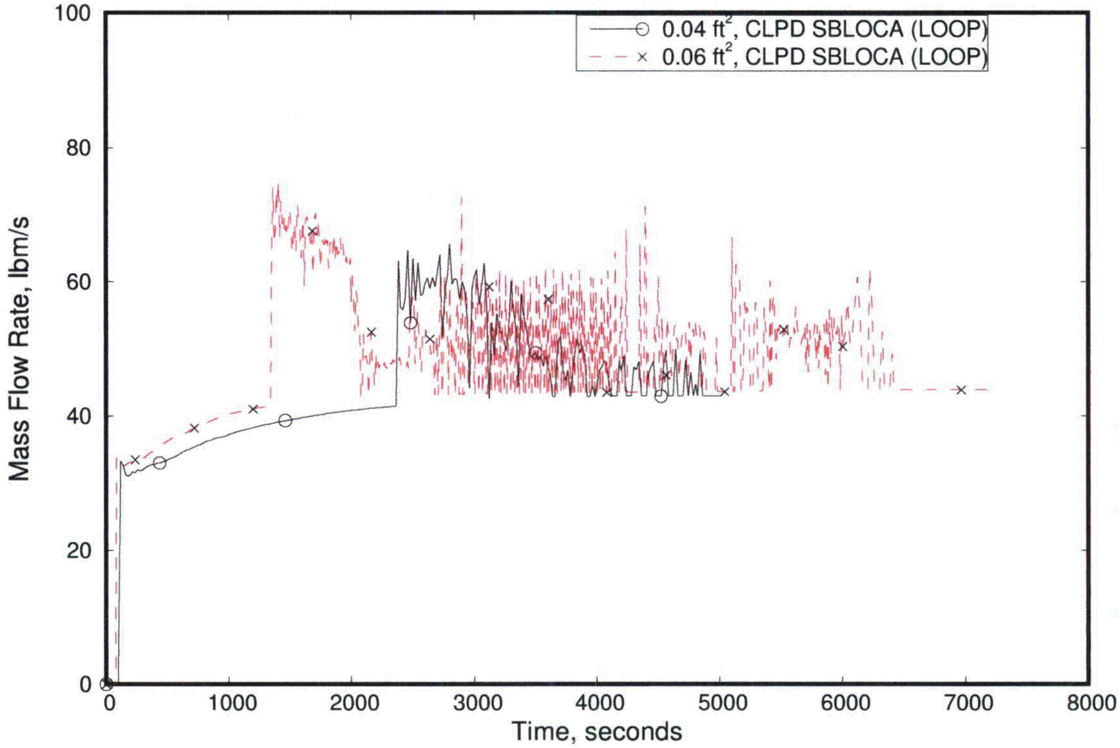


FIGURE 6–16: Category 3 CLPD Breaks, Full Power with FCS Comparison of RCS Liquid Fractions

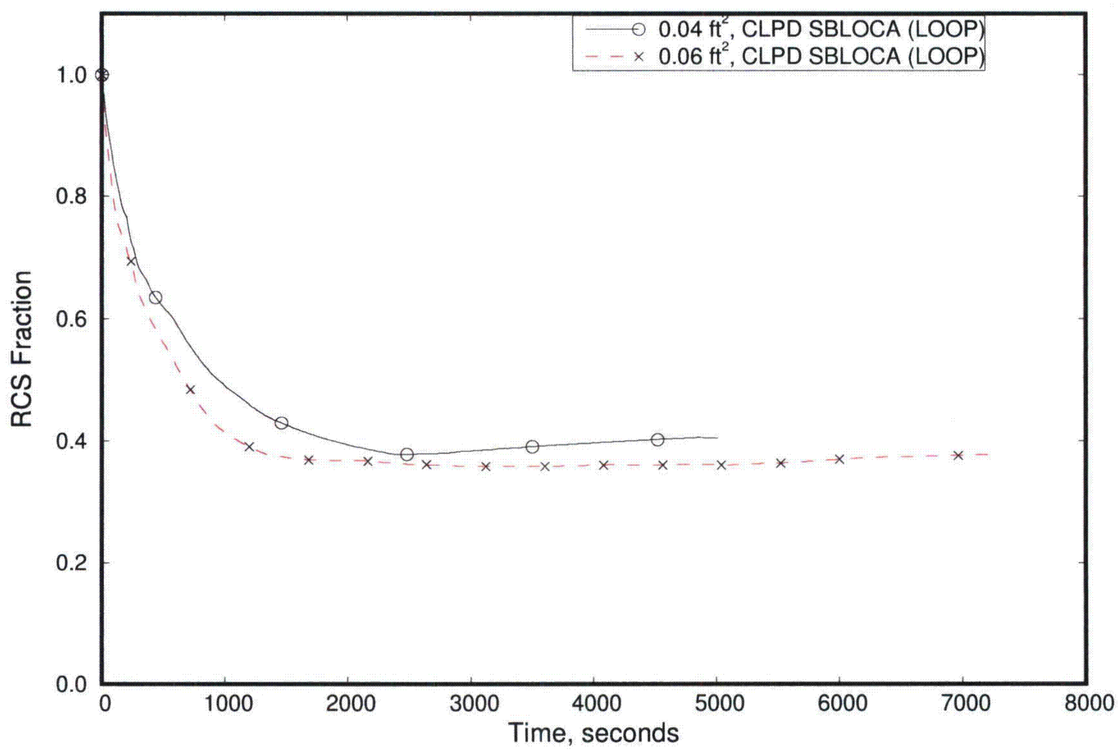


FIGURE 6-17: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of Primary Pressures

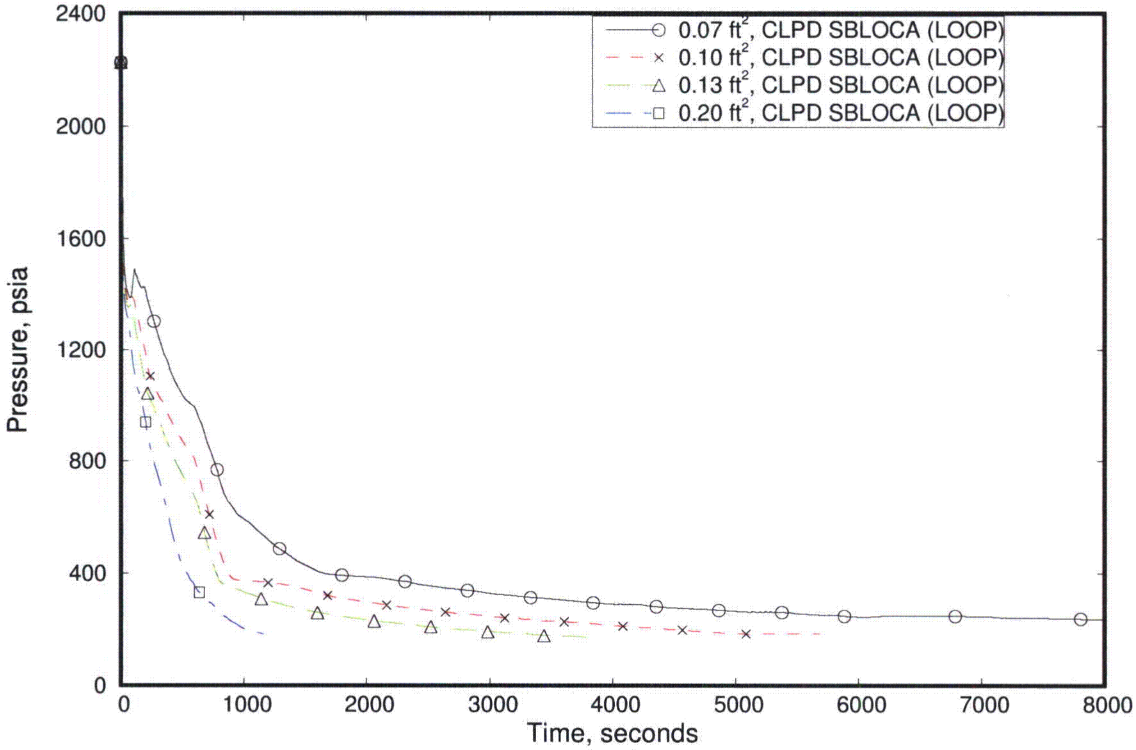


FIGURE 6-18: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of Peak Clad Temperatures

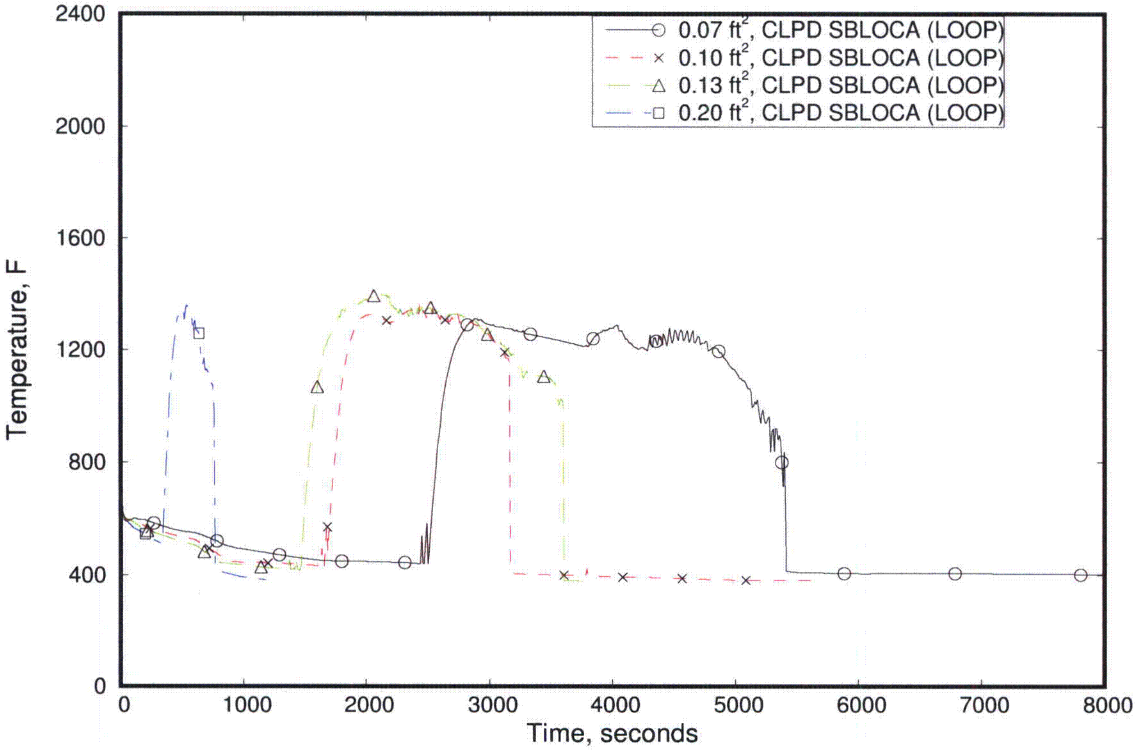


FIGURE 6-19: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of HC Mixture Levels

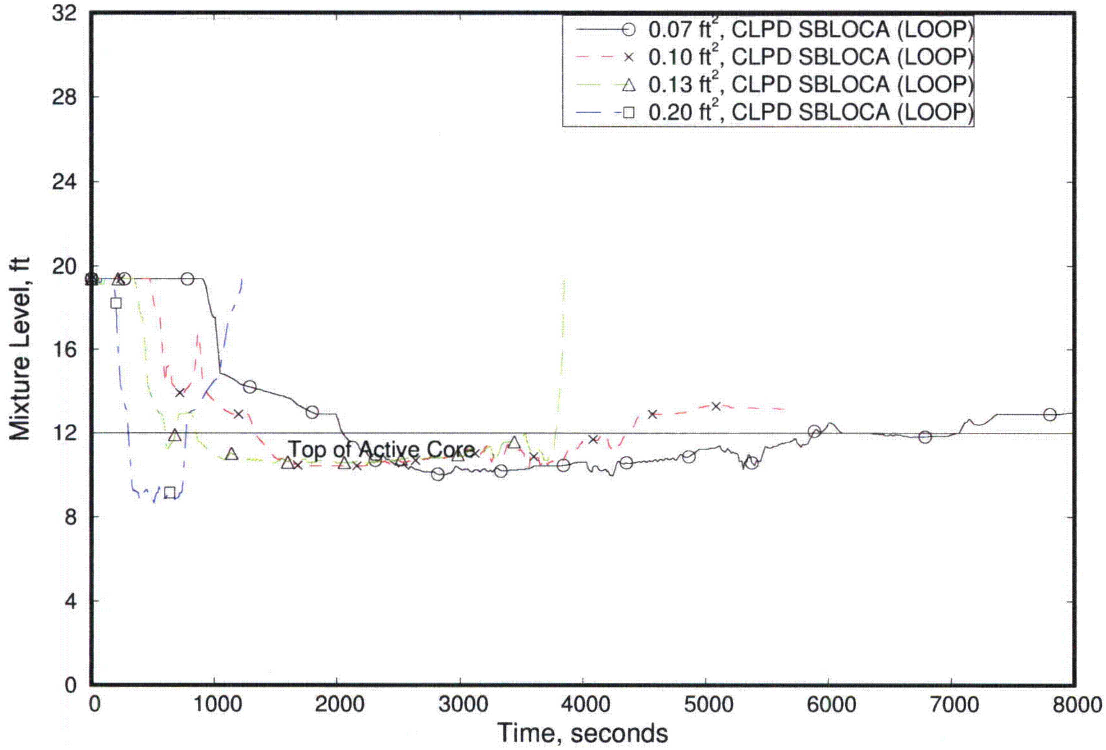


FIGURE 6-20: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of Break Mass Flow Rates

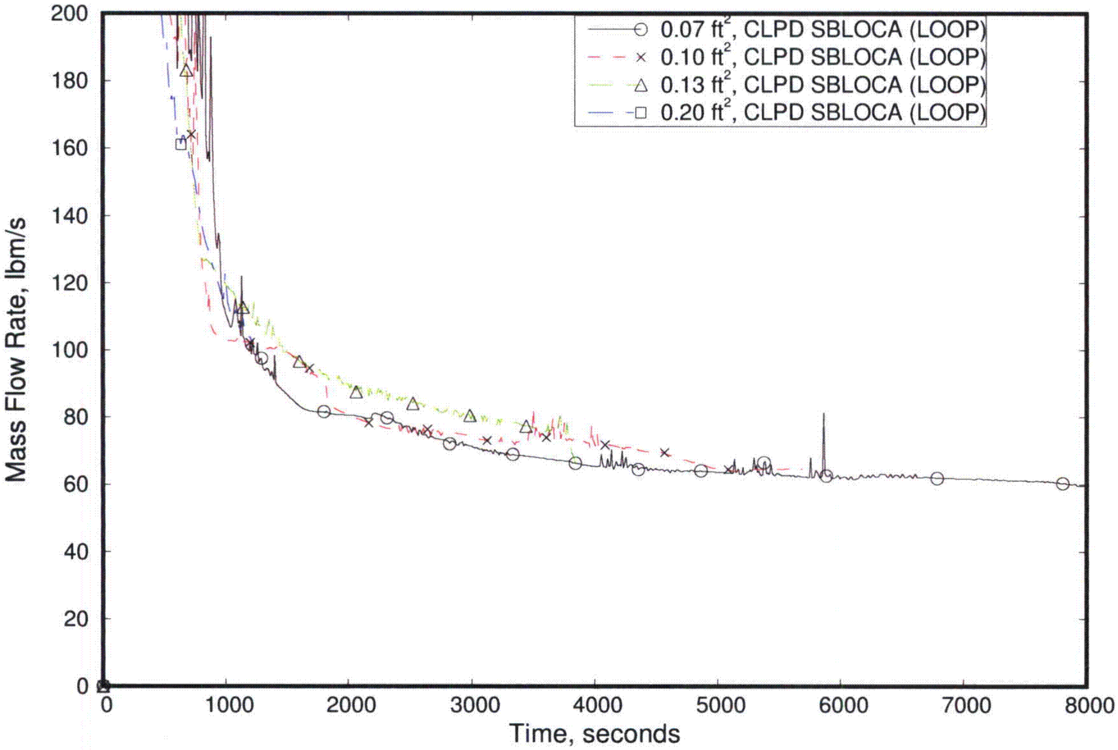


FIGURE 6-21: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of ECCS Flows

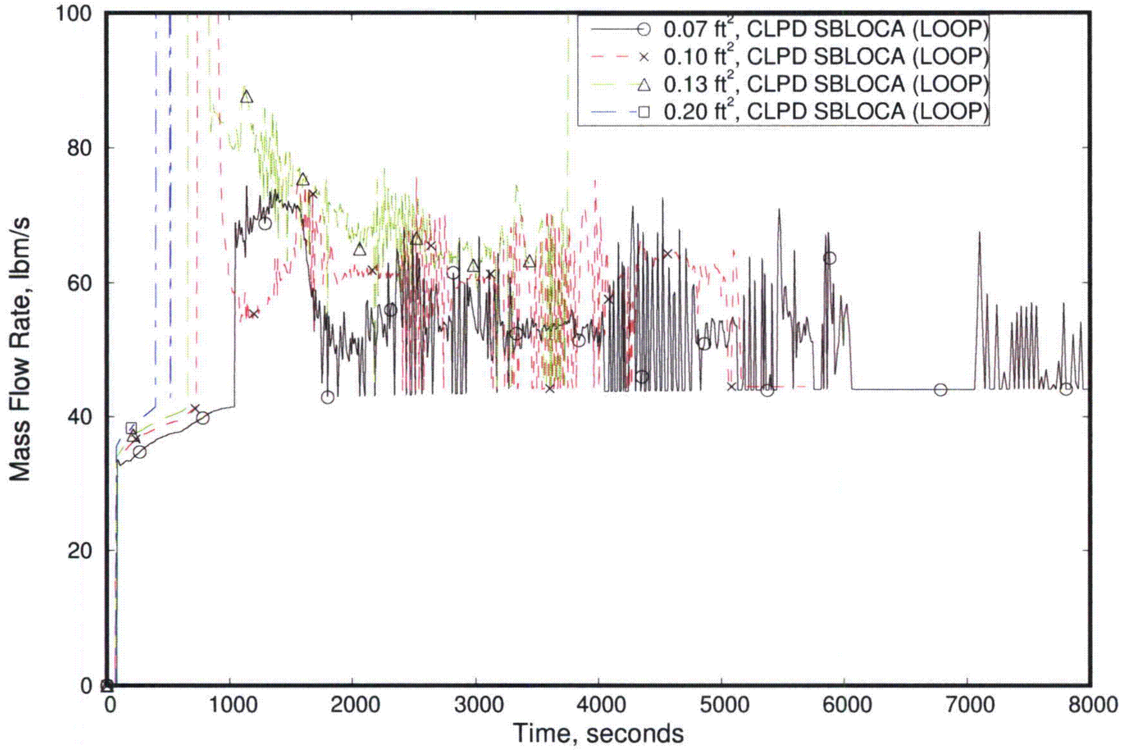


FIGURE 6-22: Select Category 4 CLPD Breaks, Full Power with FCS Comparison of RCS Liquid Fractions

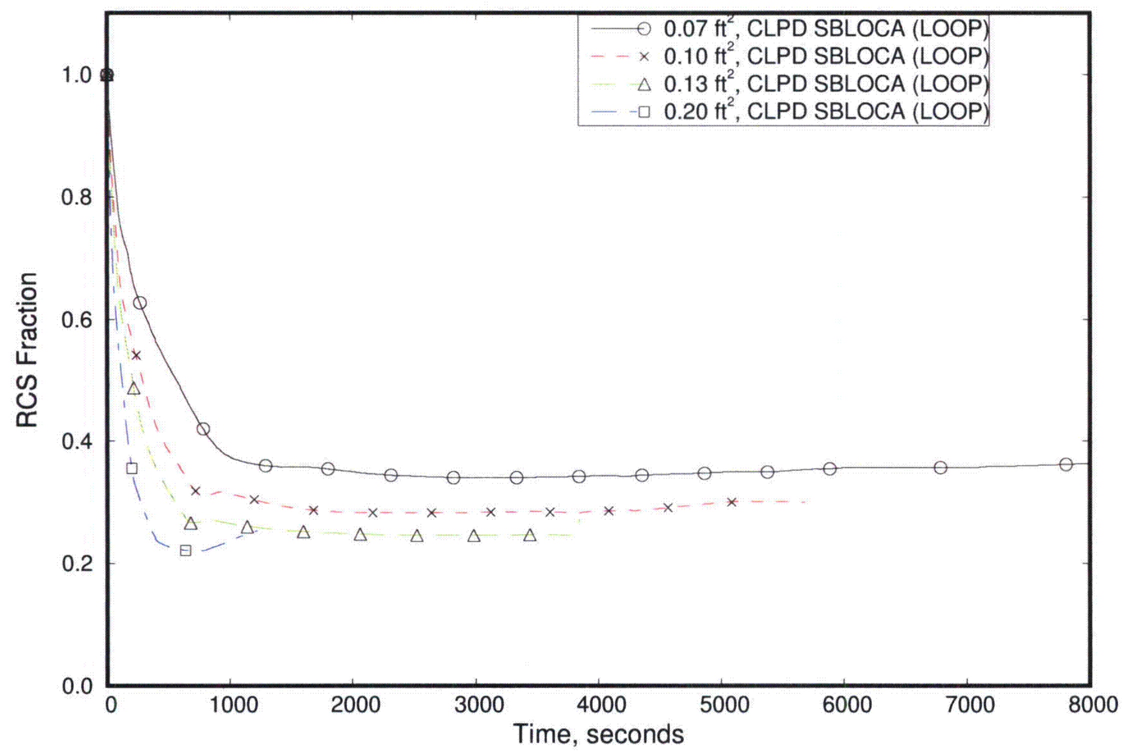


FIGURE 6-23: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of Primary Pressures

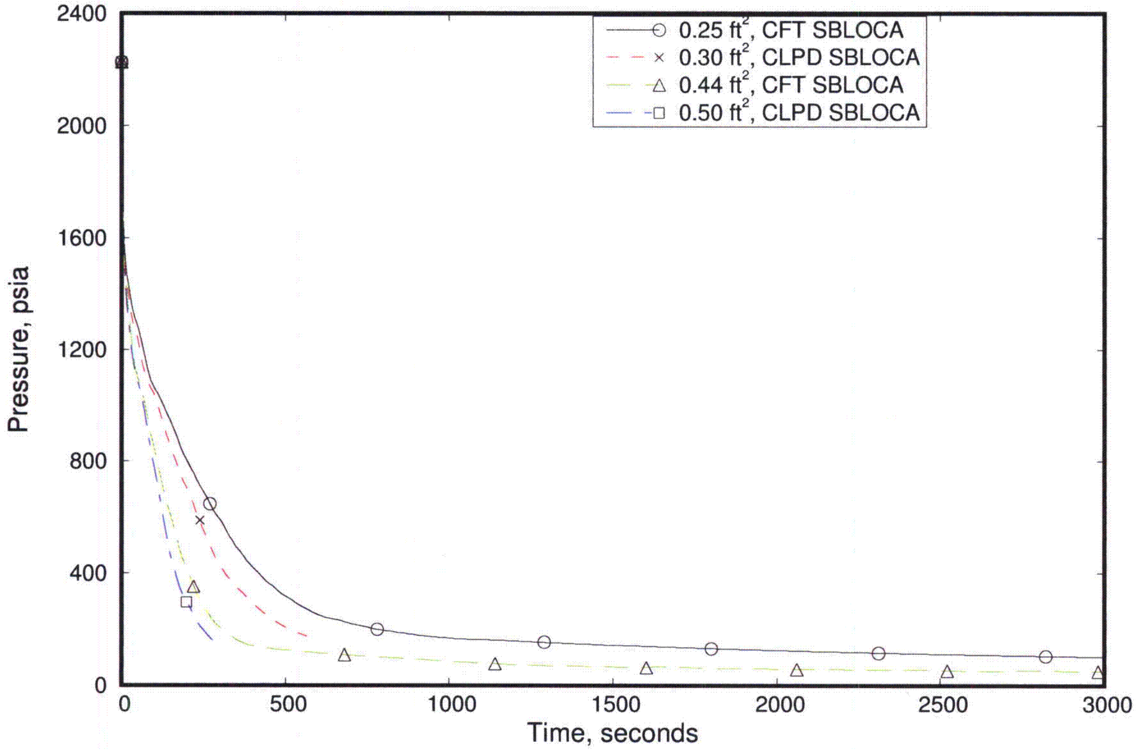


FIGURE 6-24: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of Peak Clad Temperatures

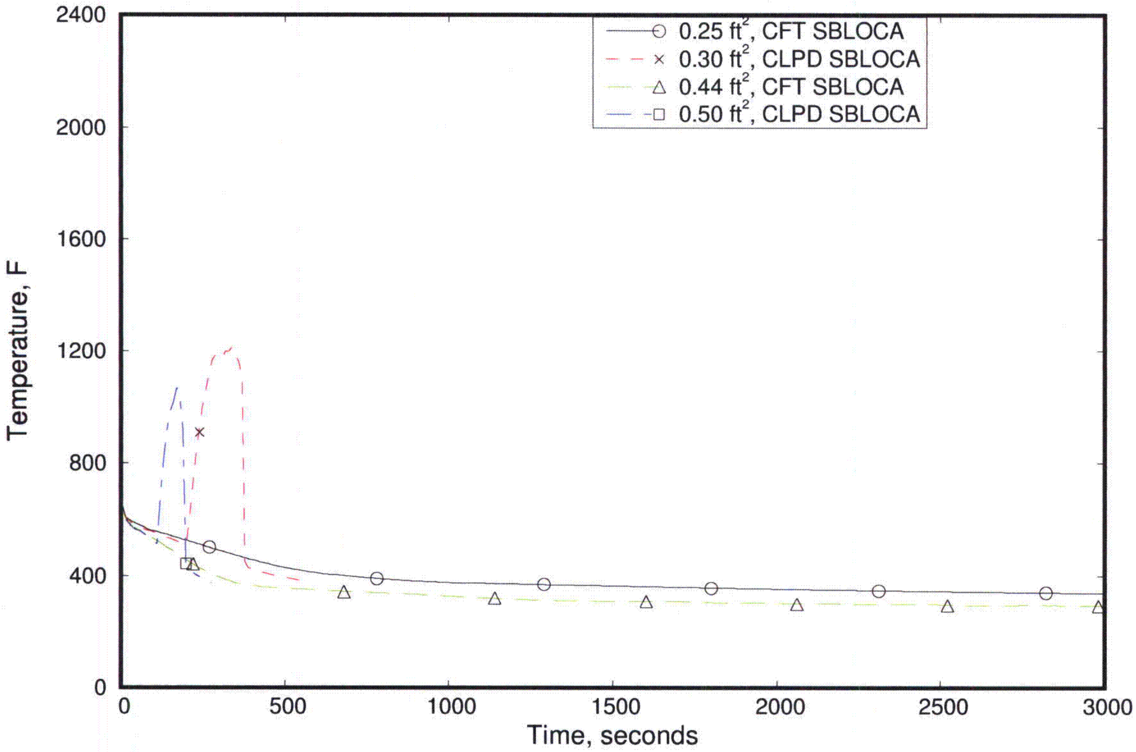


FIGURE 6-25: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of HC Mixture Levels

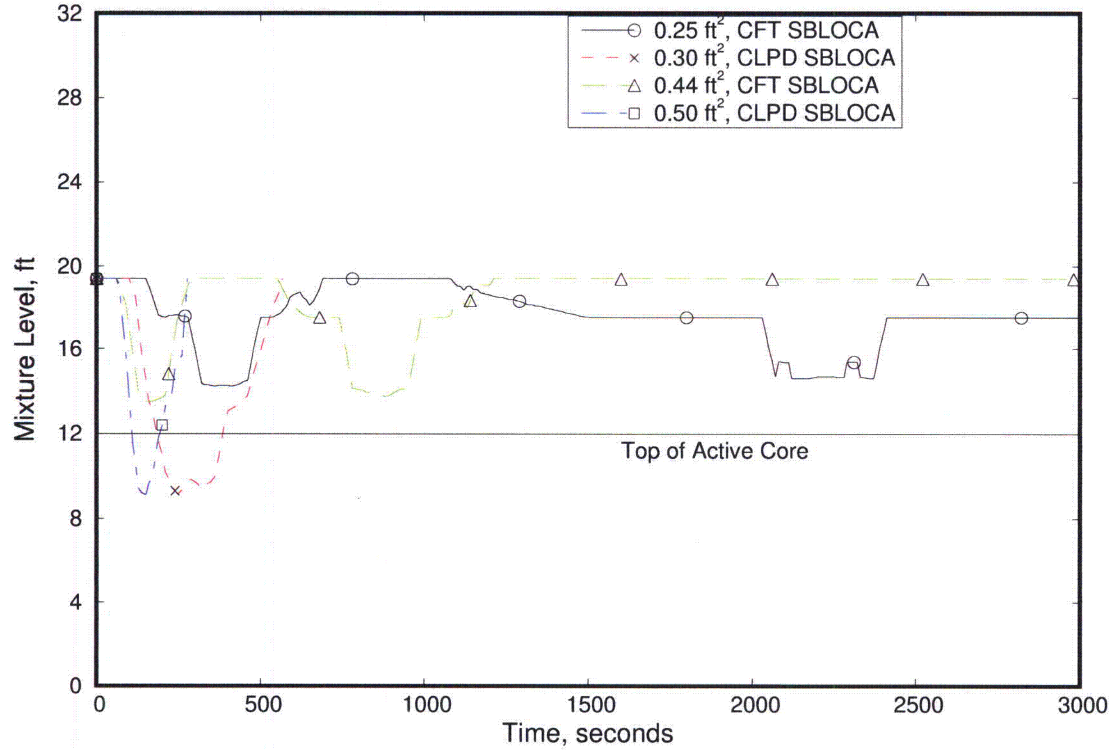


FIGURE 6-26: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of Break Mass Flow Rates

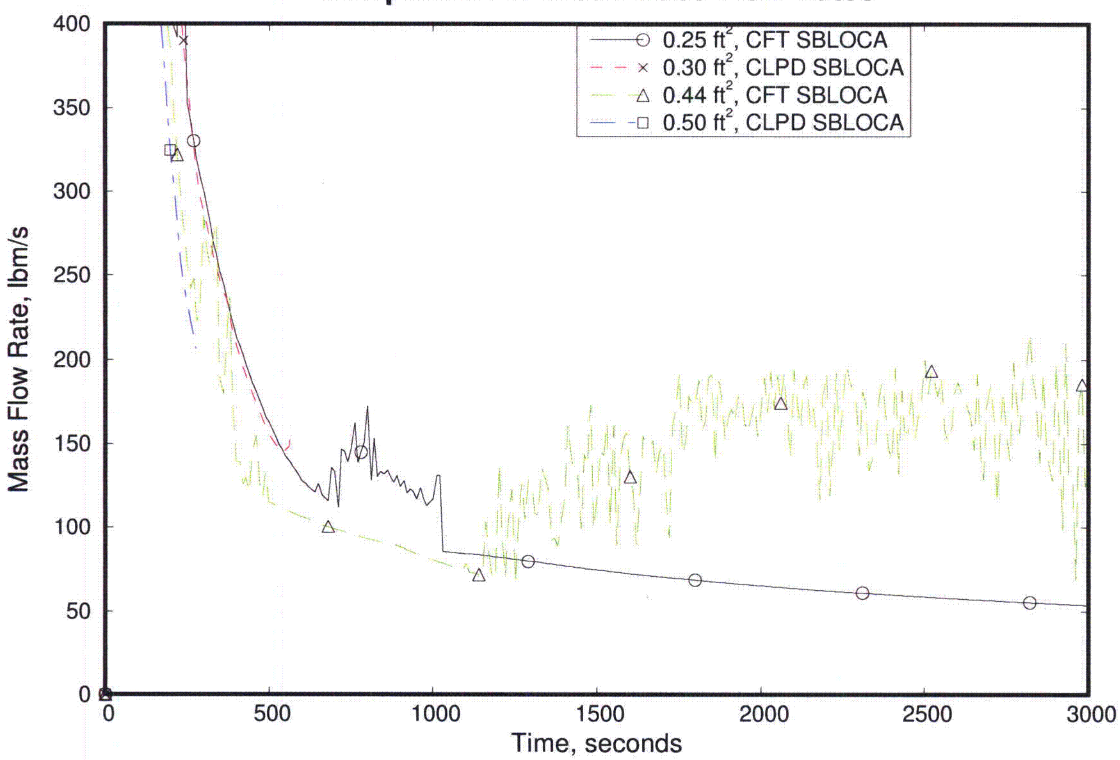


FIGURE 6-27: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of ECCS Flows

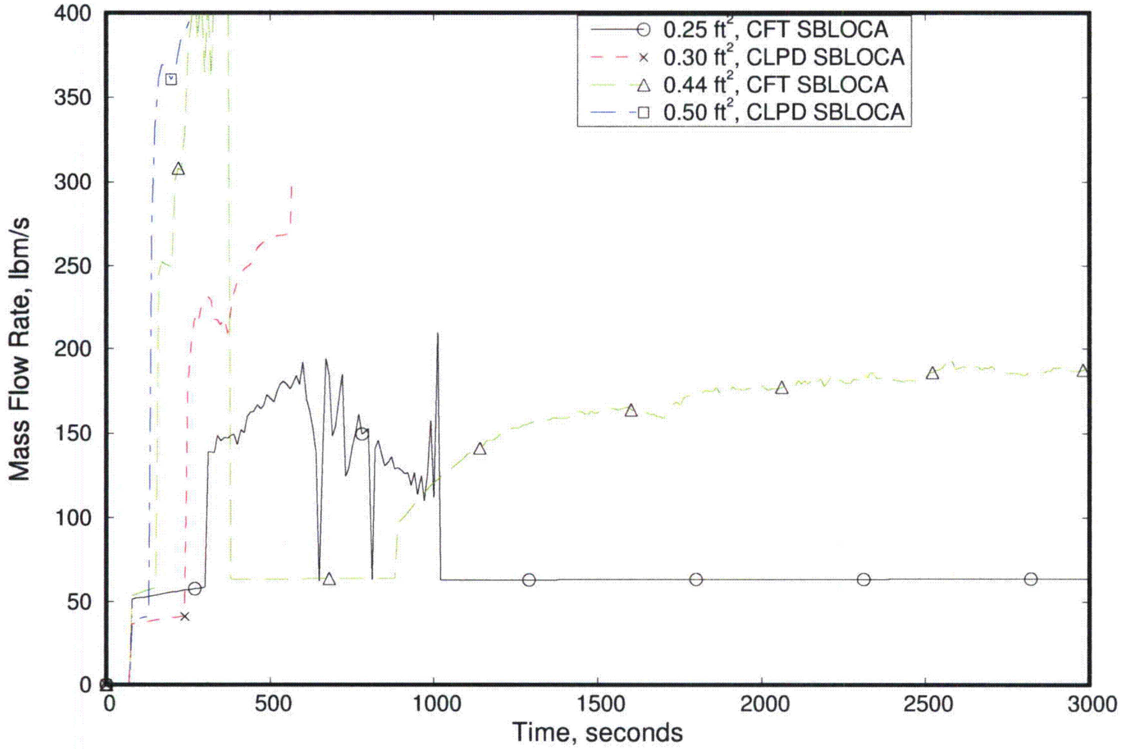


FIGURE 6-28: Select Category 5 CLPD Breaks (LOOP), Full Power with FCS Comparison of RCS Liquid Fractions

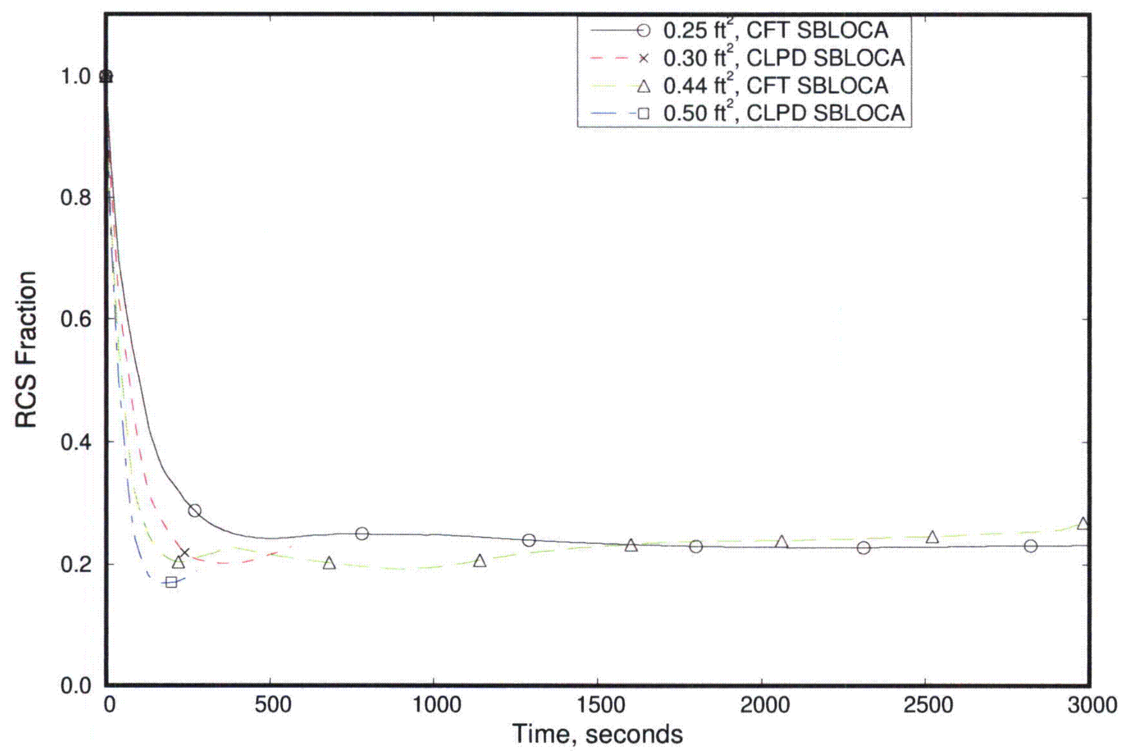


FIGURE 6-29: Select Category 5 CLPD Breaks (1-min RCP Trip), Full Power with FCS Comparison of Primary Pressures

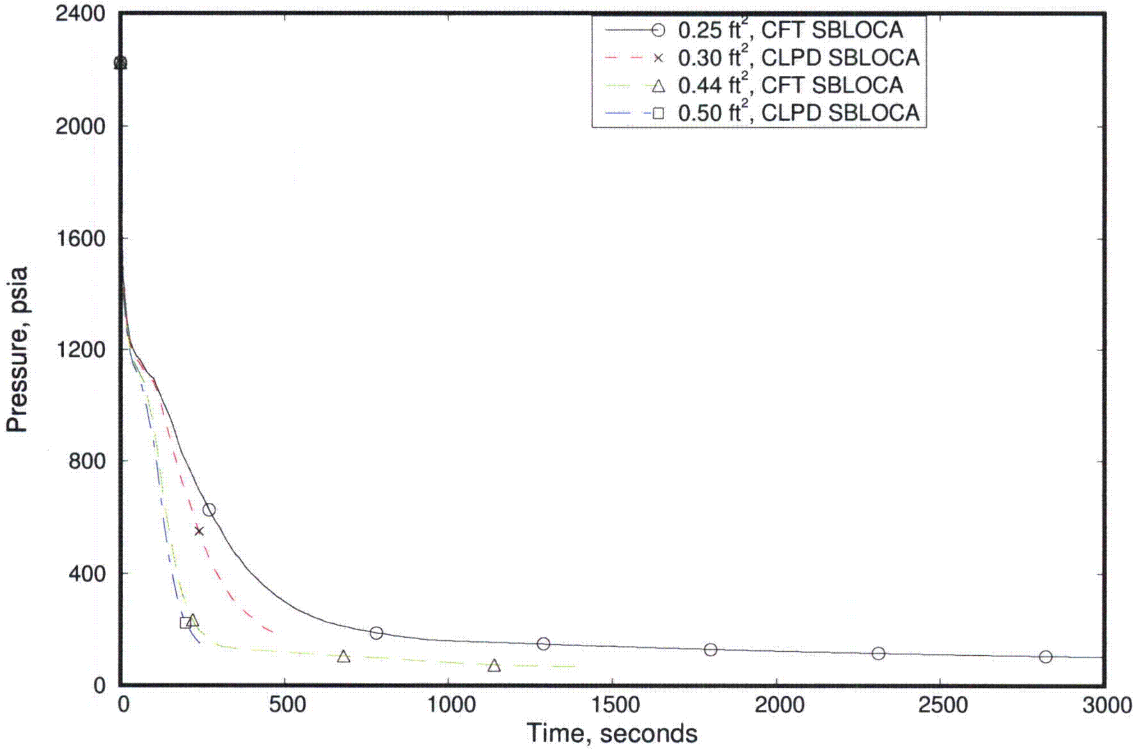


FIGURE 6-30: Select Category 5 CLPD Breaks (1-min RCP Trip), Full Power with FCS Comparison of Peak Clad Temperatures

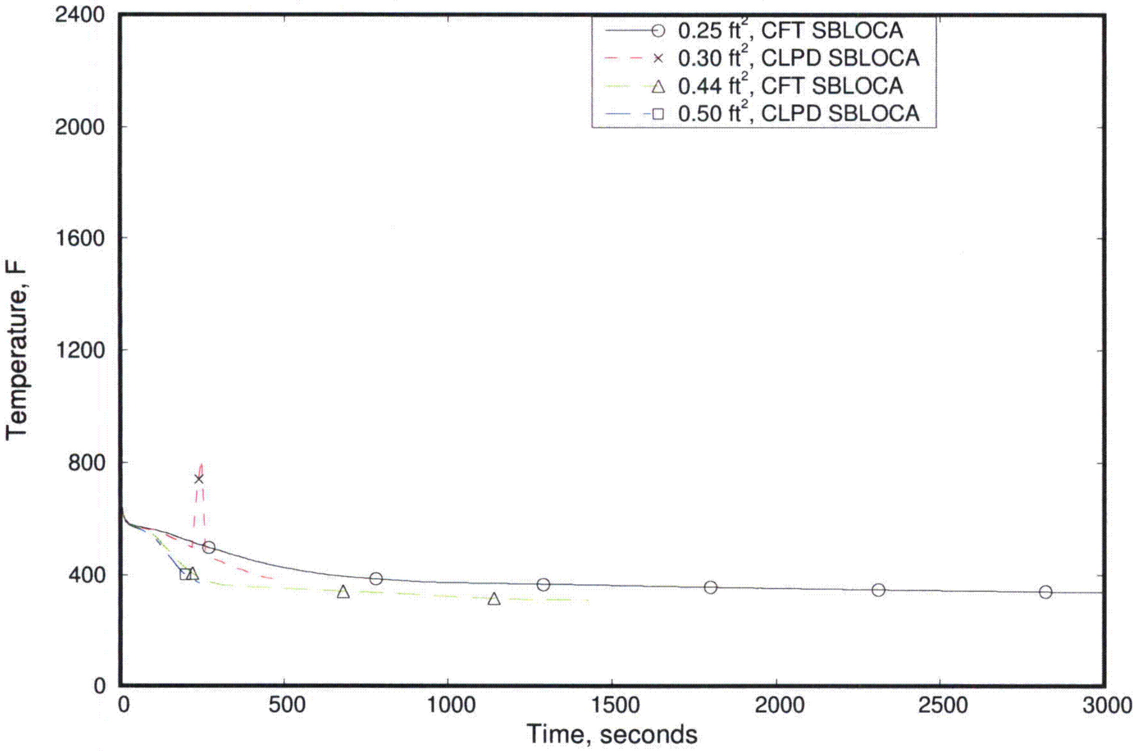


FIGURE 6–31: Select Category 5 CLPD Breaks (1–min RCP Trip), Full Power with FCS Comparison of HC Mixture Levels

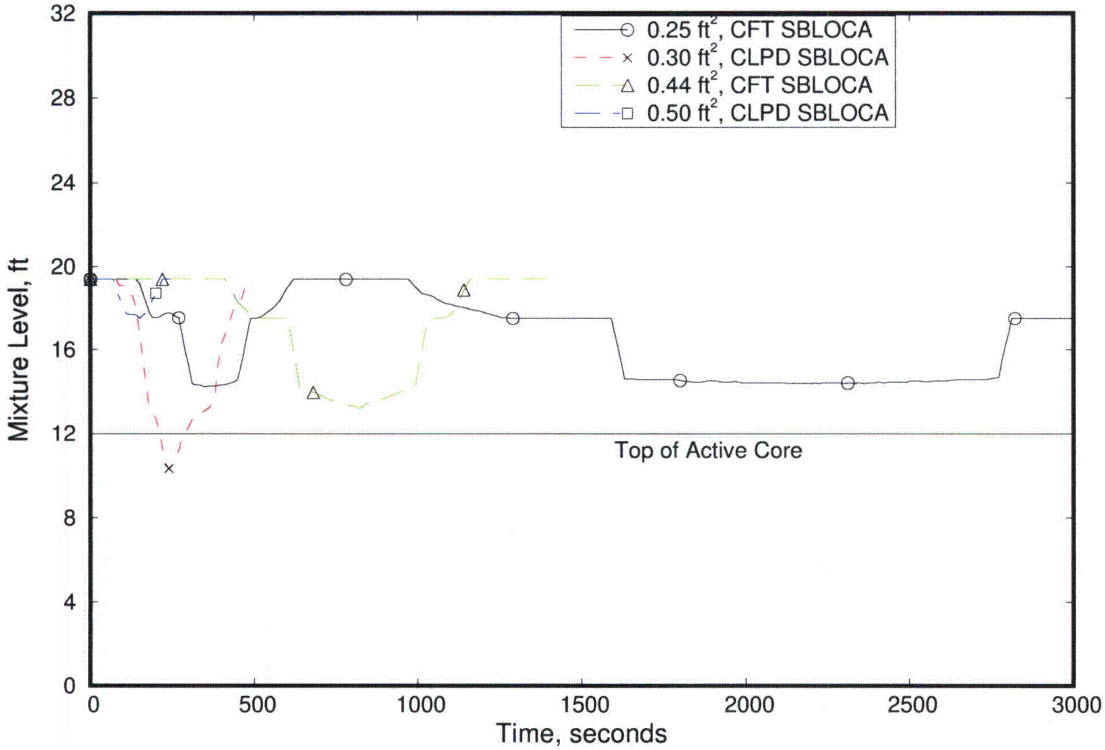


FIGURE 6–32: Select Category 5 CLPD Breaks (1–min RCP Trip), Full Power with FCS Comparison of Break Mass Flow Rates

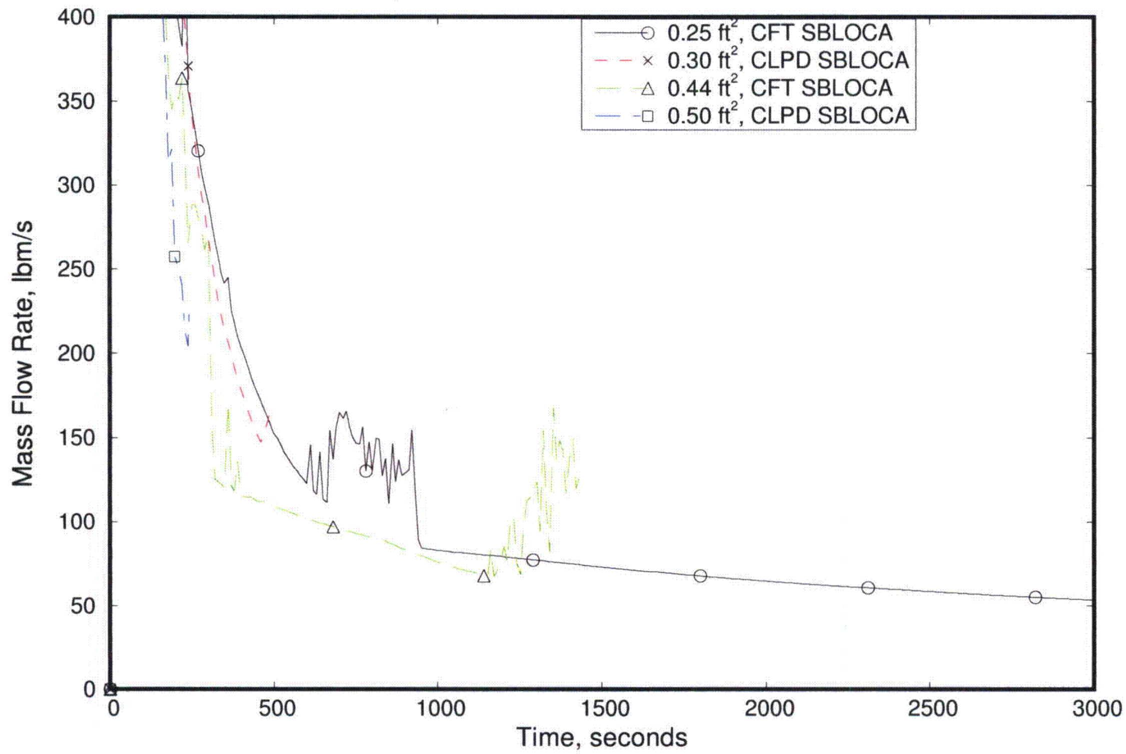


FIGURE 6–33: Select Category 5 CLPD Breaks (1–min RCP Trip), Full Power with FCS Comparison of ECCS Flows

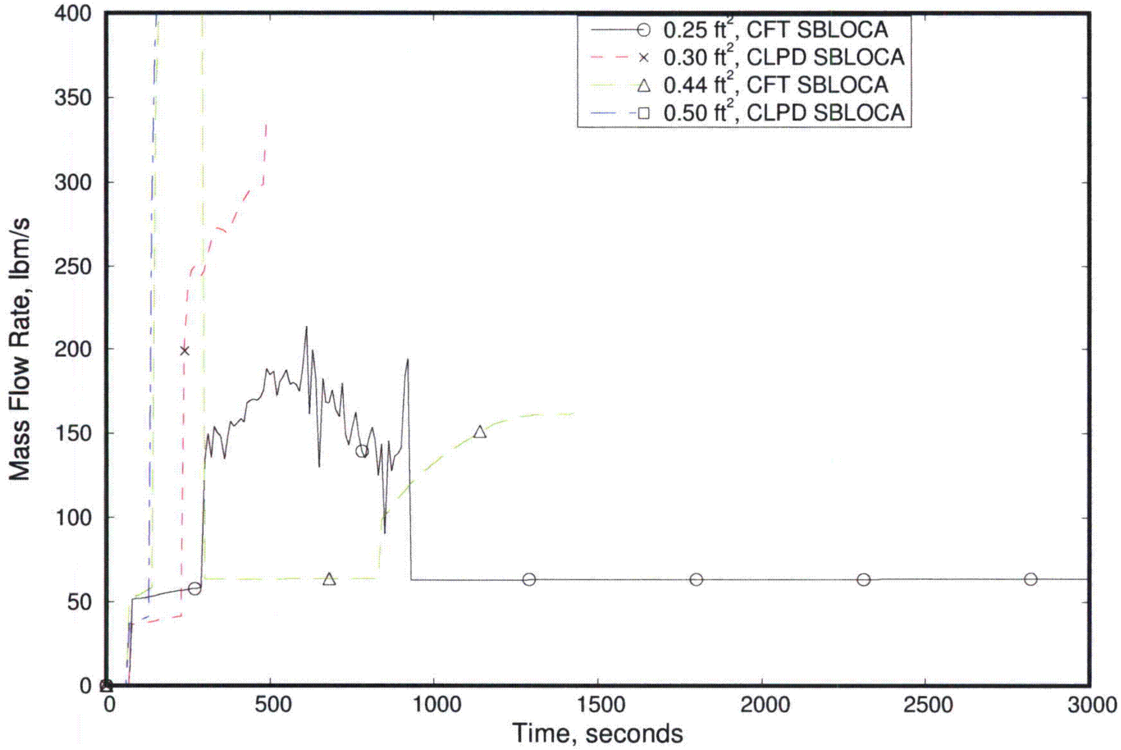


FIGURE 6–34: Select Category 5 CLPD Breaks (1–min RCP Trip), Full Power with FCS Comparison of RCS Liquid Fractions

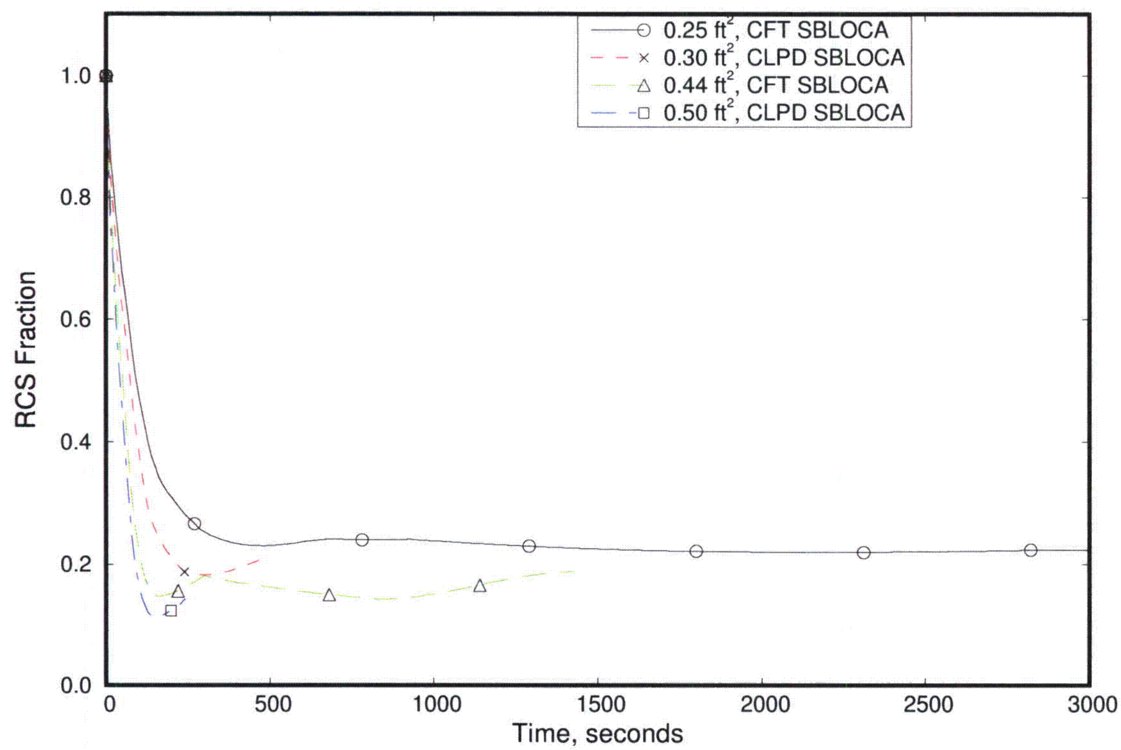


FIGURE 6-35: 0.13 ft^2 CLPD Break, Full Power with FCS System Pressures

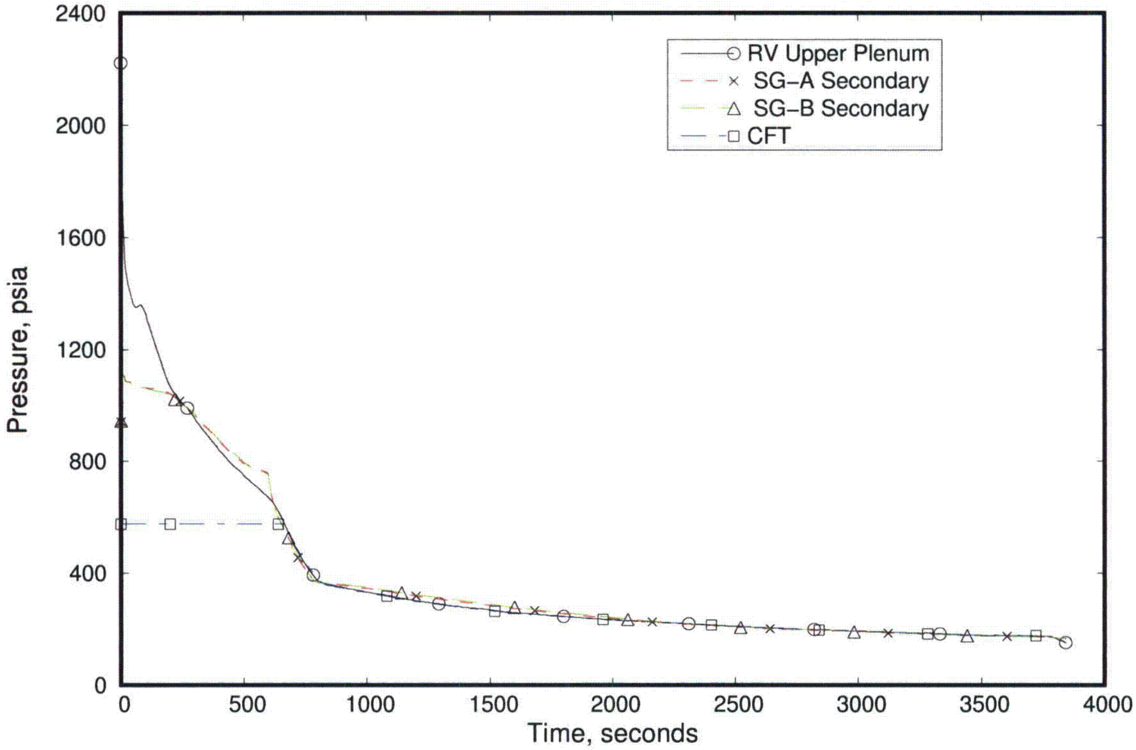


FIGURE 6-36: 0.13 ft^2 CLPD Break, Full Power with FCS Downcomer and Core Collapsed Liquid Levels

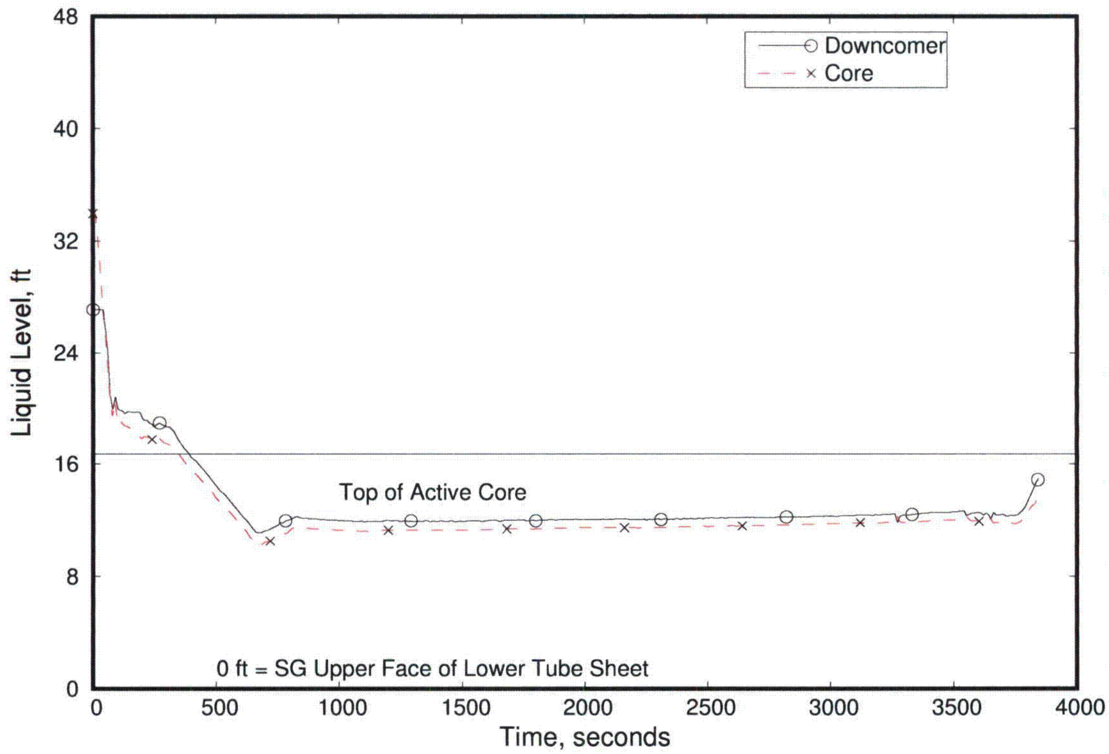


FIGURE 6–37: 0.13 ft^2 CLPD Break, Full Power with FCS Break and Core ECCS Mass Flow Rates

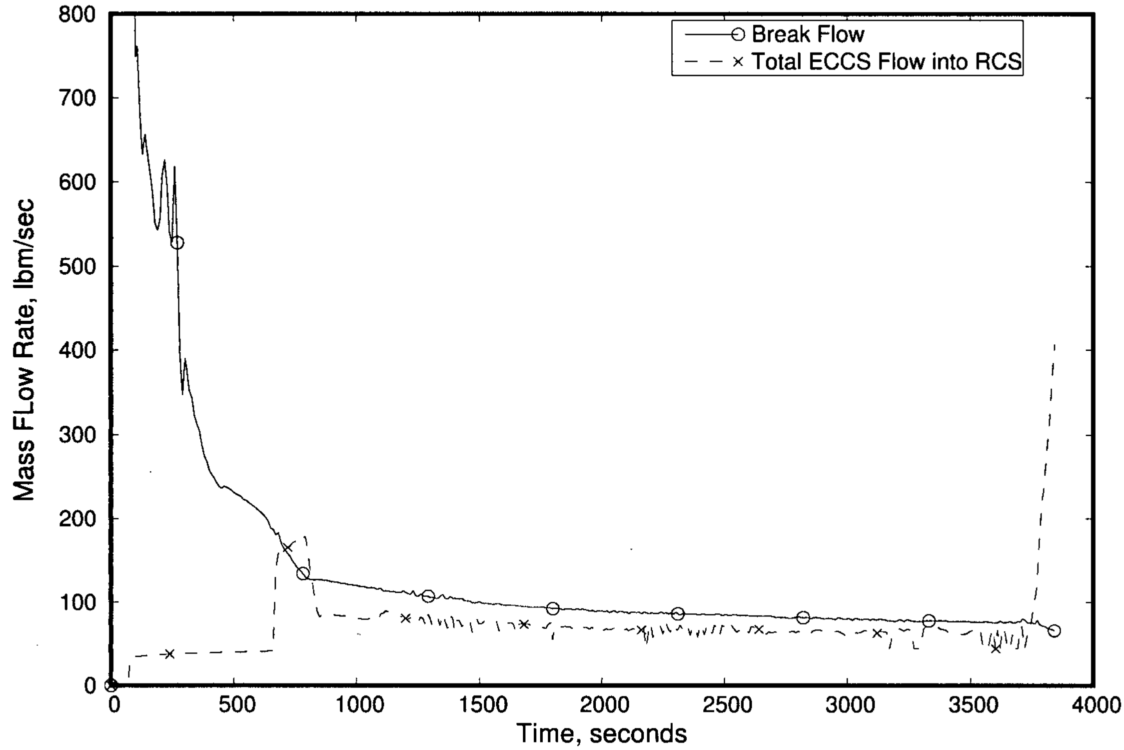


FIGURE 6–38: 0.13 ft^2 CLPD Break, Full Power with FCS Break Volume Void Fraction

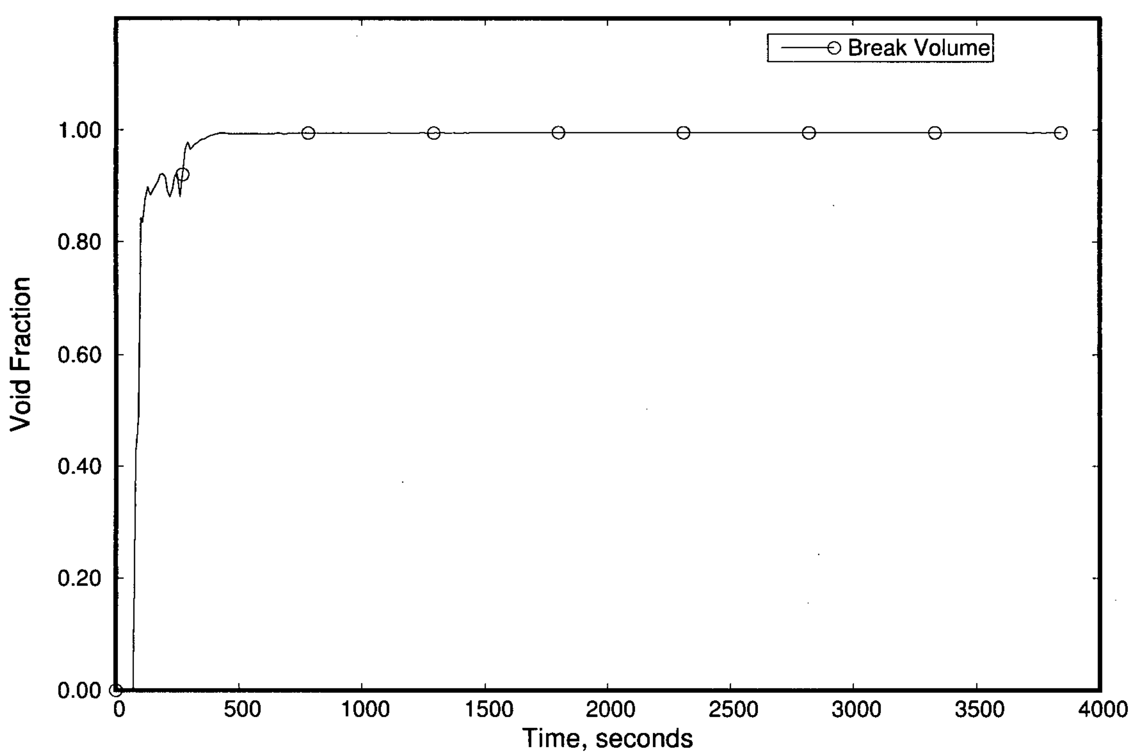


FIGURE 6-39: 0.13 ft² CLPD Break, Full Power with FCS SG-A Collapsed Liquid Levels

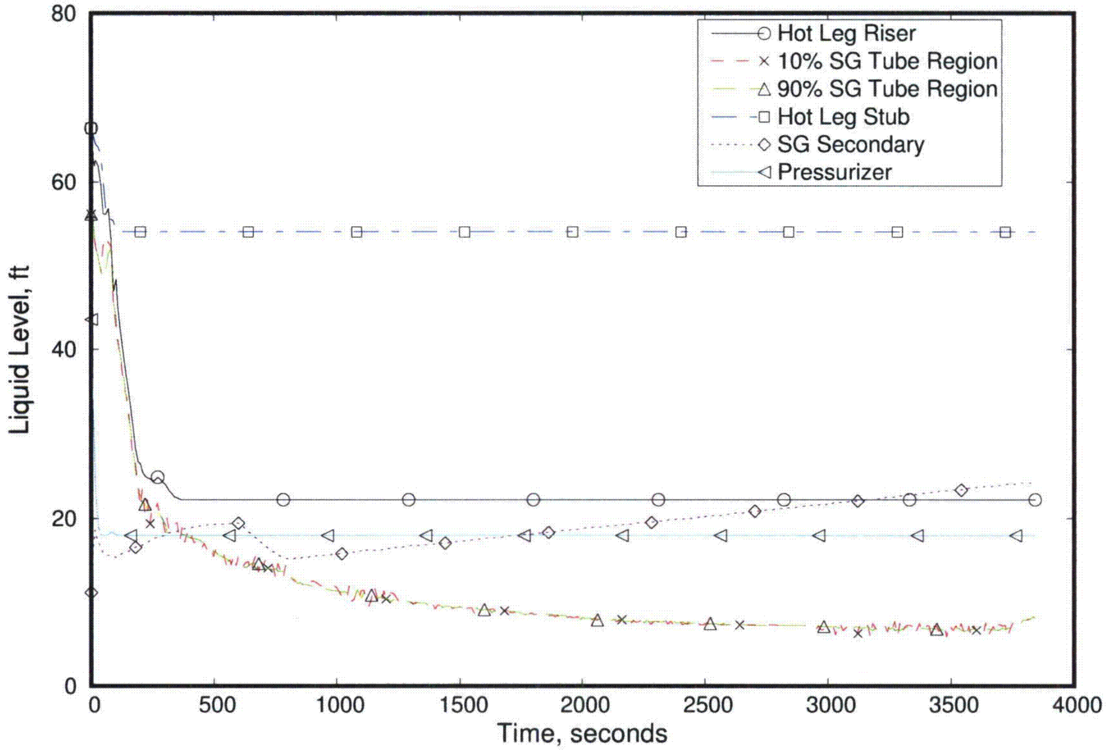


FIGURE 6-40: 0.13 ft² CLPD Break, Full Power with FCS SG-B Collapsed Liquid Levels

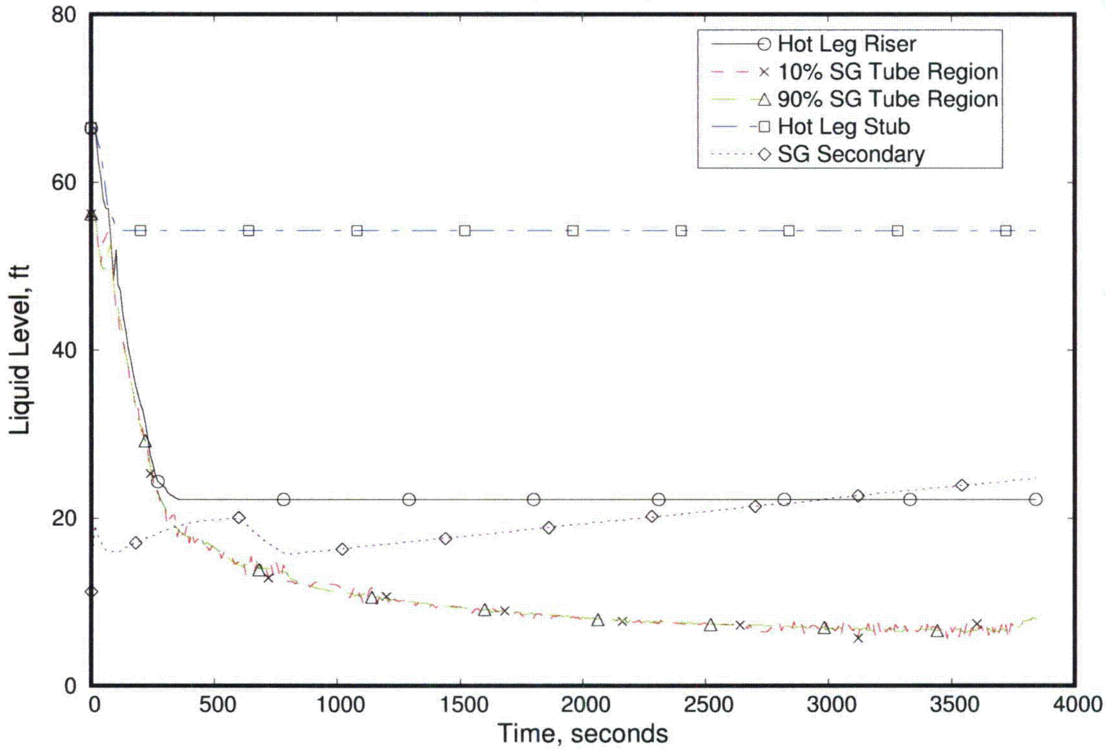


FIGURE 6-41: 0.13 ft² CLPD Break, Full Power with FCS CLPD Collapsed Liquid Levels

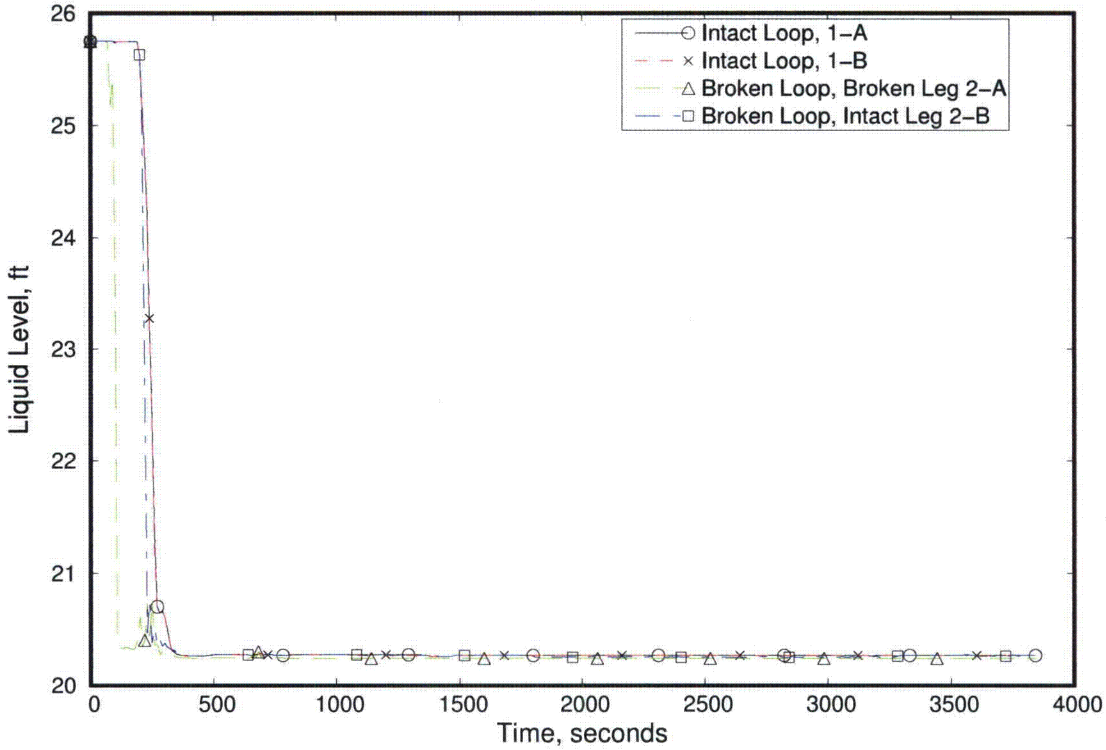


FIGURE 6-42: 0.13 ft² CLPD Break, Full Power with FCS CLPS Collapsed Liquid Levels

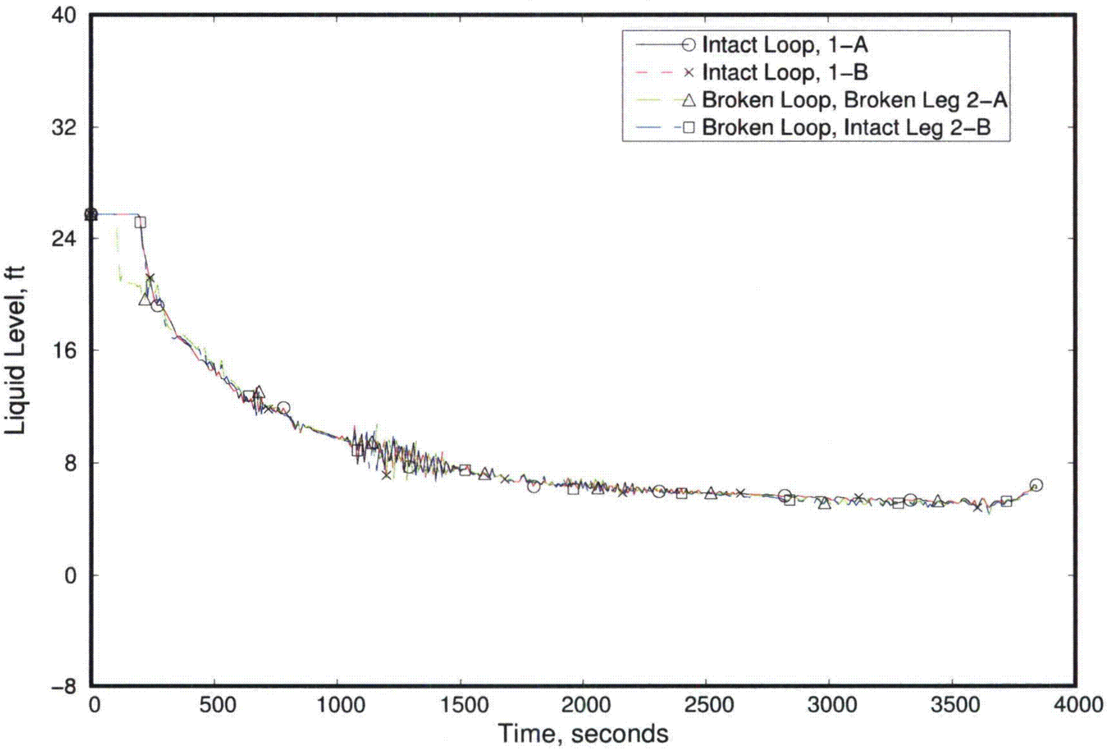


FIGURE 6–43: 0.13 ft^2 CLPD Break, Full Power with FCS RVVV Mass Flow Rate

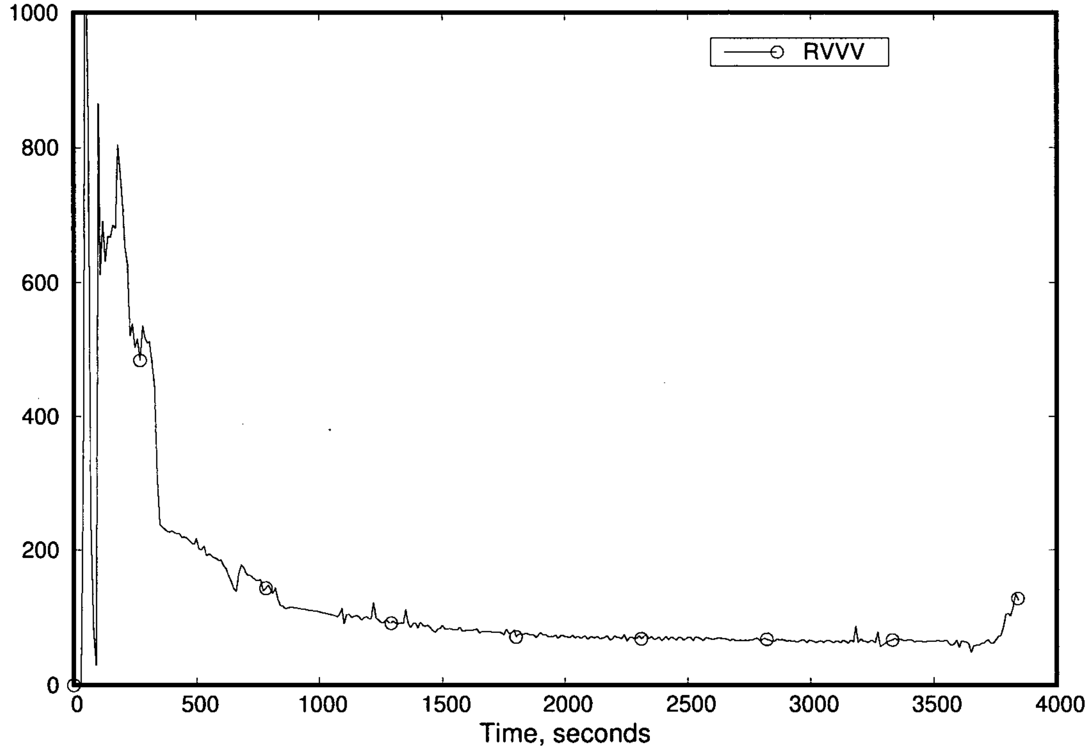


FIGURE 6–44: 0.13 ft^2 CLPD Break, Full Power with FCS Core Mixture Levels

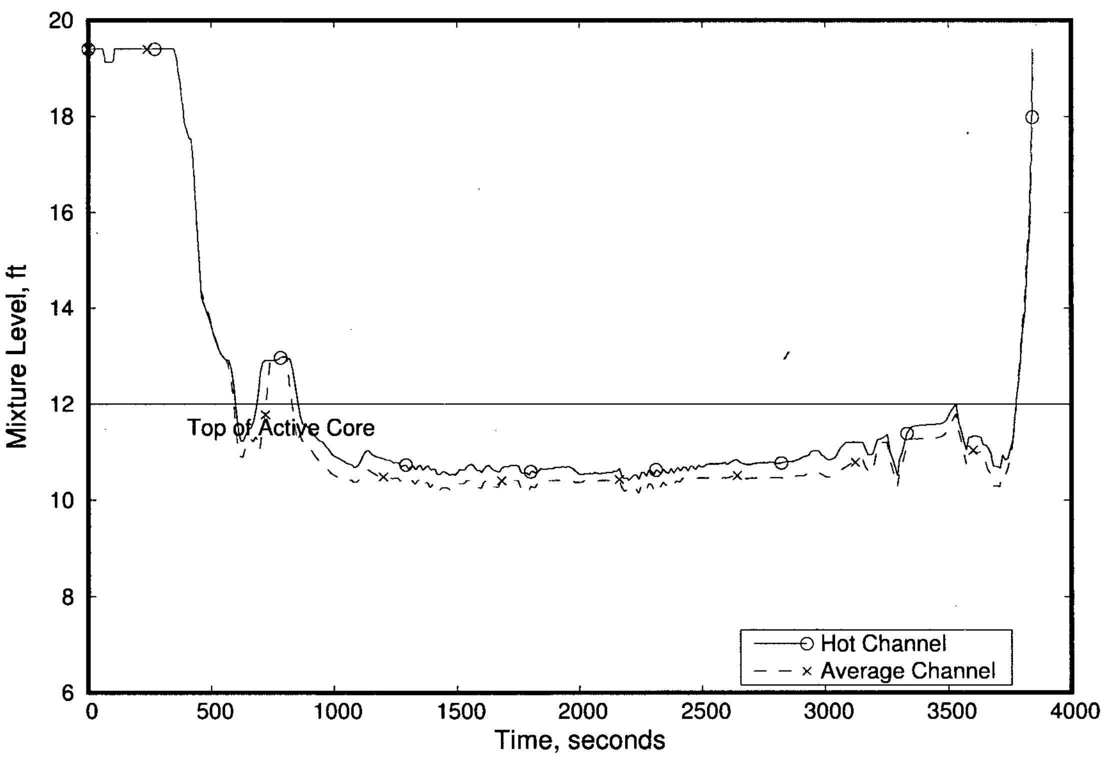


FIGURE 6-45: 0.13 ft² CLPD Break, Full Power with FCS Hot Pin Clad Temperatures

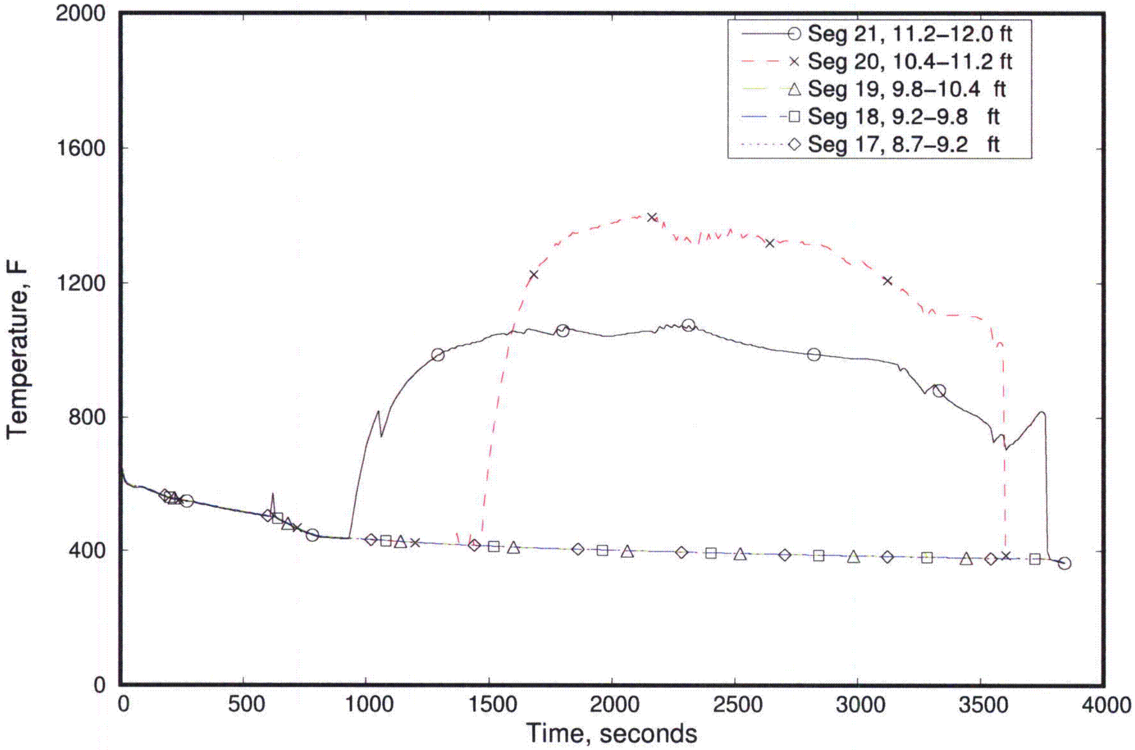


FIGURE 6-46: 0.13 ft² CLPD Break, Full Power with FCS Hot Channel Steam Temperatures

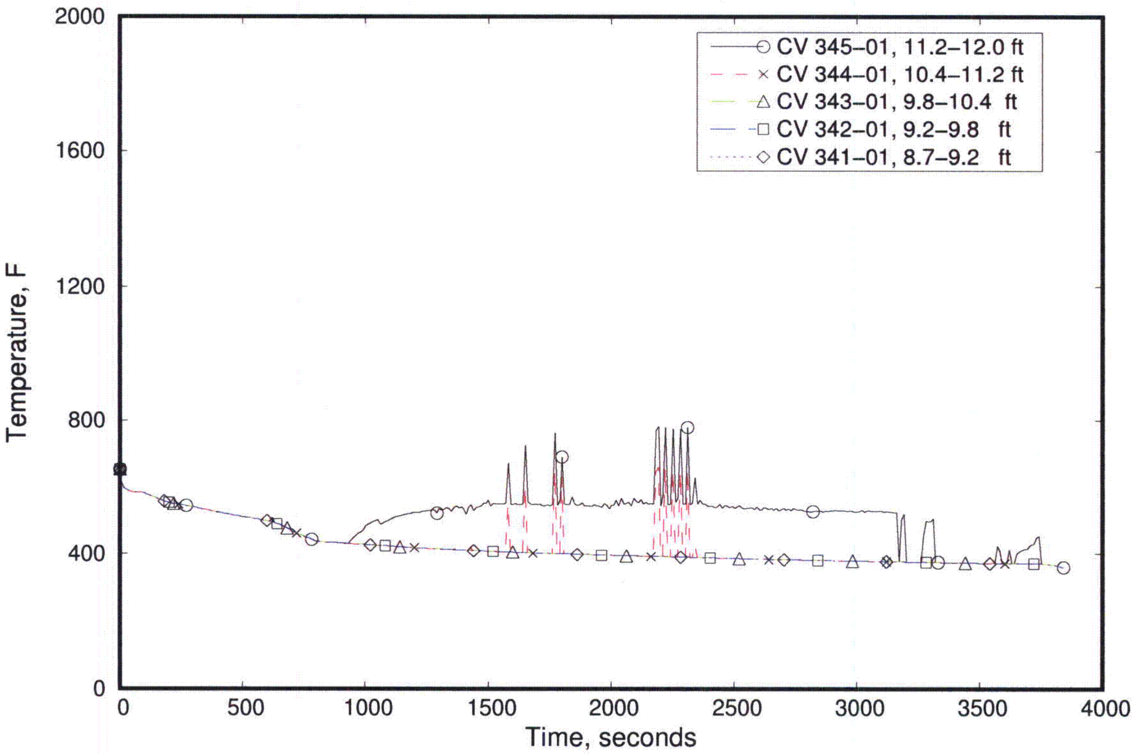


FIGURE 6–47: 0.13 ft^2 CLPD Break, Full Power with FCS Average Channel Clad Temperatures

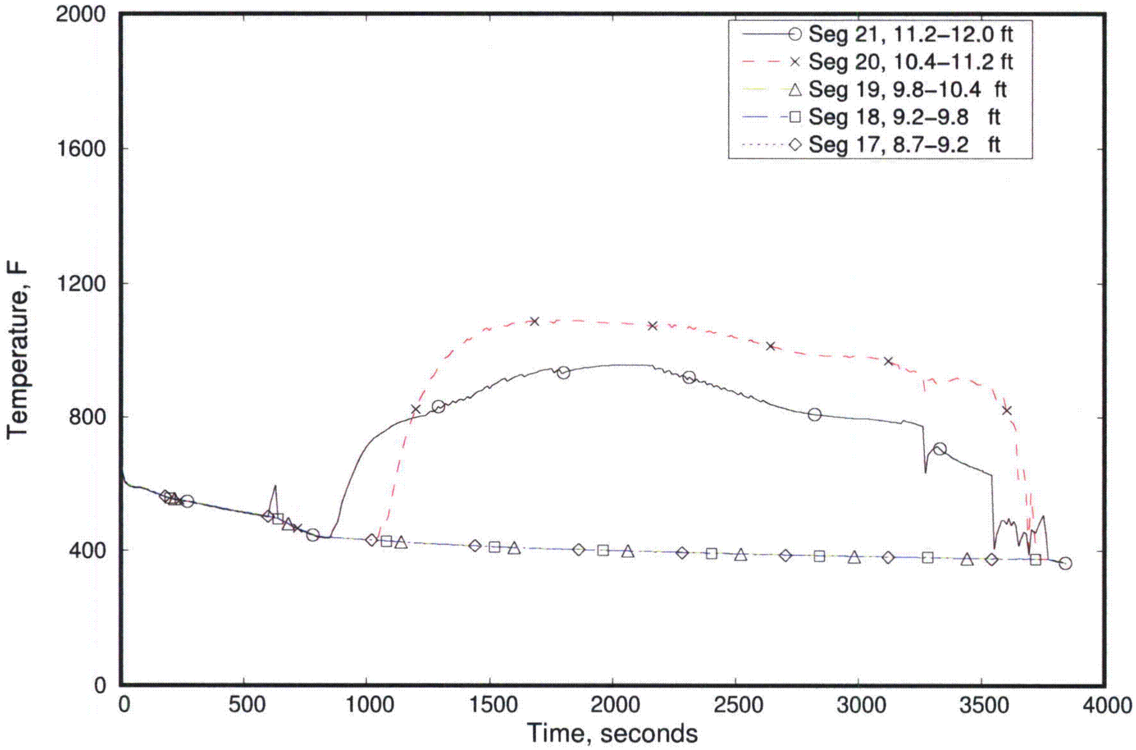


FIGURE 6–48: 0.13 ft^2 CLPD Break, Full Power with FCS Average Channel Steam Temperatures

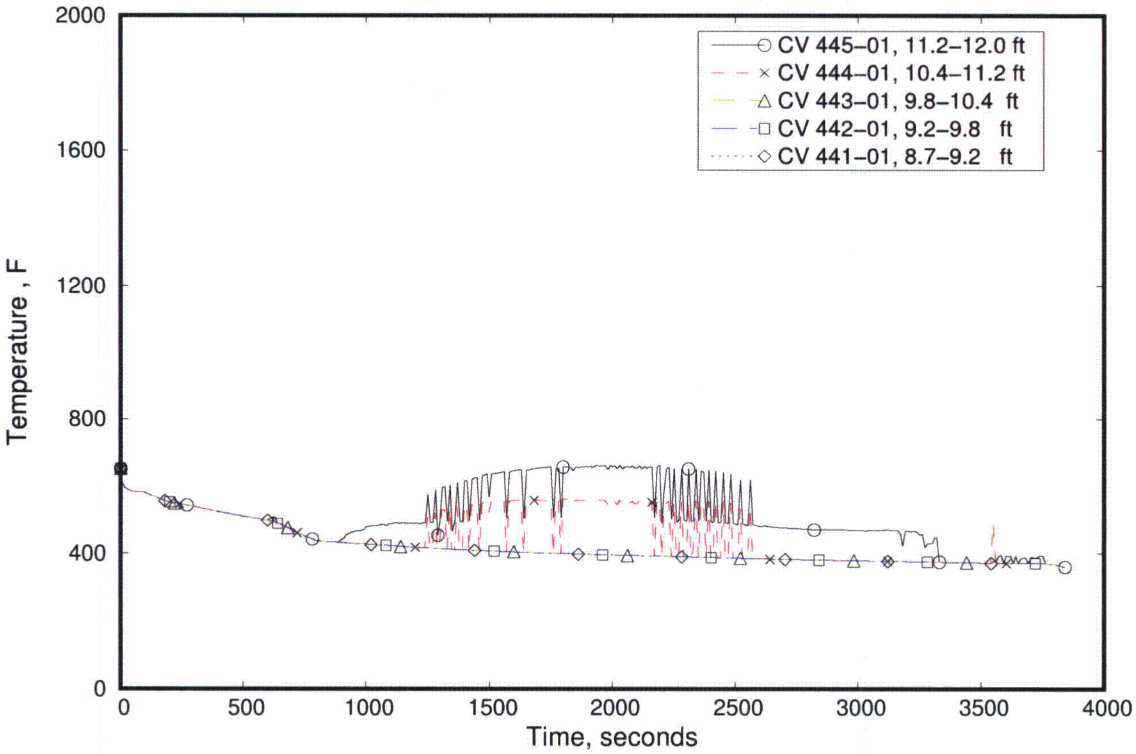


FIGURE 6-49: Category 5 CFT Line Breaks (LOOP), Full Power with FCS Comparison of Downcomer Pressure and Containment Pressure

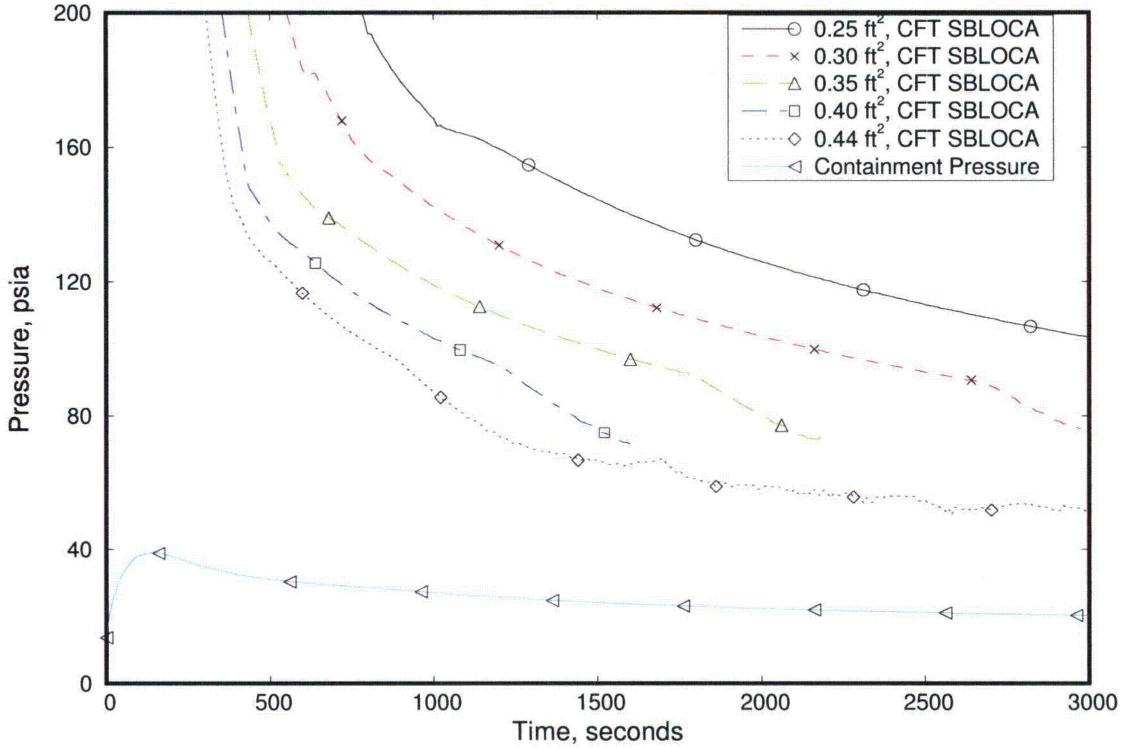


FIGURE 6-50: Category 5 CFT Line Breaks (1 min RCP), Full Power with FCS Comparison of Downcomer Pressure and Containment Pressure

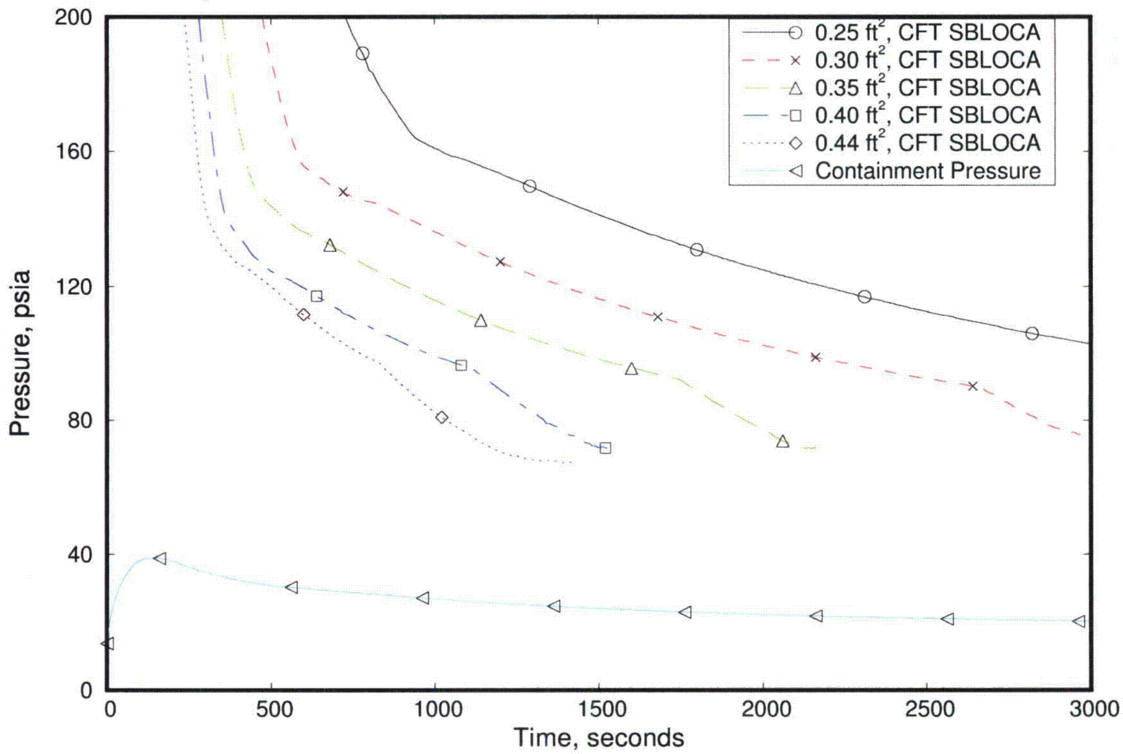


FIGURE 6-51: Select Category 2 Breaks (LOOP), Reduced Power without FCS Comparison of Primary Pressures

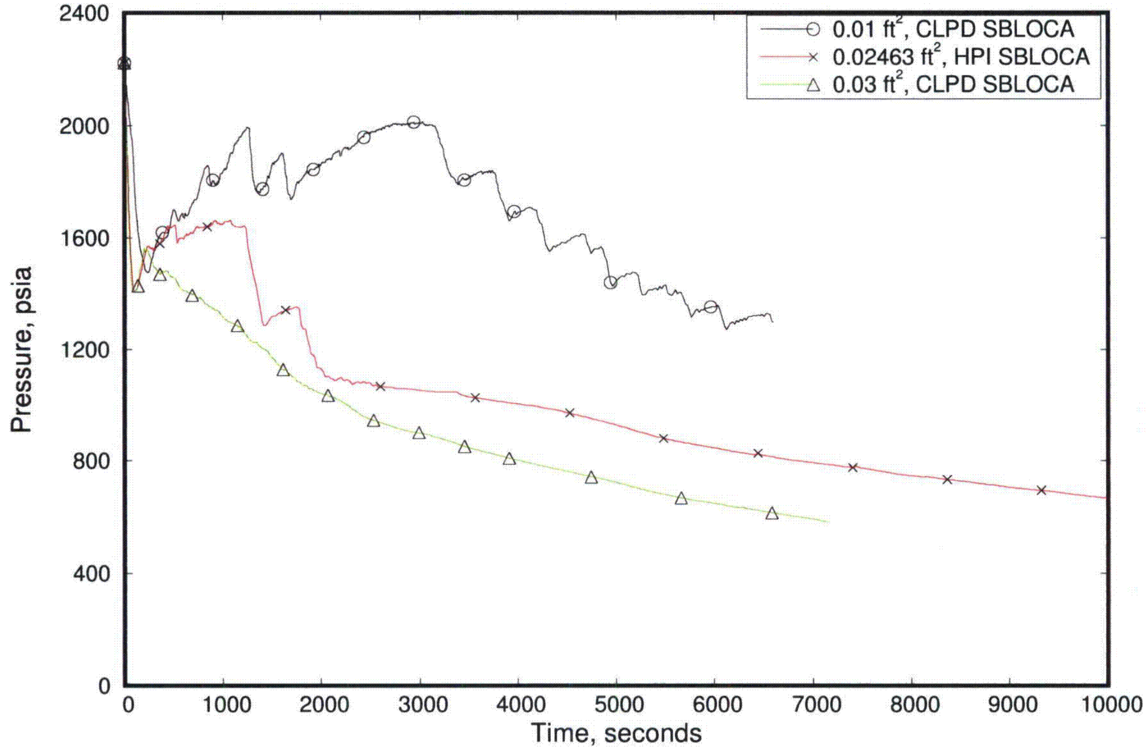


FIGURE 6-52: Select Category 2 Breaks (LOOP), Reduced Power without FCS Comparison of Peak Cladding Temperatures

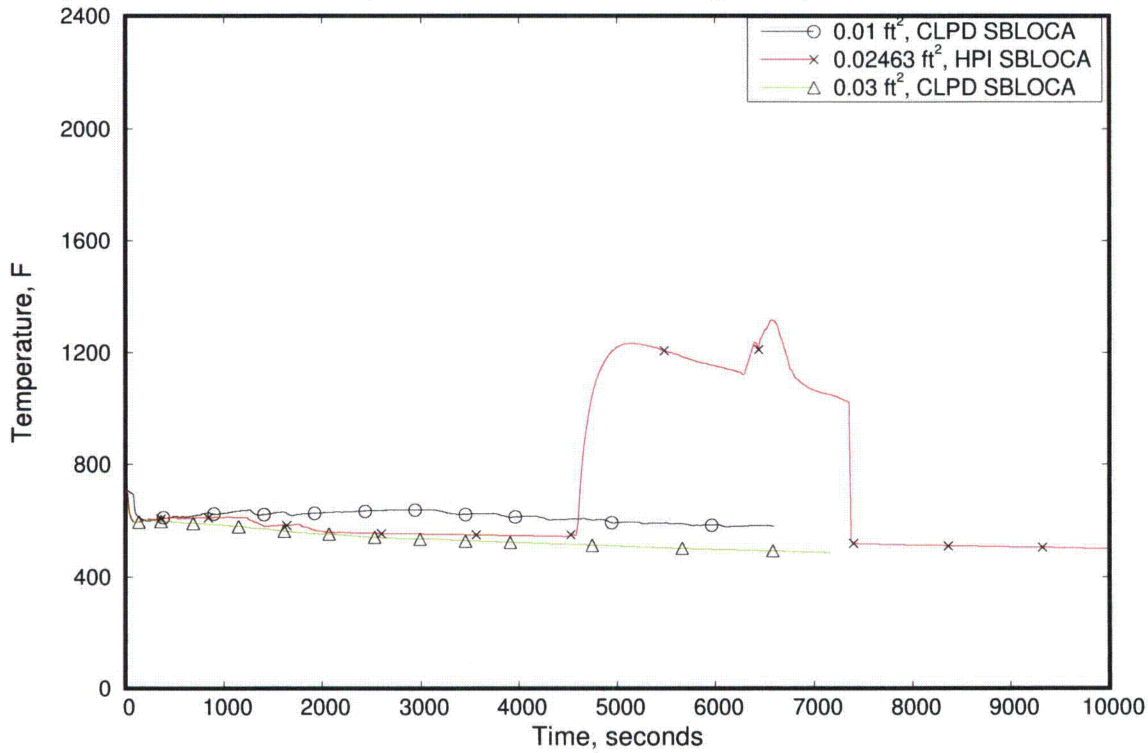


FIGURE 6–53: Select Category 2 Breaks (LOOP), Reduced Power without FCS Comparison of HC Mixture Levels

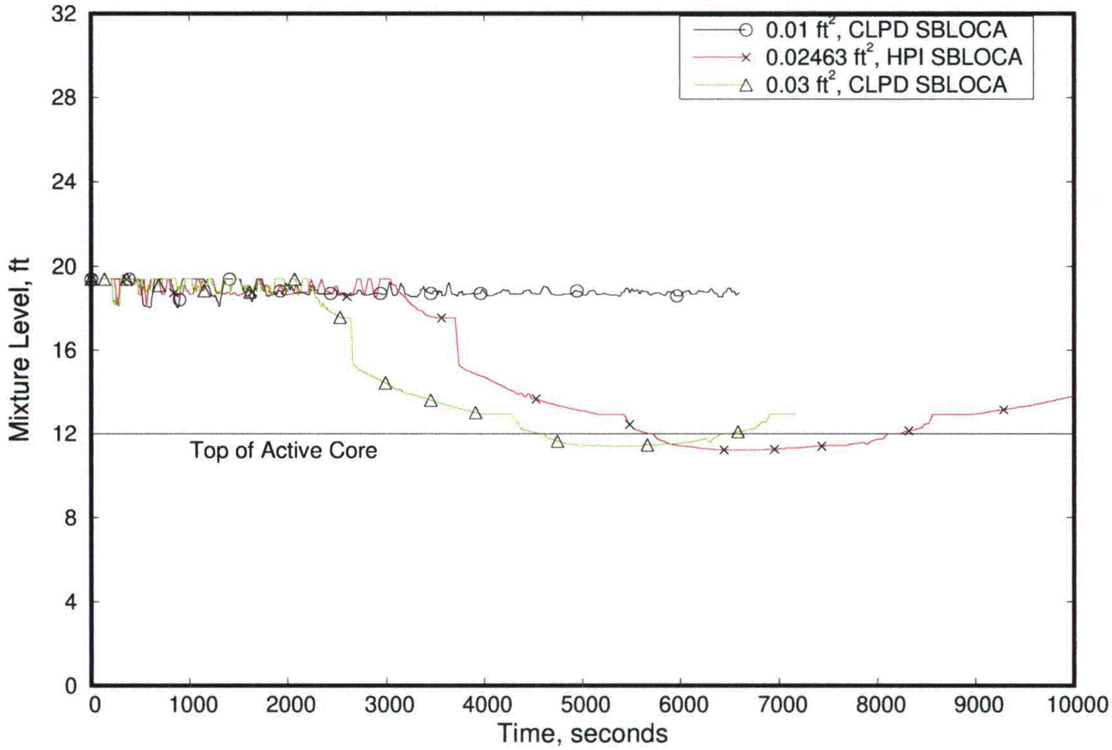


FIGURE 6–54: Select Category 2 Breaks (LOOP), Reduced Power without FCS Comparison of Break and ECCS Mass Flow Rates

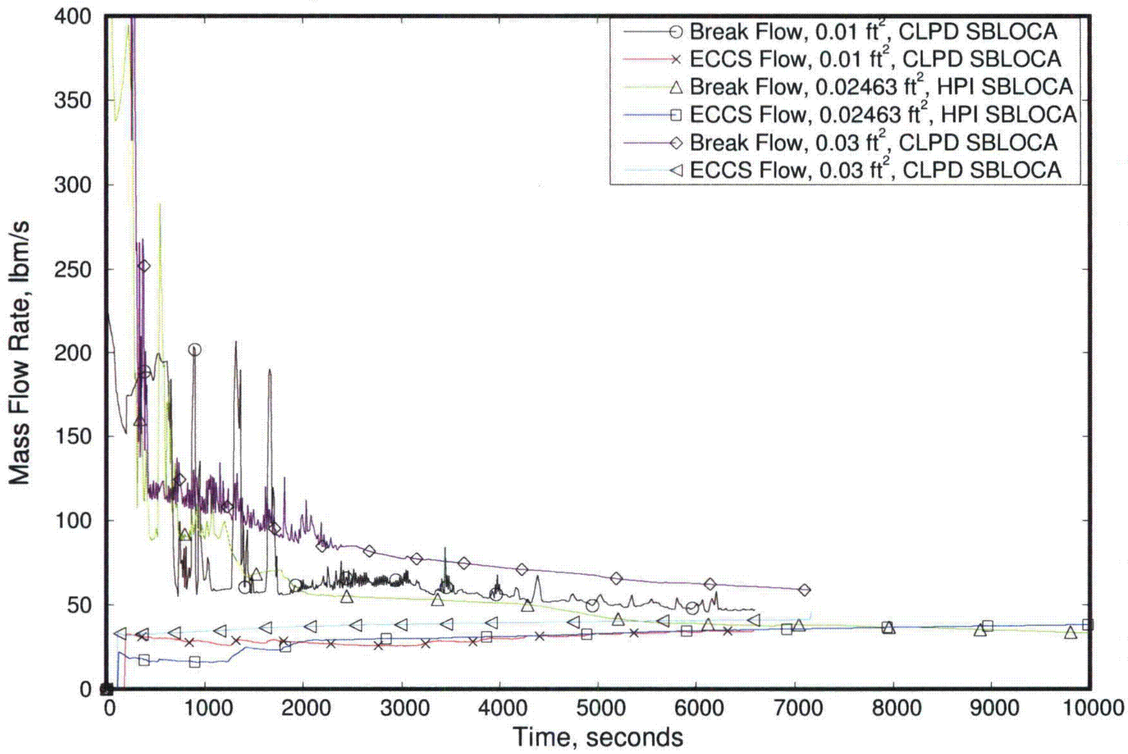


FIGURE 6–55: Select Category 3 Breaks (LOOP), Reduced Power without FCS Comparison of Primary Pressures

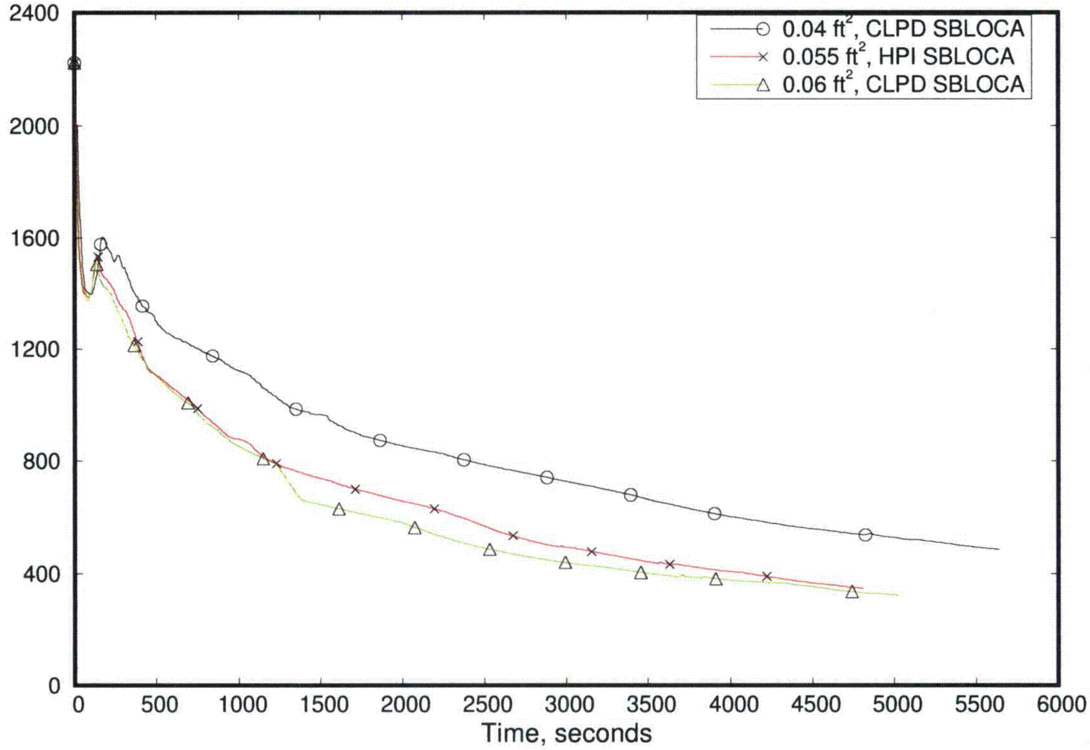


FIGURE 6–56: Select Category 3 Breaks (LOOP), Reduced Power without FCS Comparison of Peak Cladding Temperatures

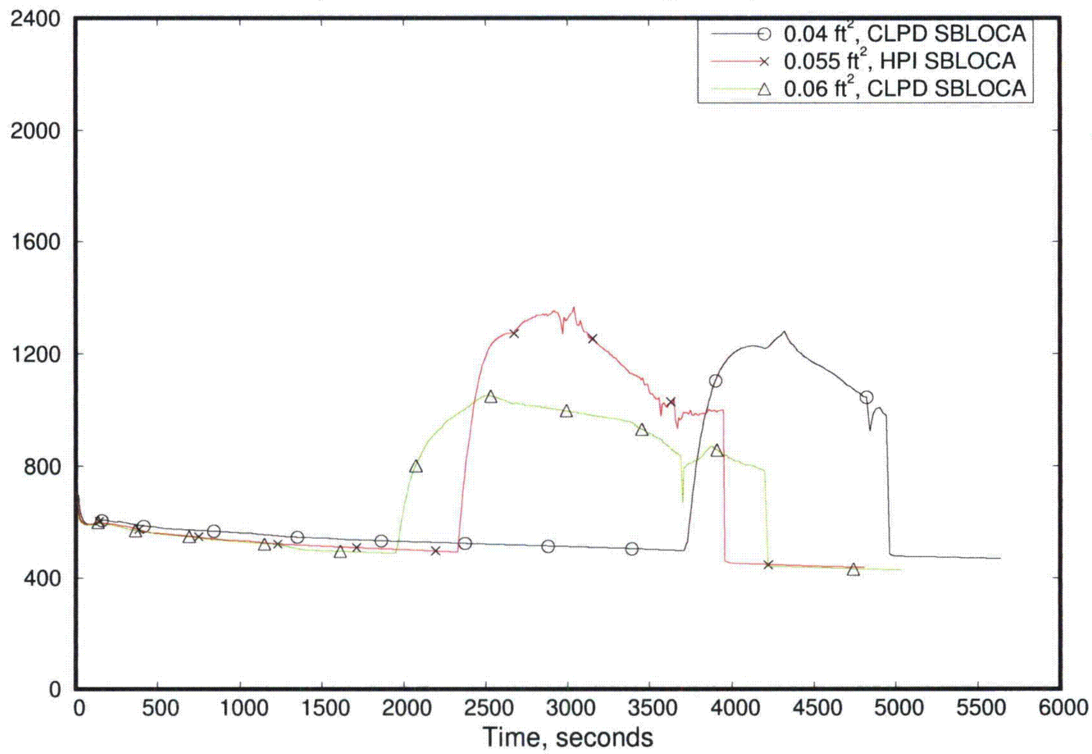


FIGURE 6-57: Select Category 3 Breaks (LOOP), Reduced Power without FCS Comparison of HC Mixture Levels

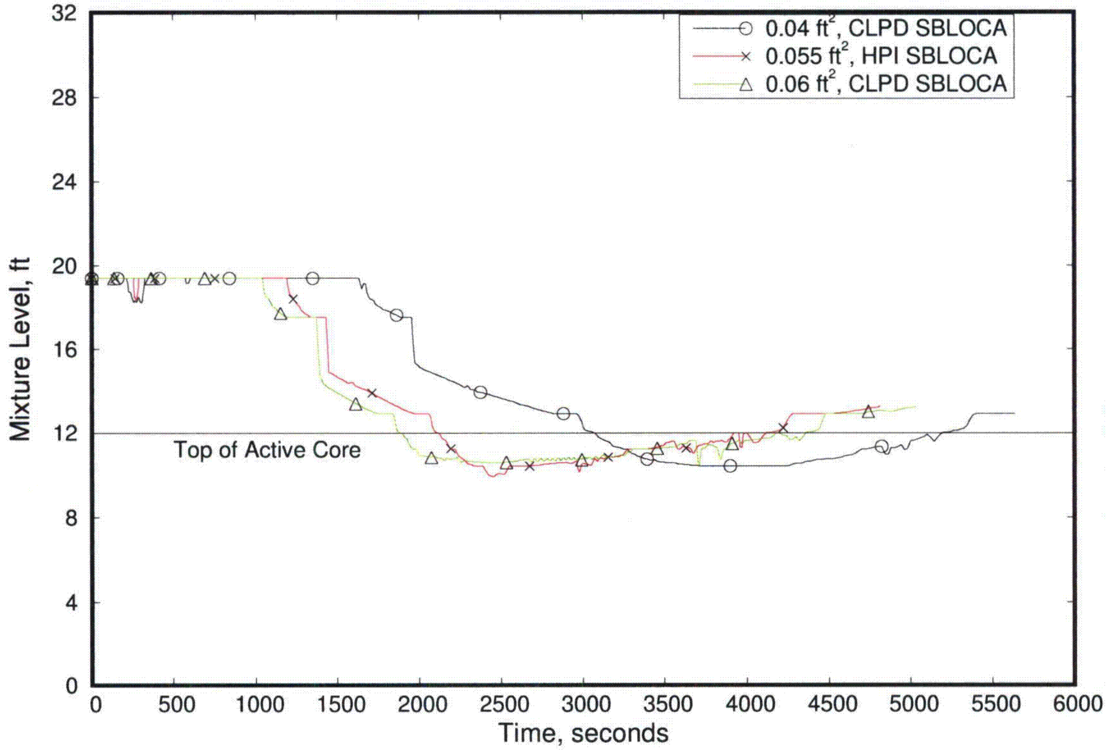


FIGURE 6-58: Select Category 3 Breaks (LOOP), Reduced Power without FCS Comparison of Break and ECCS Mass Flow Rates

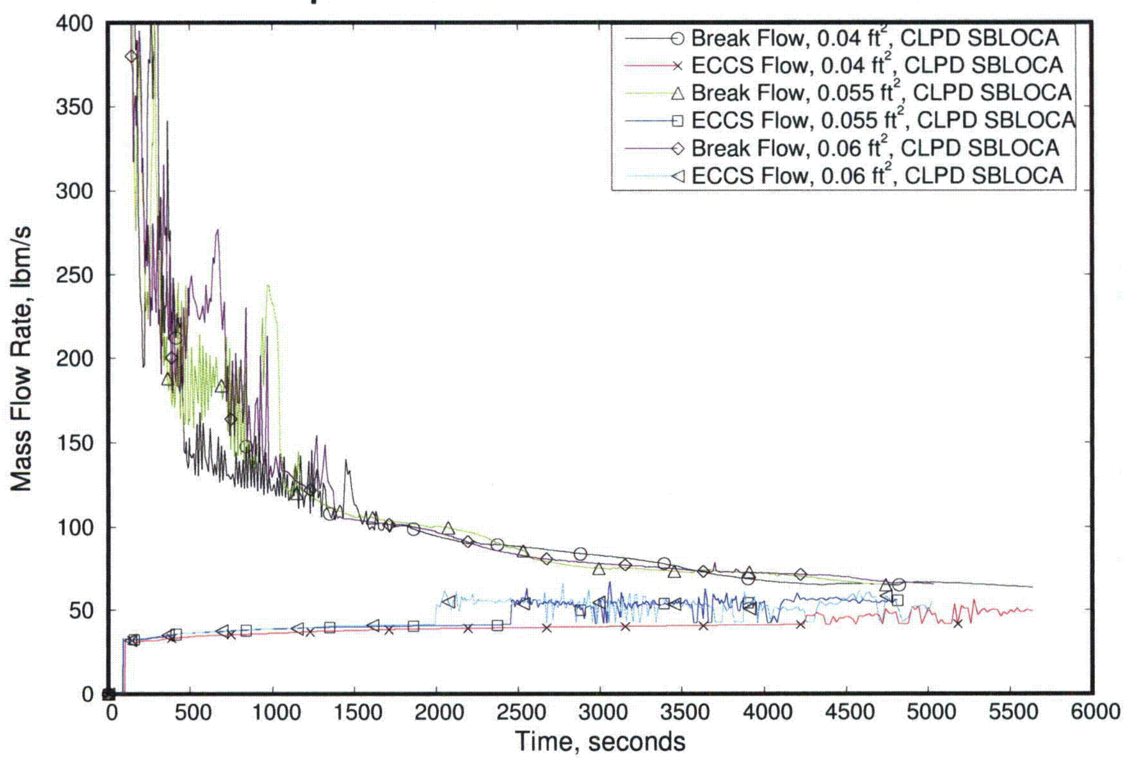


FIGURE 6 59: Select Category 4 Breaks (LOOP), Reduced Power without FCS Comparison of Primary Pressures

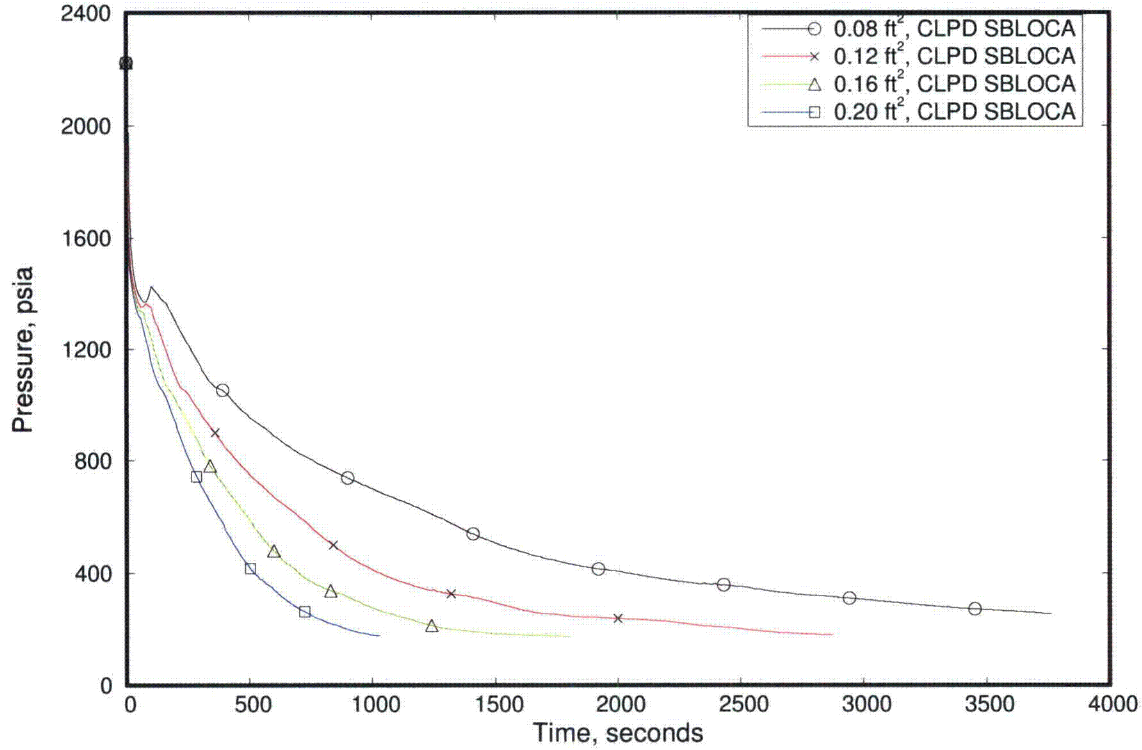


FIGURE 6 60: Select Category 4 Breaks (LOOP), Reduced Power without FCS Comparison of Peak Cladding Temperatures

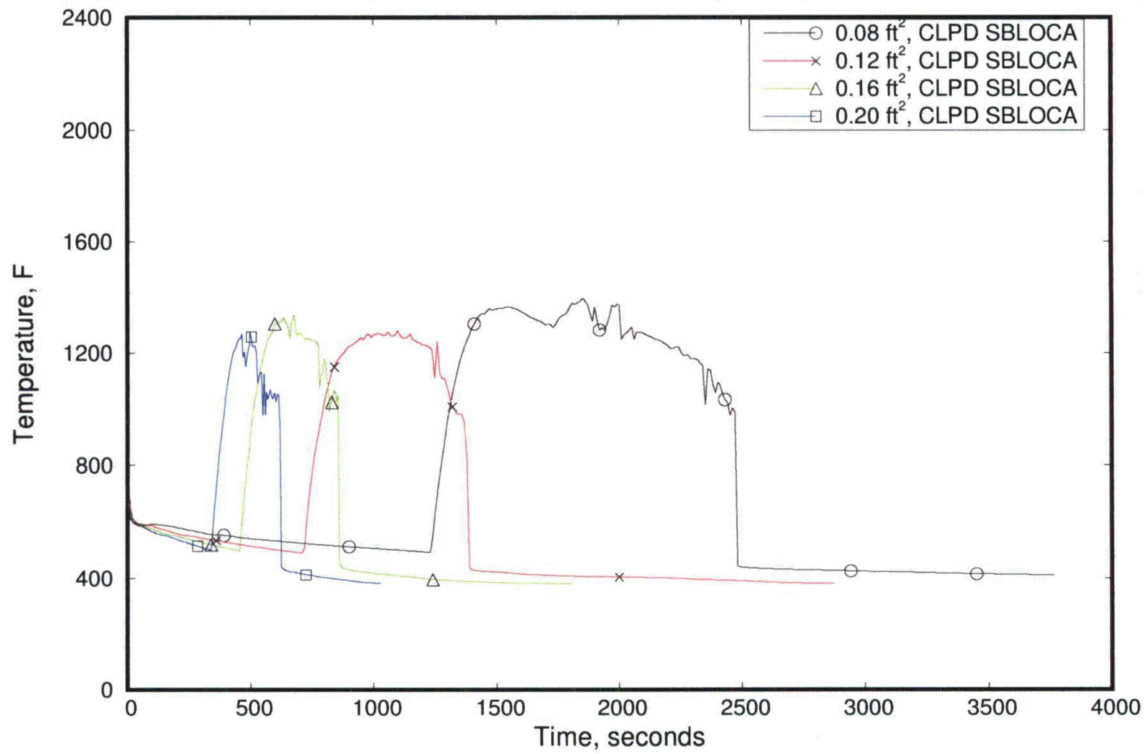


FIGURE 6 61: Select Category 4 Breaks (LOOP), Reduced Power without FCS Comparison of HC Mixture Levels

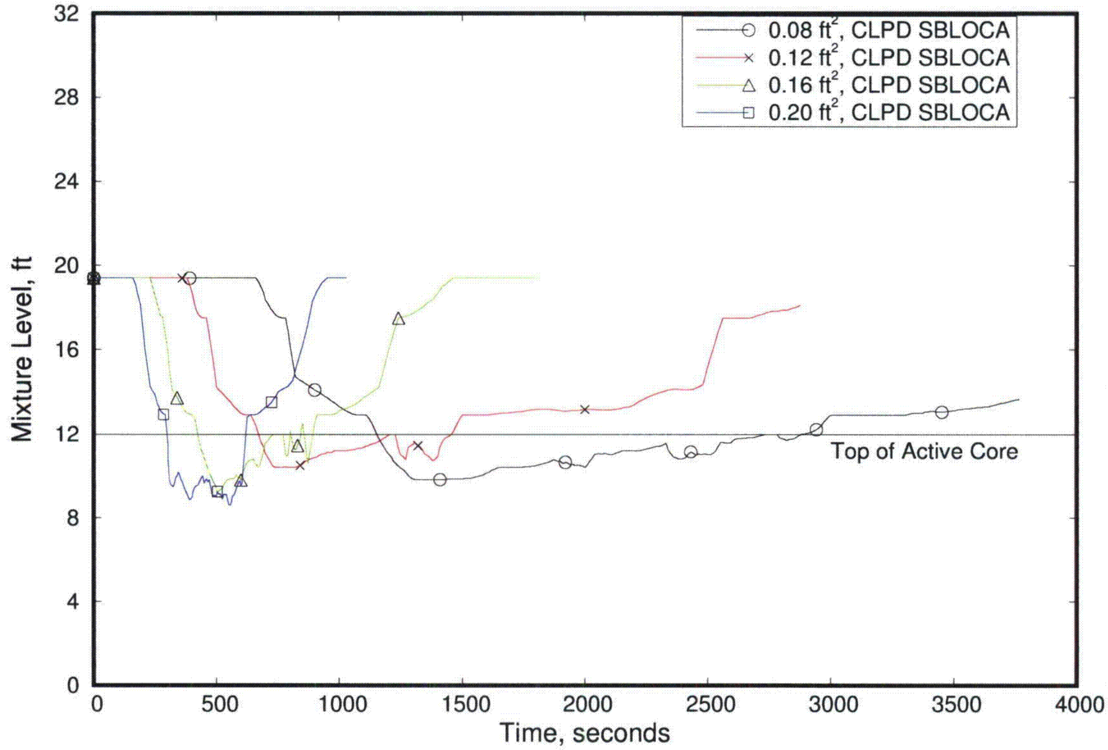


FIGURE 6 62: Select Category 4 Breaks (LOOP), Reduced Power without FCS Comparison of Break and ECCS Mass Flow Rates

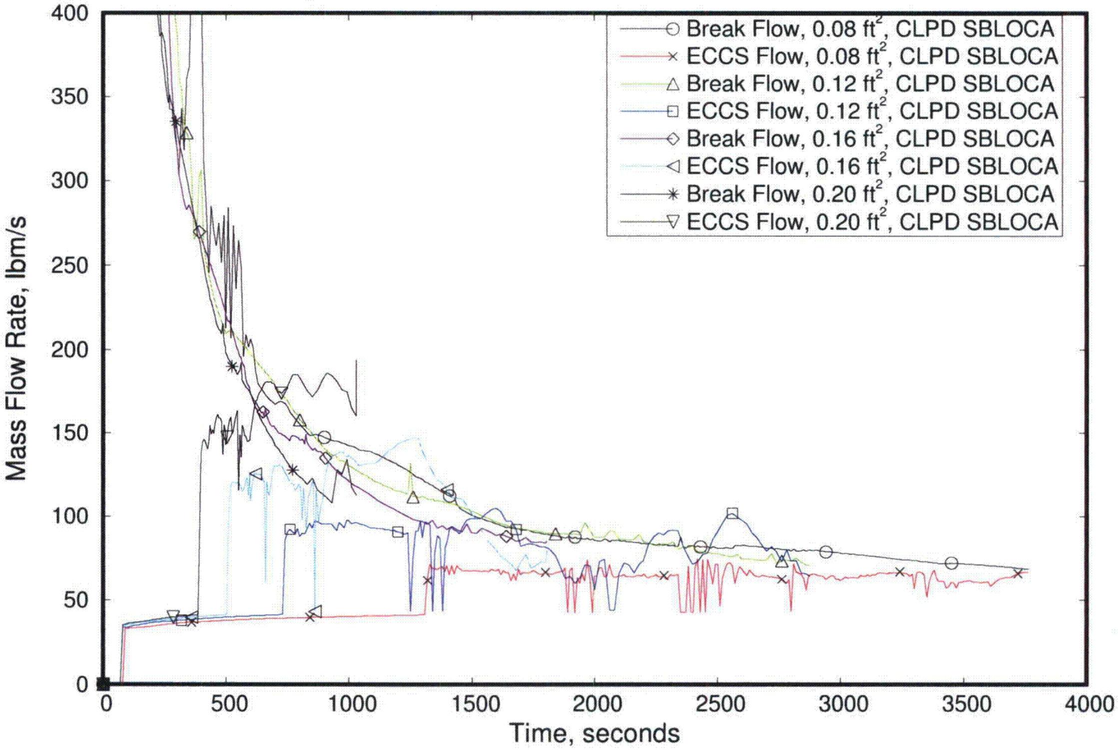


FIGURE 6 63: Select Category 5 Breaks (LOOP), Reduced Power without FCS Comparison of Primary Pressures

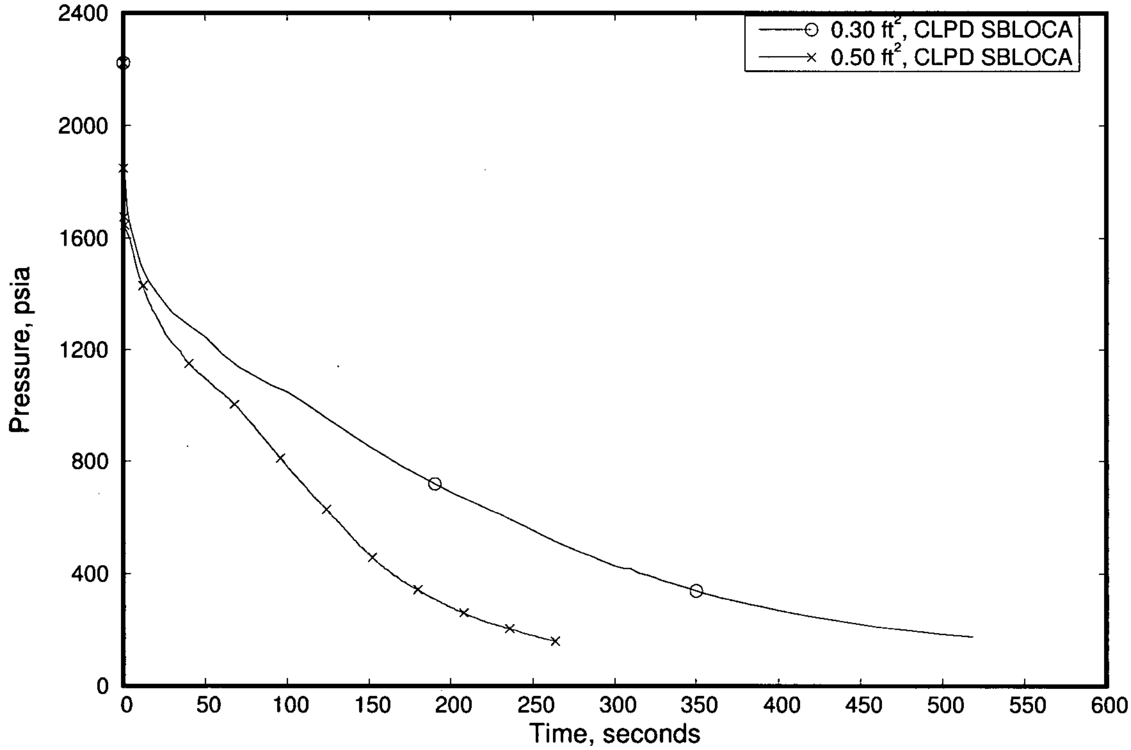


FIGURE 6 64: Select Category 5 Breaks (LOOP), Reduced Power without FCS Comparison of Peak Cladding Temperatures

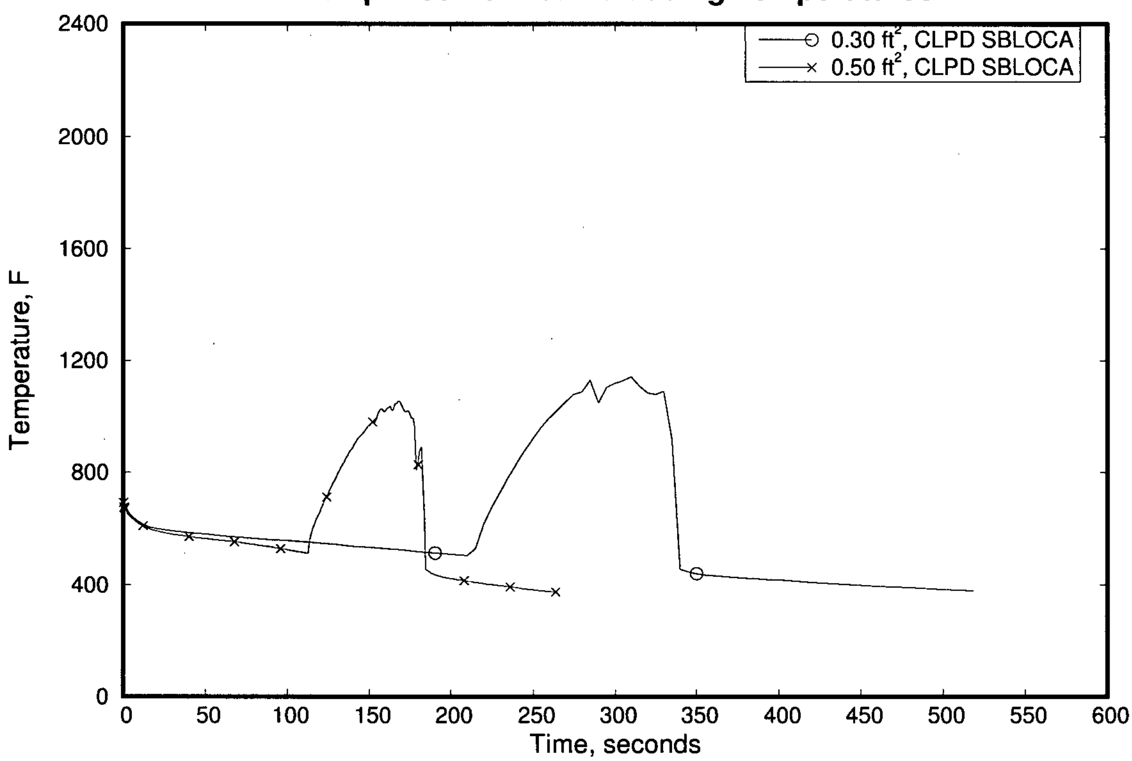


FIGURE 6-65: Select Category 5 Breaks (LOOP), Reduced Power without FCS Comparison of HC Mixture Levels

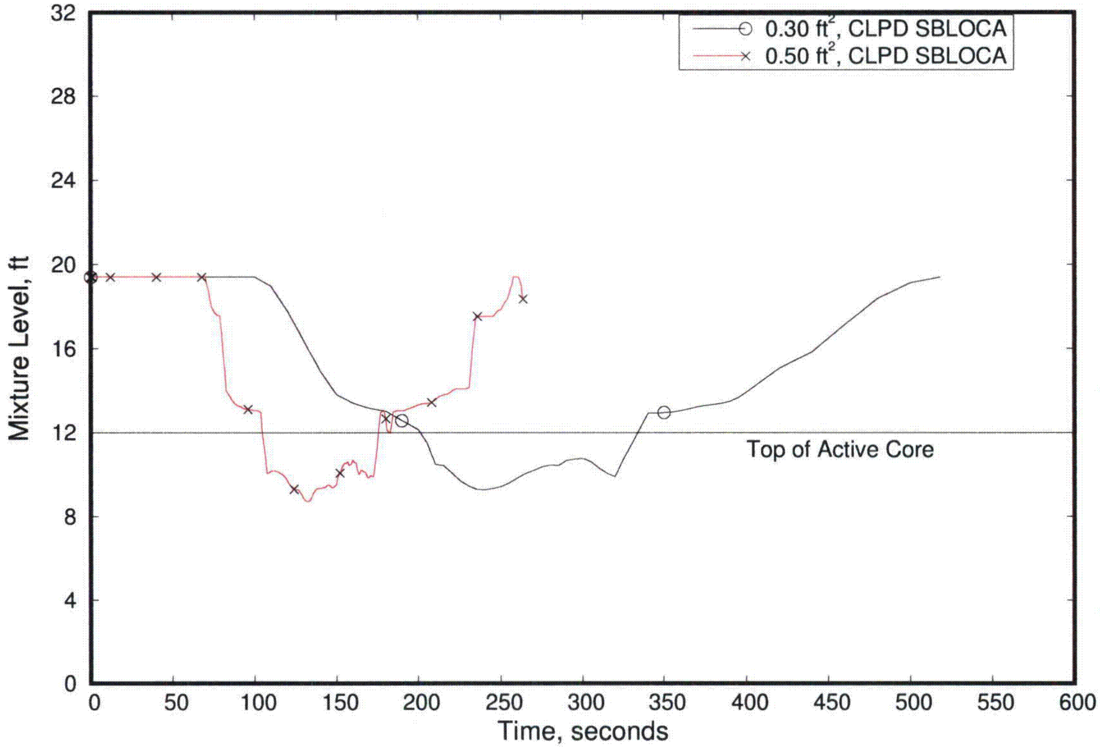


FIGURE 6-66: Select Category 5 Breaks (LOOP), Reduced Power without FCS Comparison of Break and ECCS Mass Flow Rates

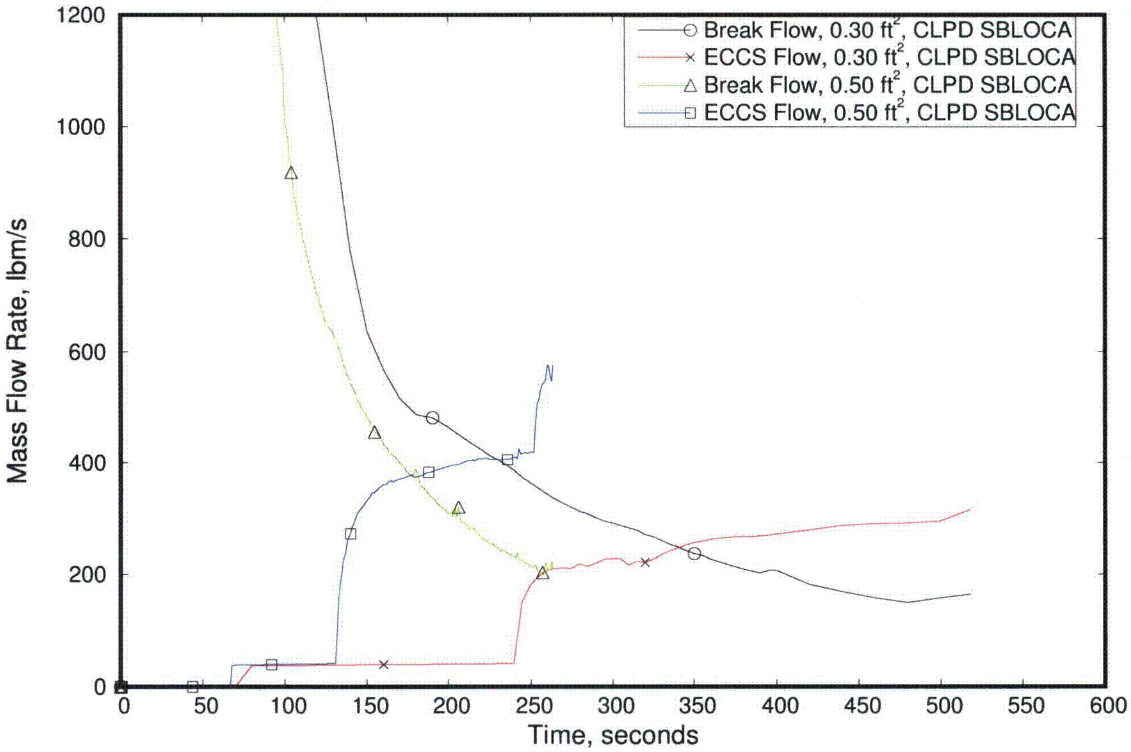


FIGURE 6-67: 0.08 ft^2 CLPD Break, Reduced Power without FCS System Pressures

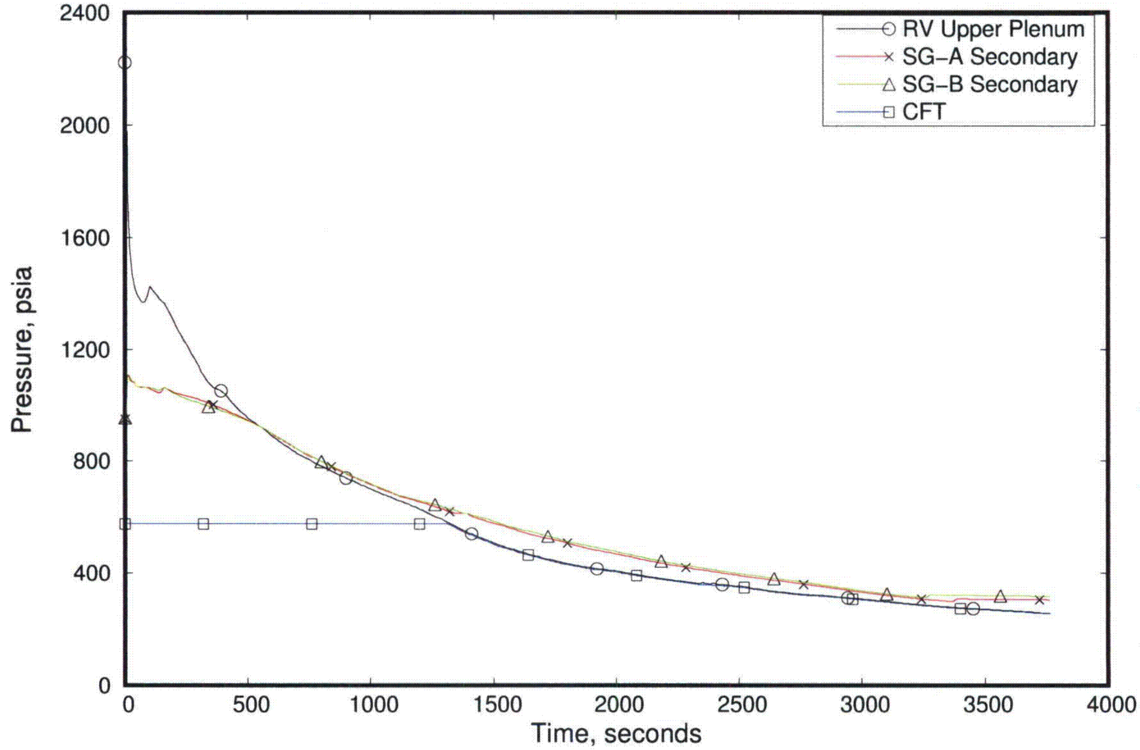


FIGURE 6-68: 0.08 ft^2 CLPD Break, Reduced Power without FCS Downcomer and Core Collapsed Liquid Levels

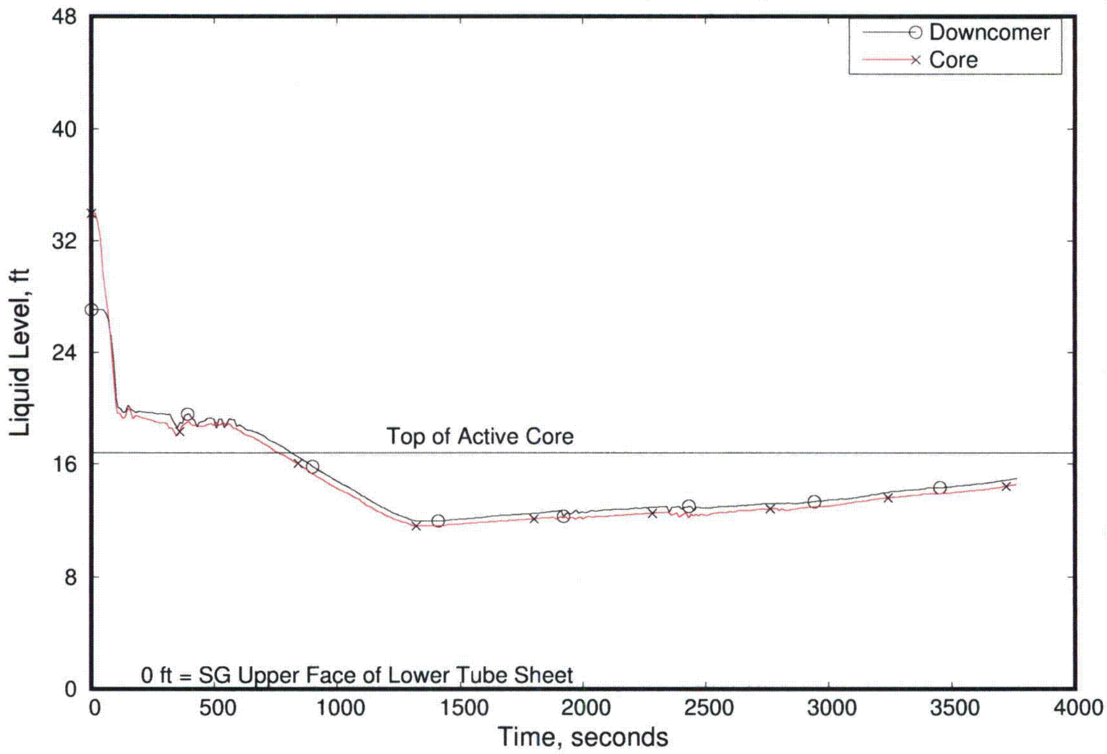


FIGURE 6-69: 0.08 ft^2 CLPD Break, Reduced Power without FCS
Break and Core ECCS Mass Flow Rates

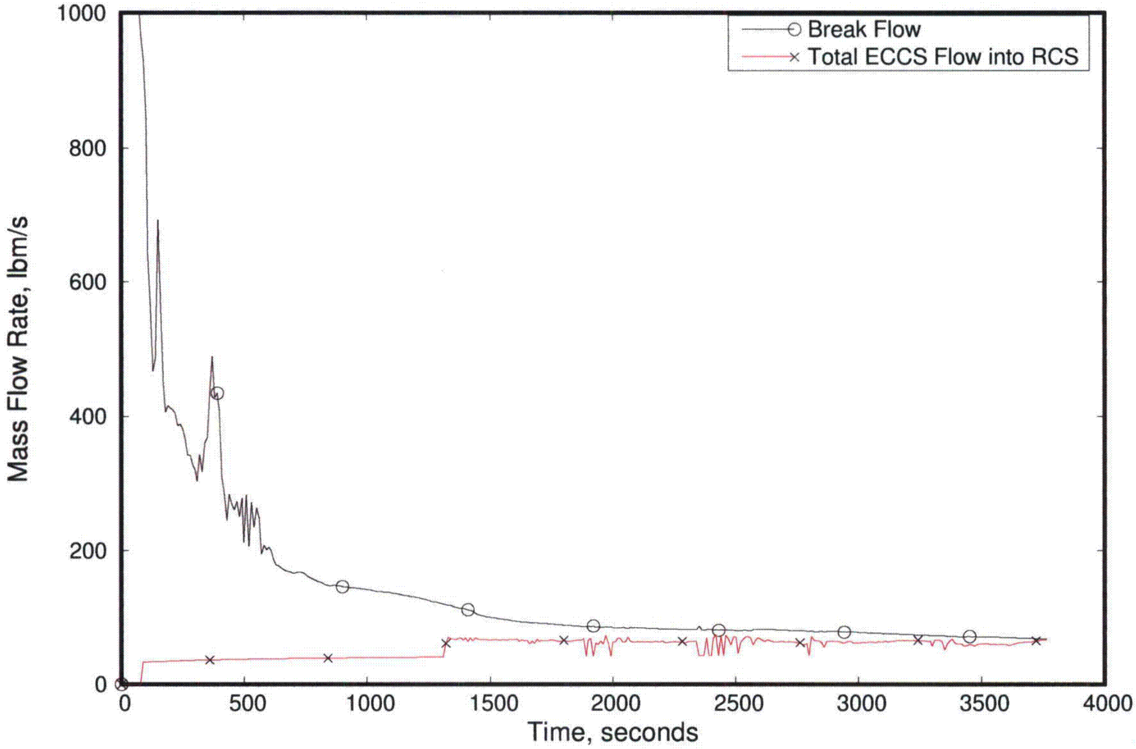


FIGURE 6-70: 0.08 ft^2 CLPD Break, Reduced Power without FCS
SG-A Collapsed Liquid Levels

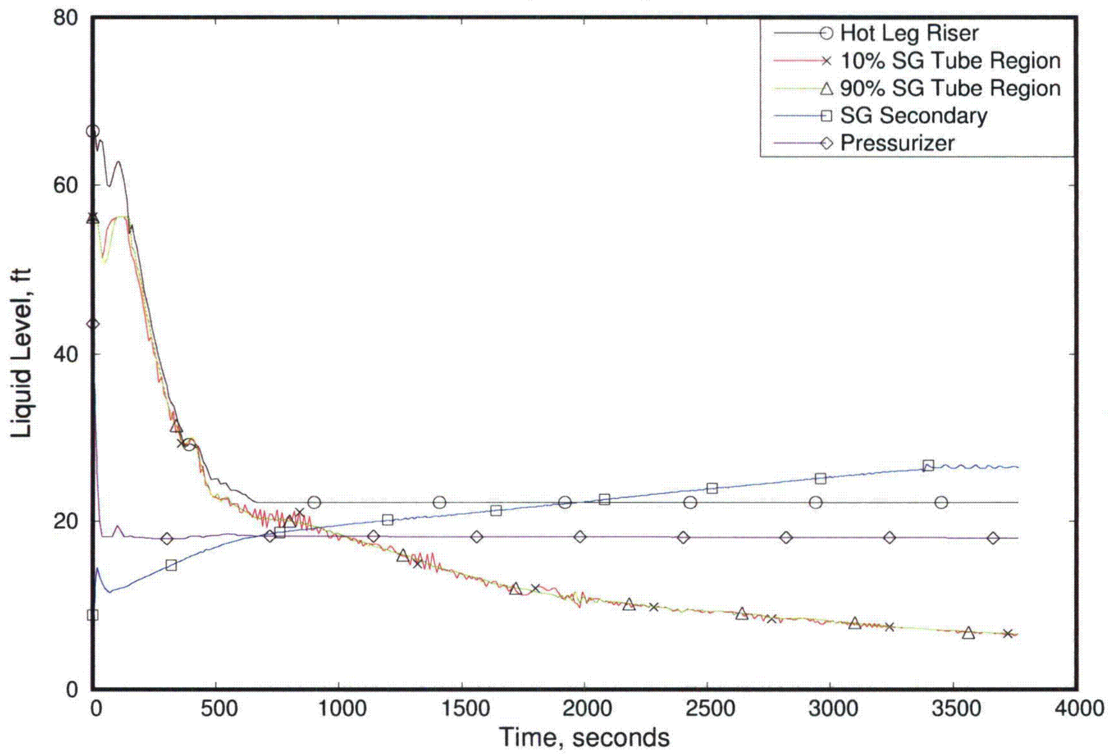


FIGURE 6-71: 0.08 ft^2 CLPD Break, Reduced Power without FCS SG-B Collapsed Liquid Levels

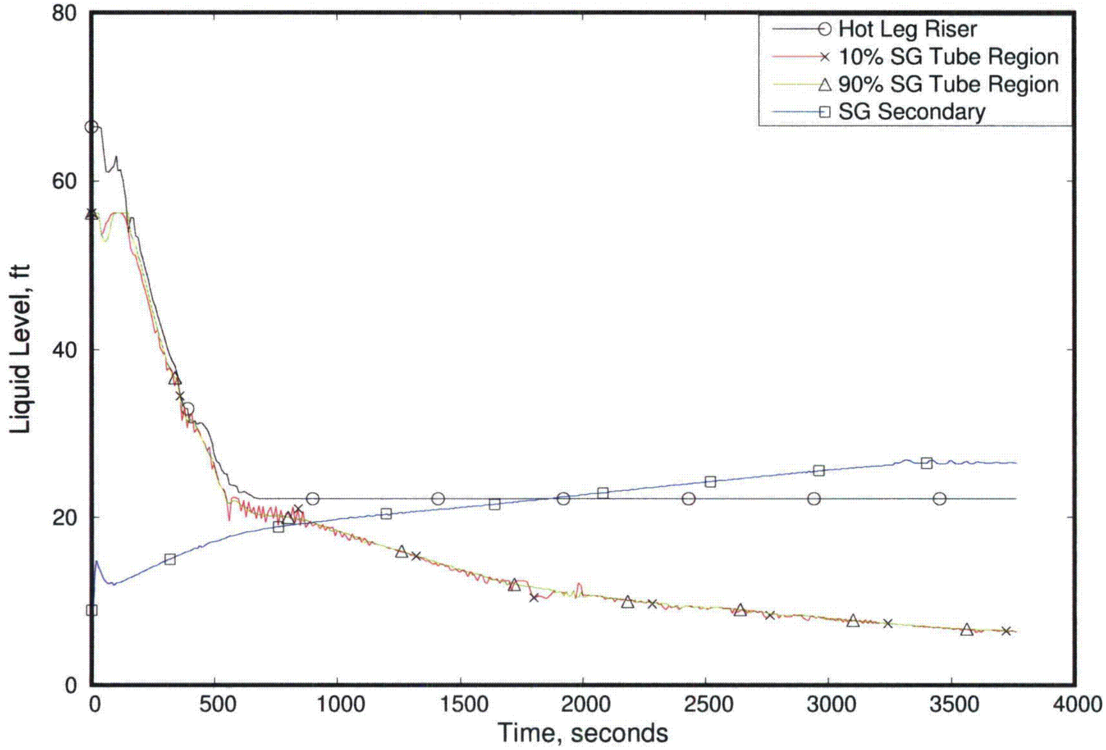


FIGURE 6-72: 0.08 ft^2 CLPD Break, Reduced Power without FCS Core Mixture Levels

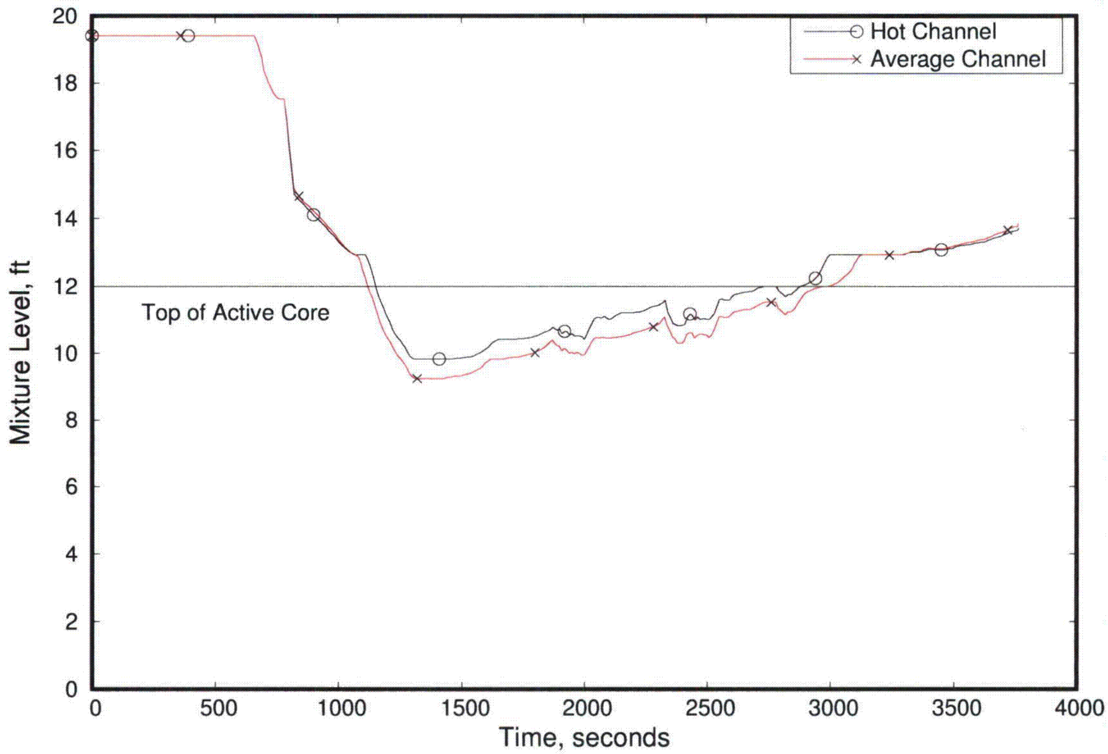


FIGURE 6 73: 0.08 ft² CLPD Break, Reduced Power without FCS Hot Channel Clad Temperatures

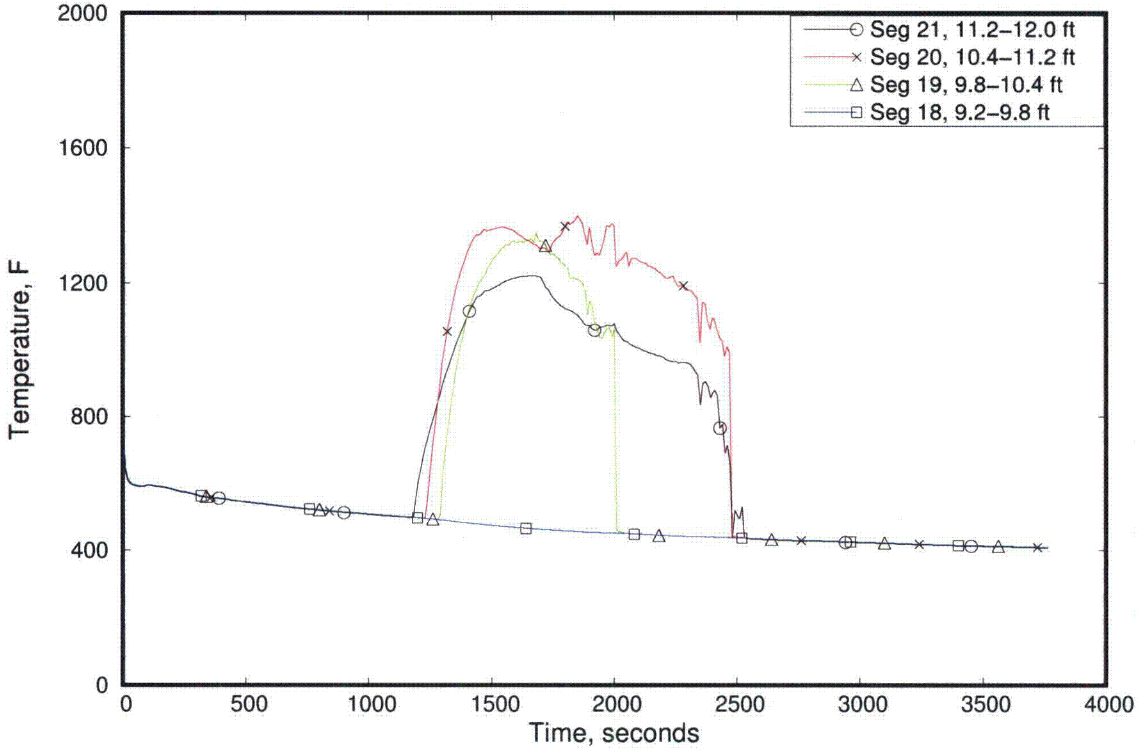


FIGURE 6 74: 0.08 ft² CLPD Break, Reduced Power without FCS Hot Channel Steam Temperatures

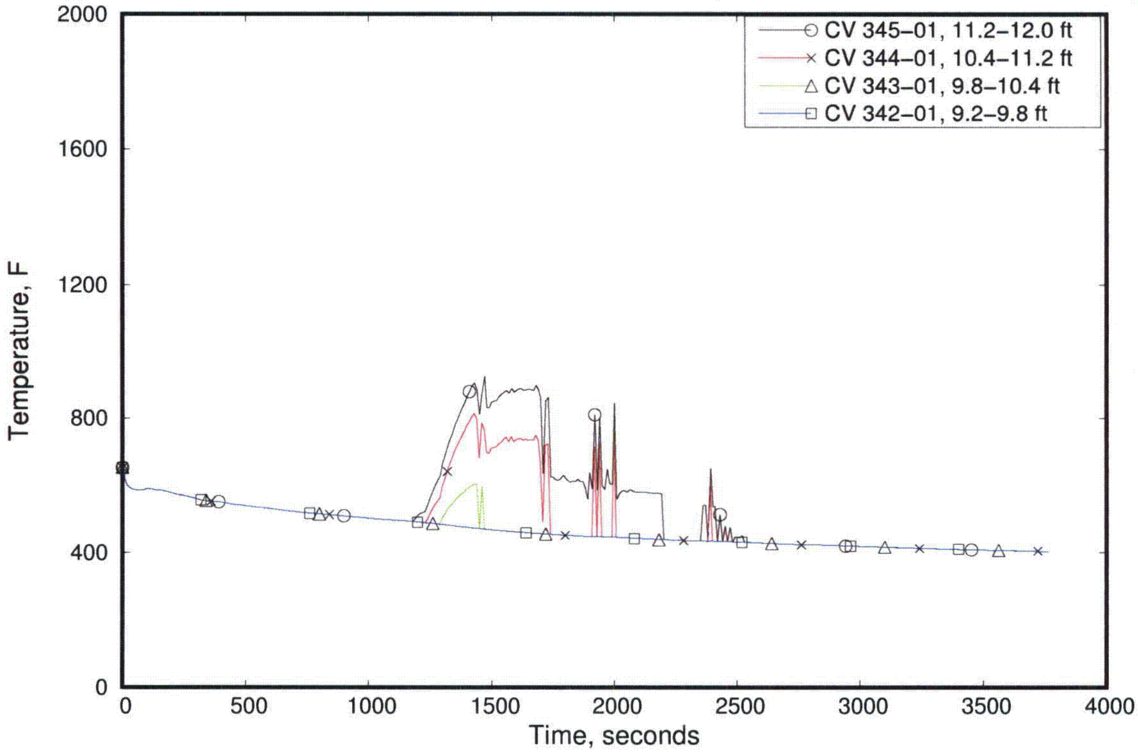


FIGURE 6–75: 0.08 ft^2 CLPD Break, Reduced Power without FCS Average Channel Clad Temperatures

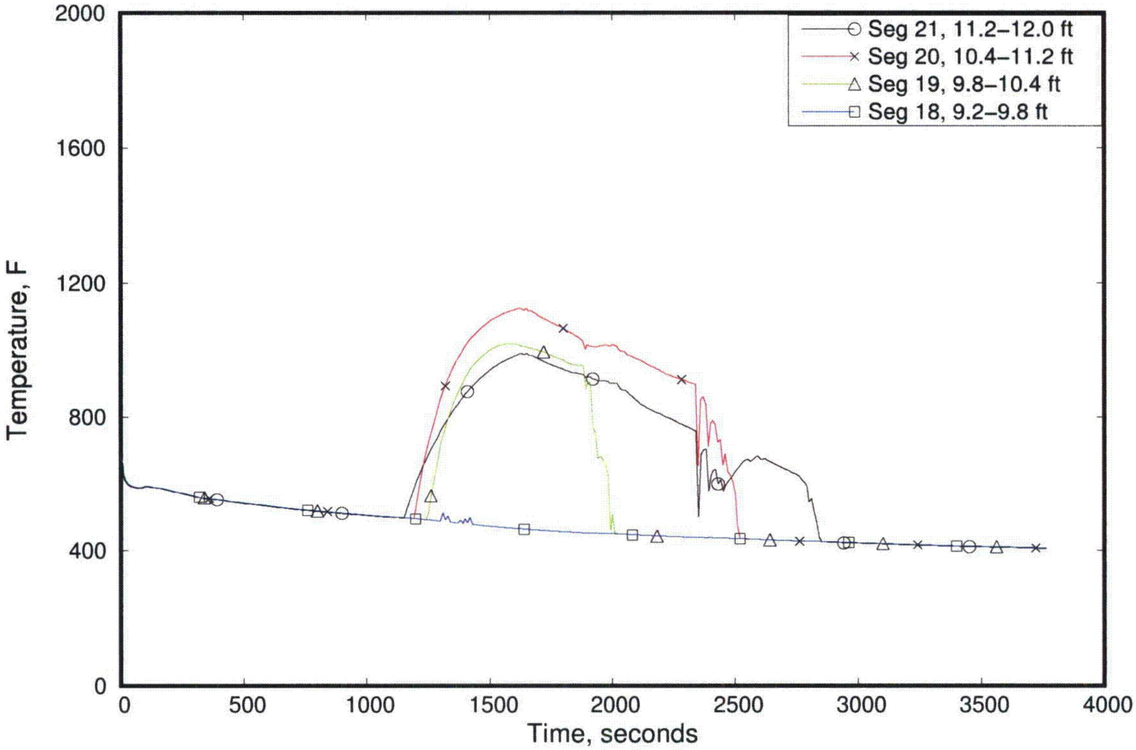


FIGURE 6–76: 0.08 ft^2 CLPD Break, Reduced Power without FCS Average Channel Steam Temperatures

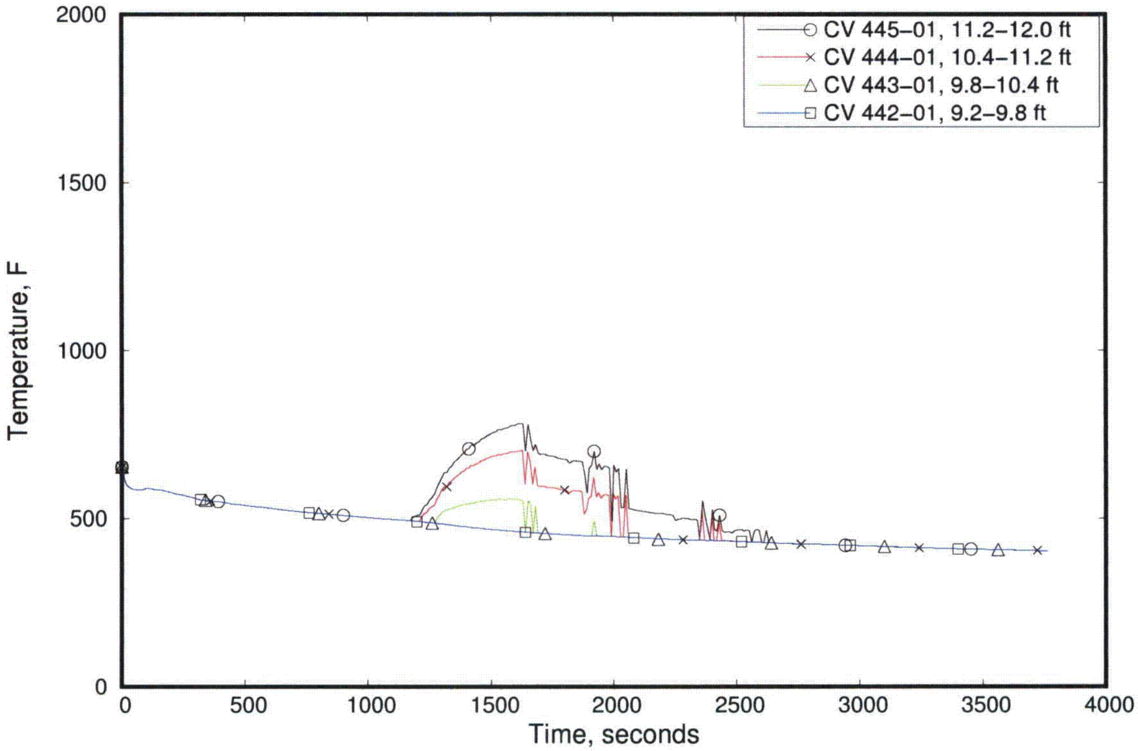


FIGURE 6-77: Category 2 Breaks (LOOP), Full Power without FCS Primary Pressure

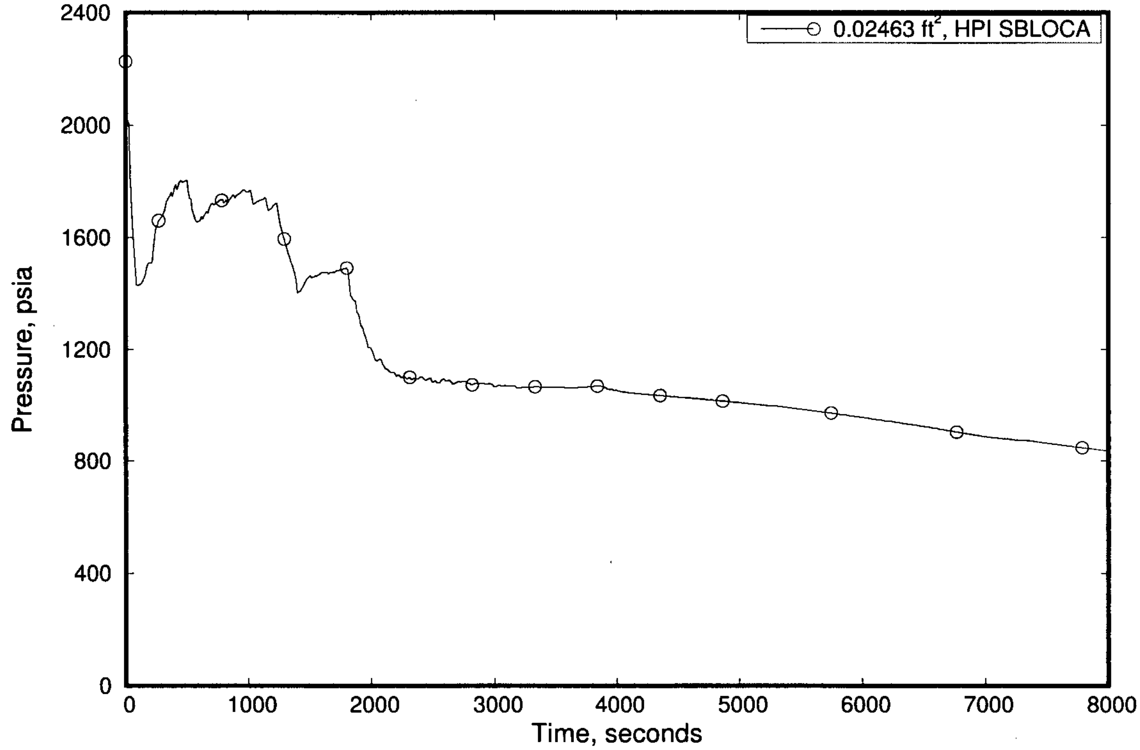


FIGURE 6-78: Category 2 Breaks (LOOP), Full Power without FCS Peak Cladding Temperature

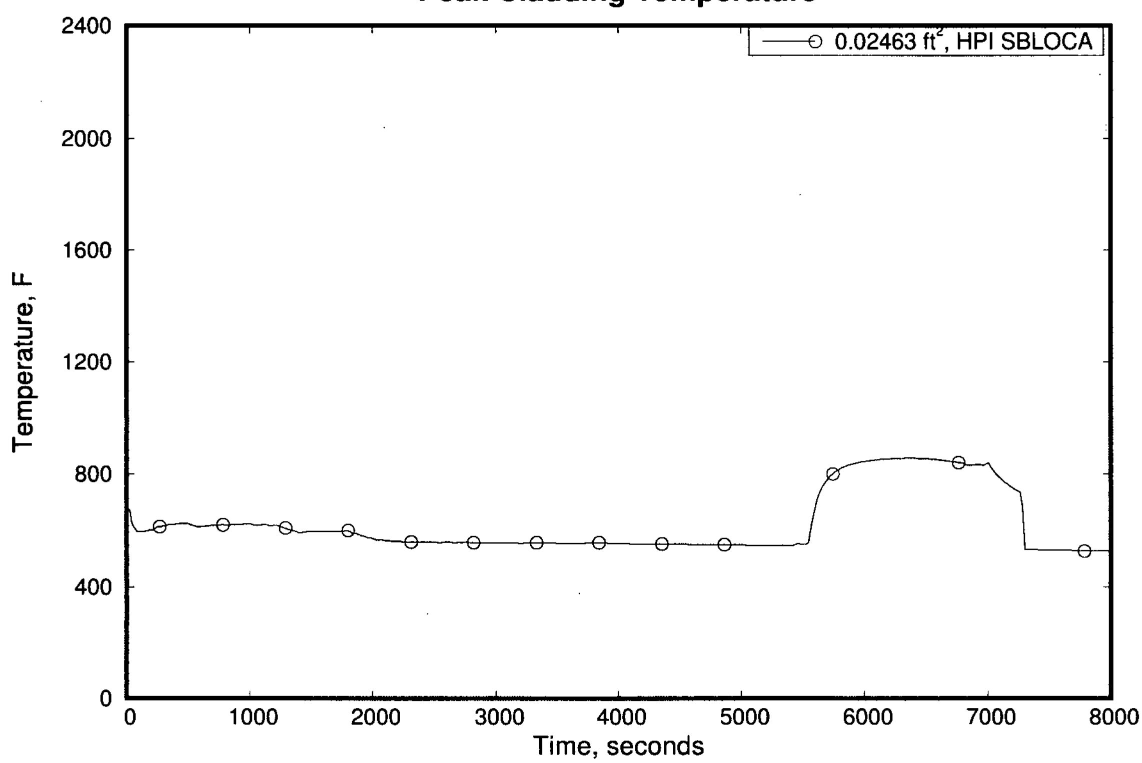


FIGURE 6-79: Category 2 Breaks (LOOP), Full Power without FCS HC Mixture Level

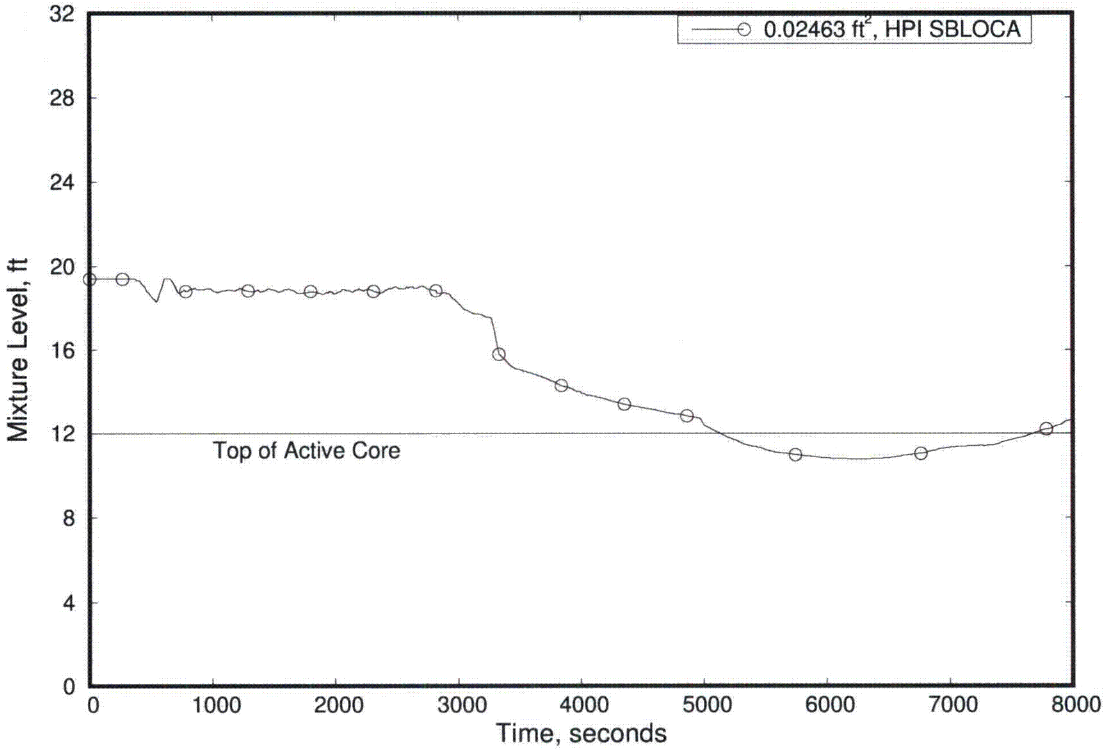


FIGURE 6-80: Category 2 Breaks (LOOP), Full Power without FCS Break and ECCS Mass Flow Rates

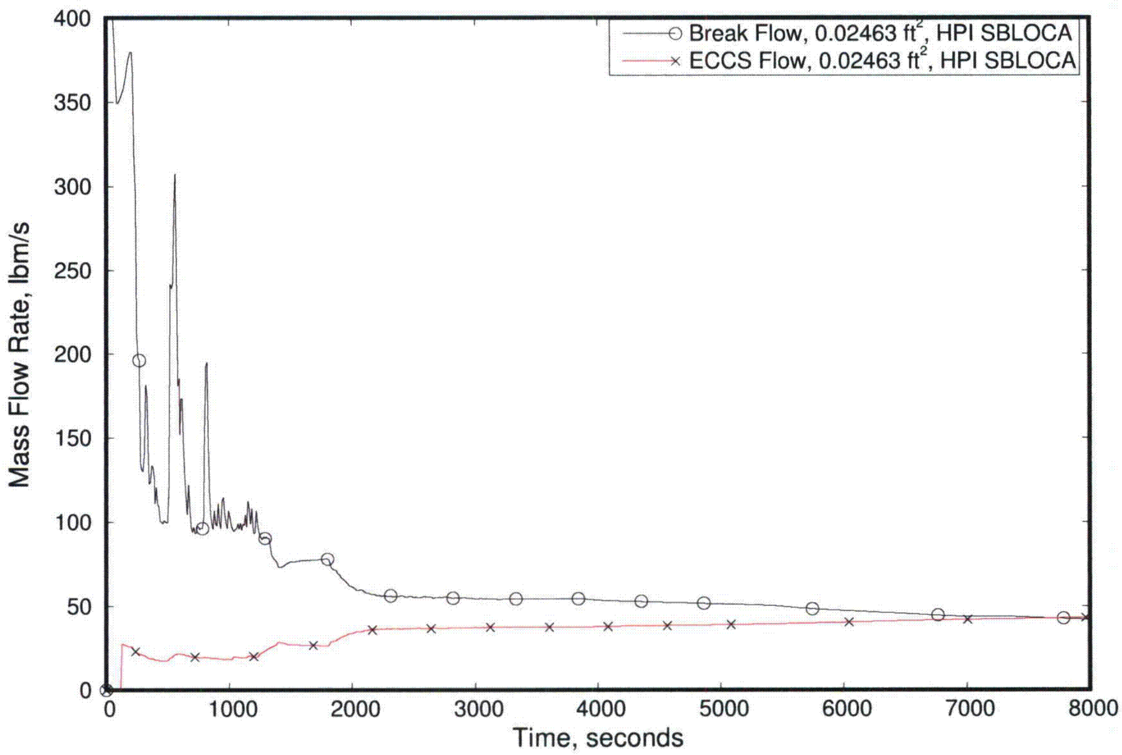


FIGURE 6-81: Category 3 Breaks (LOOP), Full Power without FCS Comparison of Primary Pressures

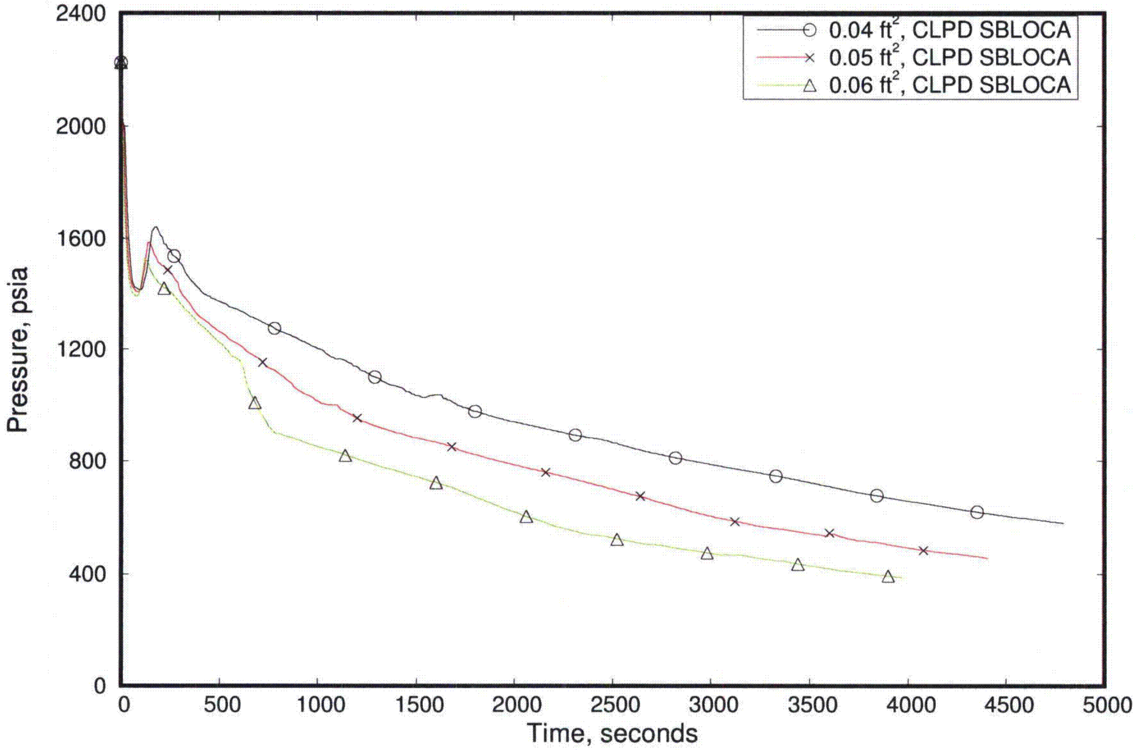


FIGURE 6-82: Category 3 Breaks (LOOP), Full Power without FCS Comparison of Peak Cladding Temperatures

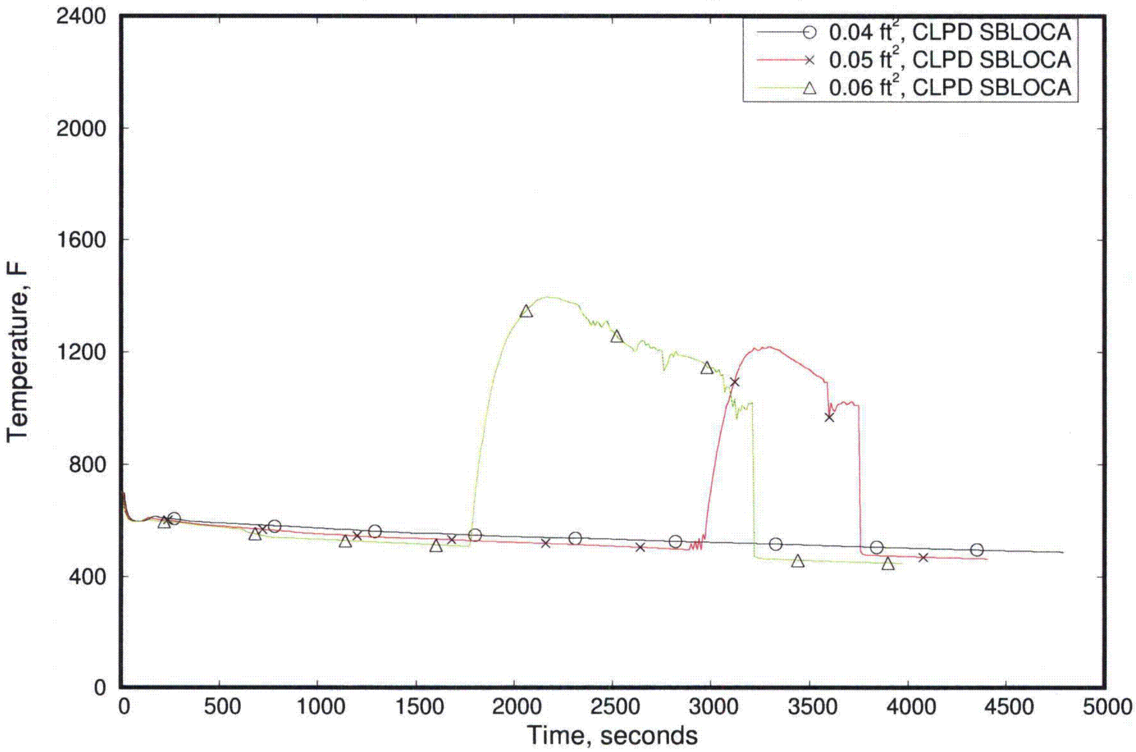


FIGURE 6–83: Category 3 Breaks (LOOP), Full Power without FCS Comparison of HC Mixture Levels

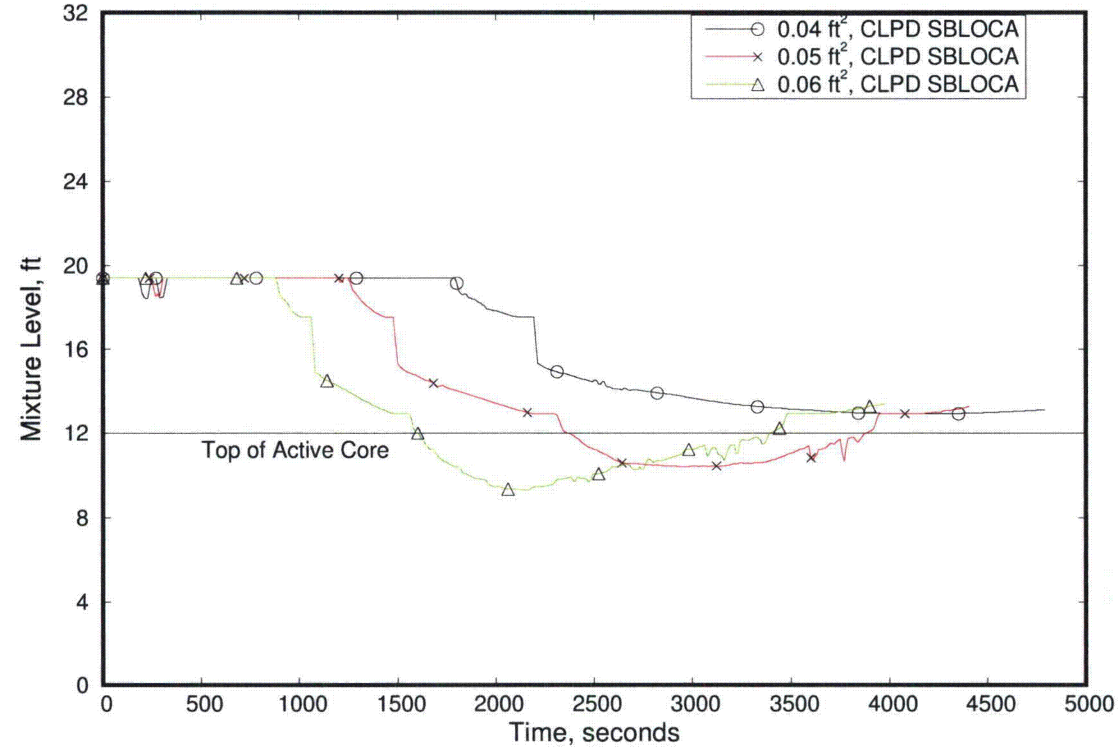


FIGURE 6–84: Category 3 Breaks (LOOP), Full Power without FCS Comparison of Break and ECCS Mass Flow Rates

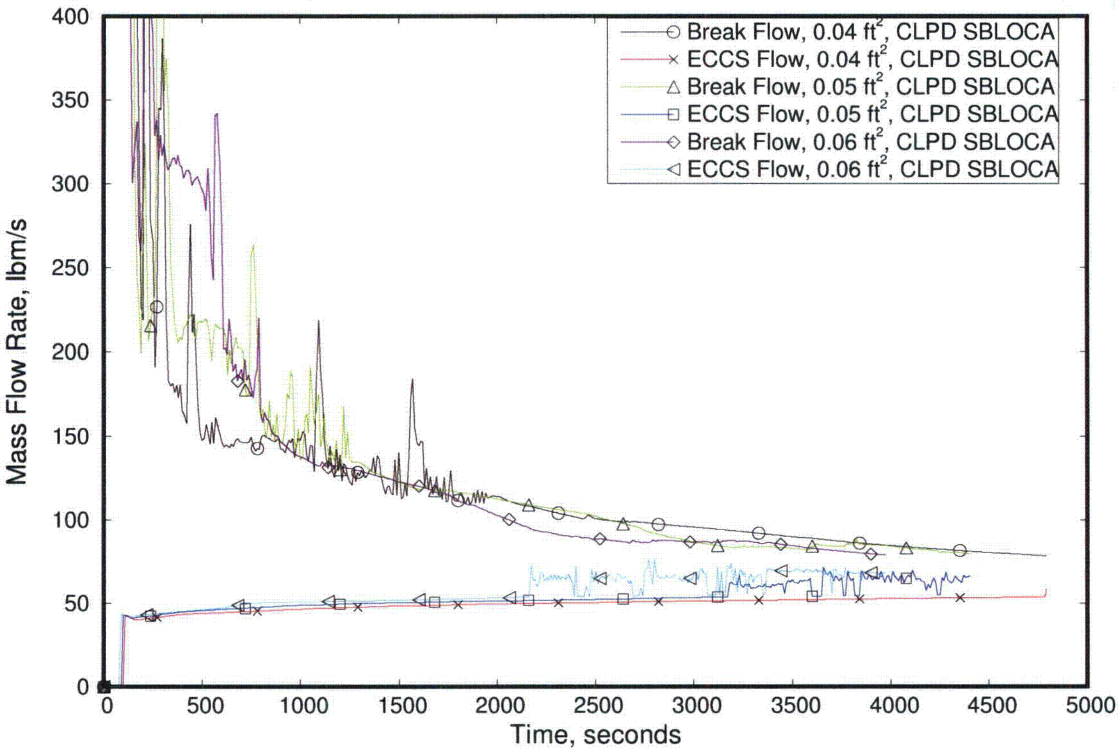


FIGURE 6 85: Select Category 4 Breaks (LOOP), Full Power without FCS Comparison of Primary Pressures

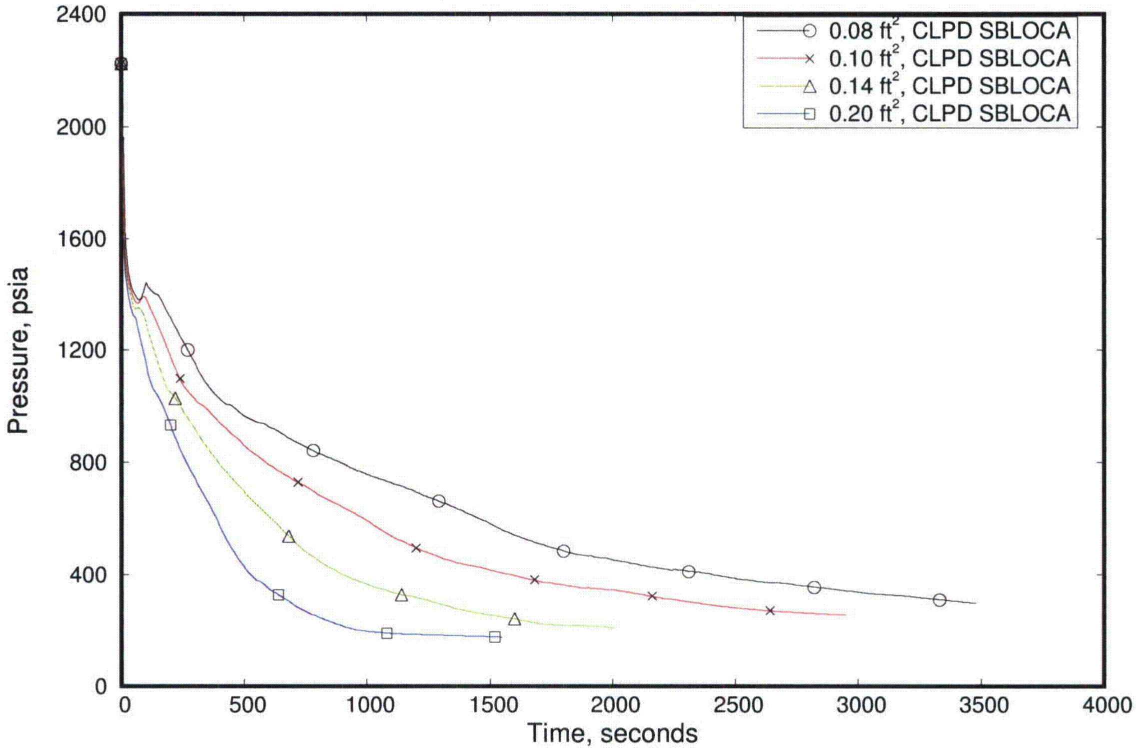


FIGURE 6 86: Select Category 4 Breaks (LOOP), Full Power without FCS Comparison of Peak Cladding Temperatures

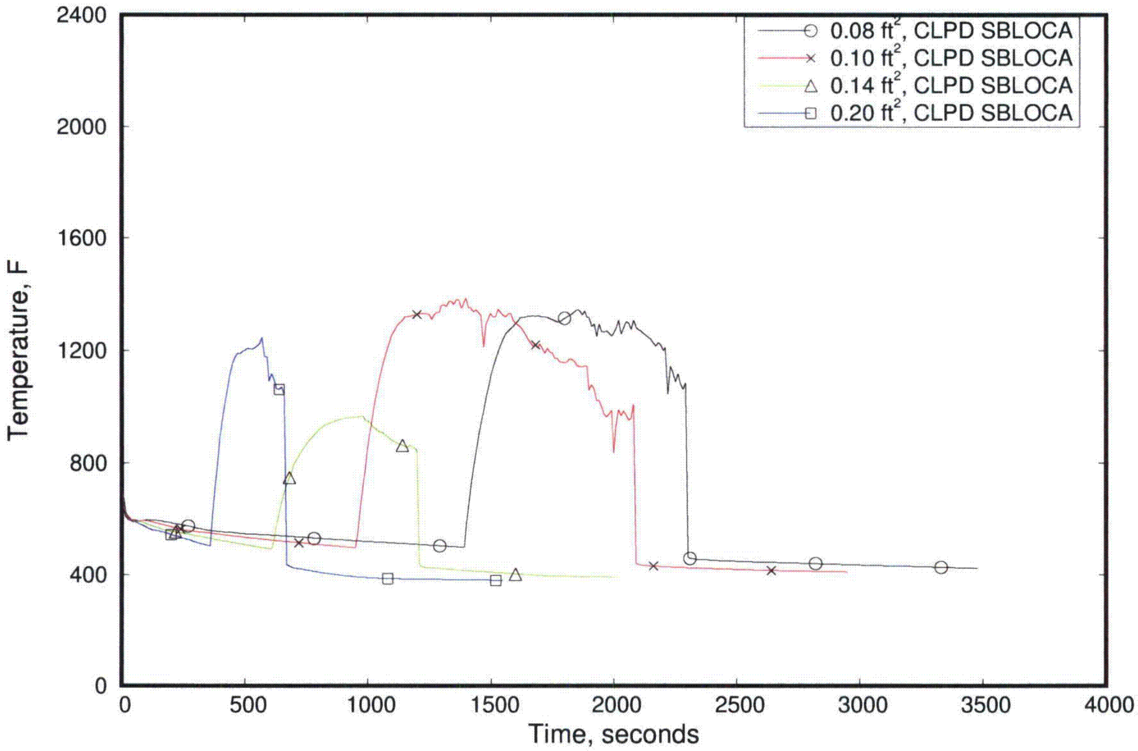


FIGURE 6 87: Select Category 4 Breaks (LOOP), Full Power without FCS Comparison of HC Mixture Levels

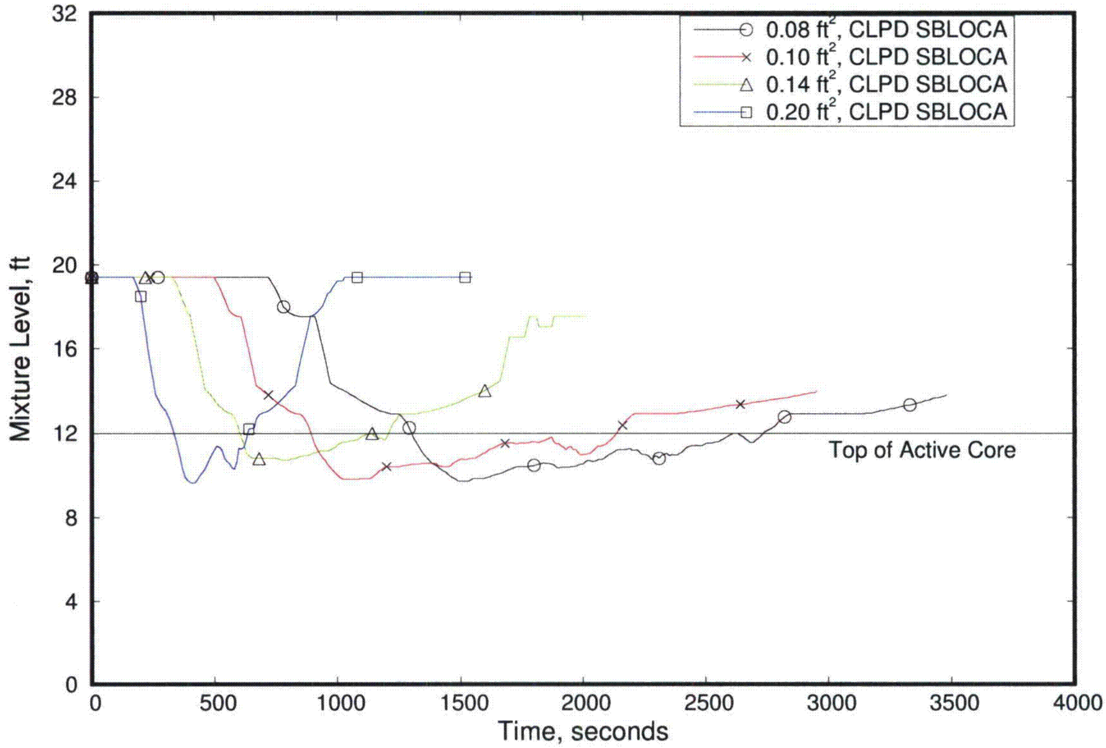


FIGURE 6 88: Select Category 4 Breaks (LOOP), Full Power without FCS Comparison of Break and ECCS Mass Flow Rates

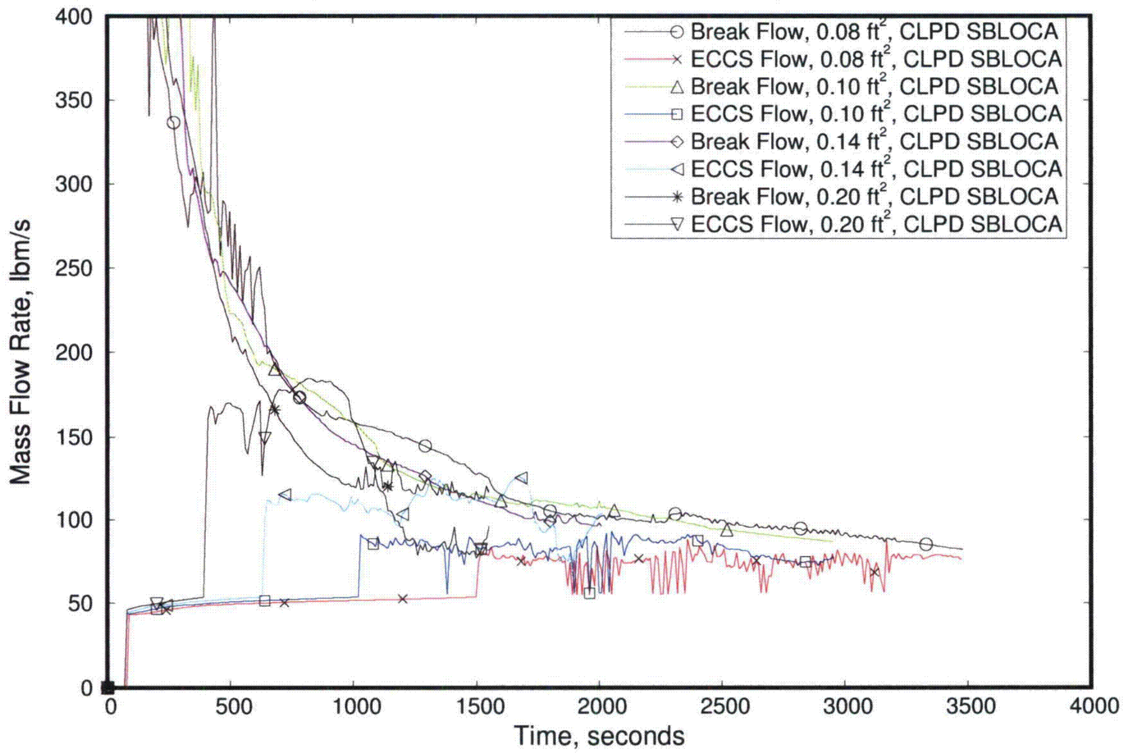


FIGURE 6 89: 0.06 ft^2 CLPD Break, Full Power without FCS System Pressures

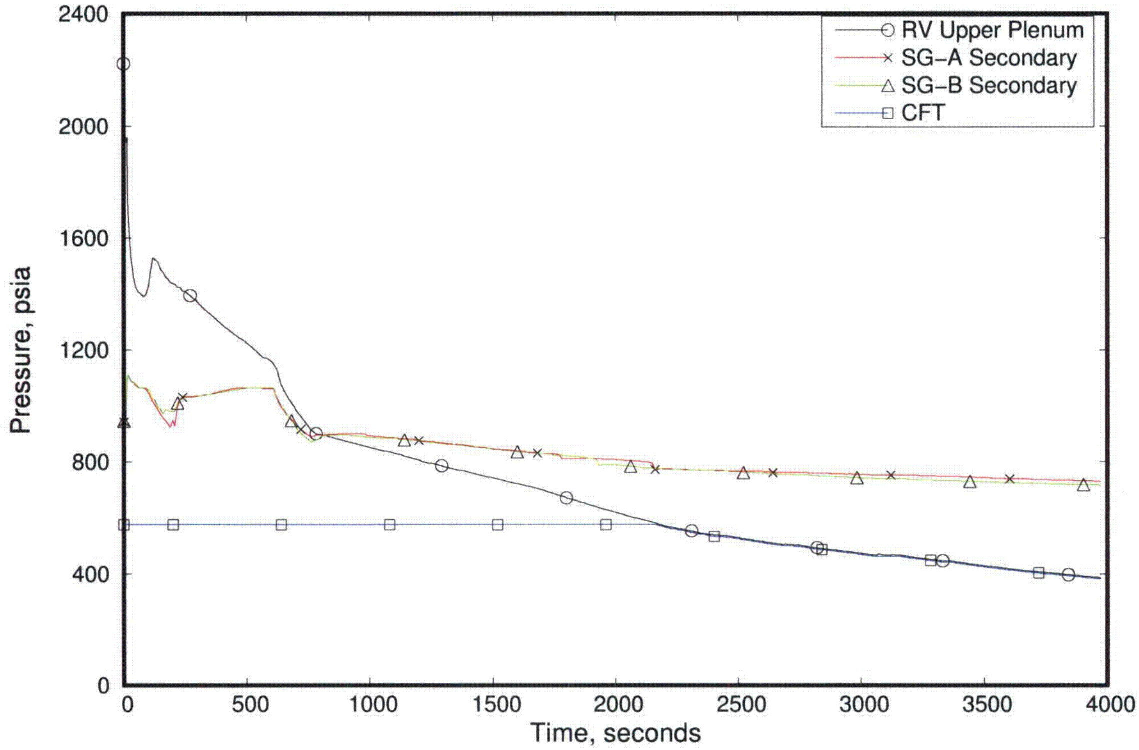


FIGURE 6 90: 0.06 ft^2 CLPD Break, Full Power without FCS Downcomer and Core Collapsed Liquid Levels

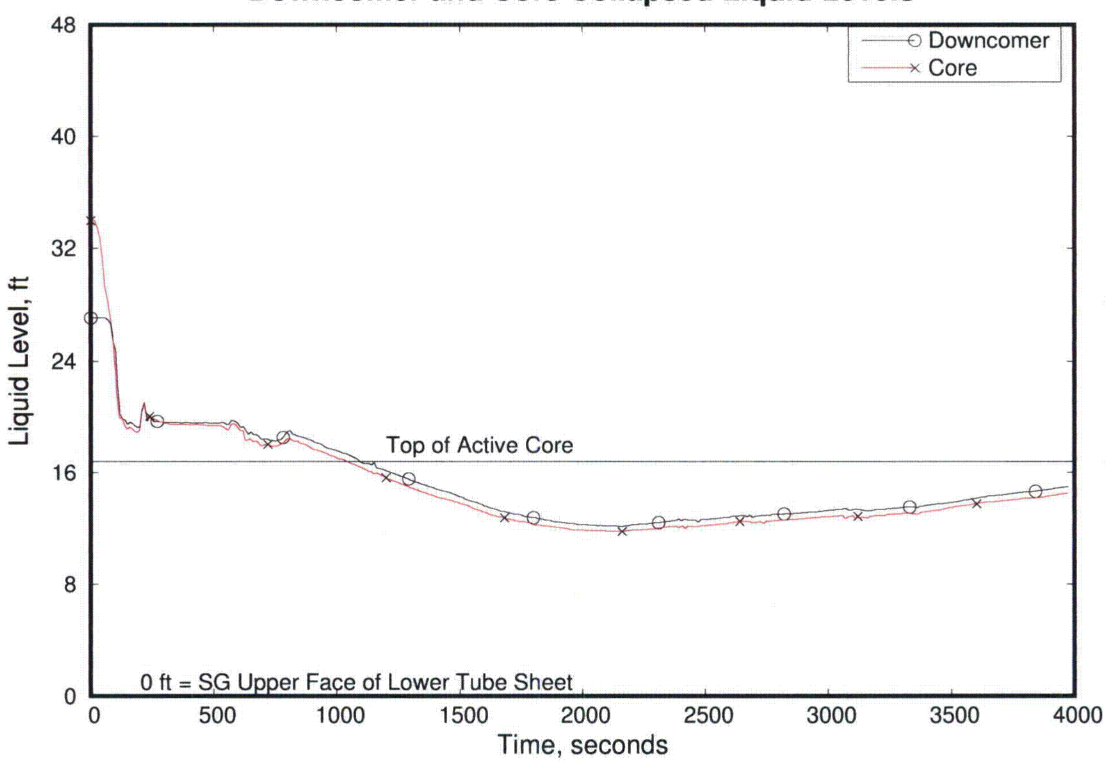


FIGURE 6-91: 0.06 ft^2 CLPD Break, Full Power without FCS
Break and Core ECCS Mass Flow Rates

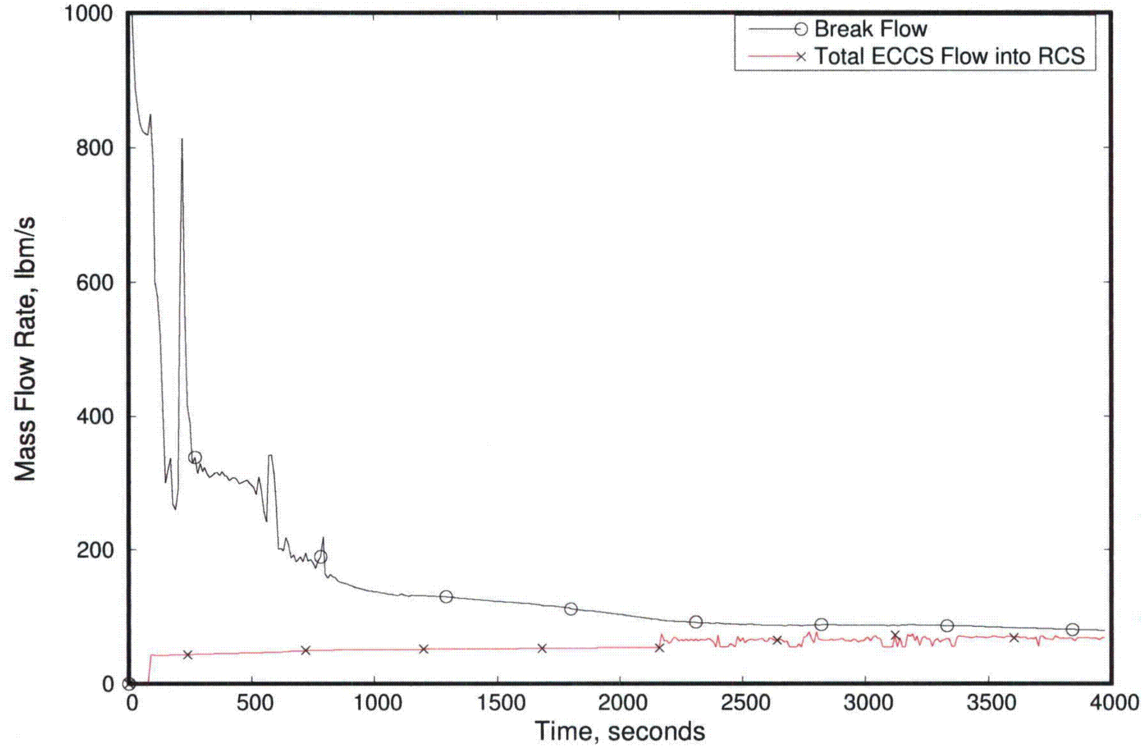


FIGURE 6-92: 0.06 ft^2 CLPD Break, Full Power without FCS
SG-A Collapsed Liquid Levels

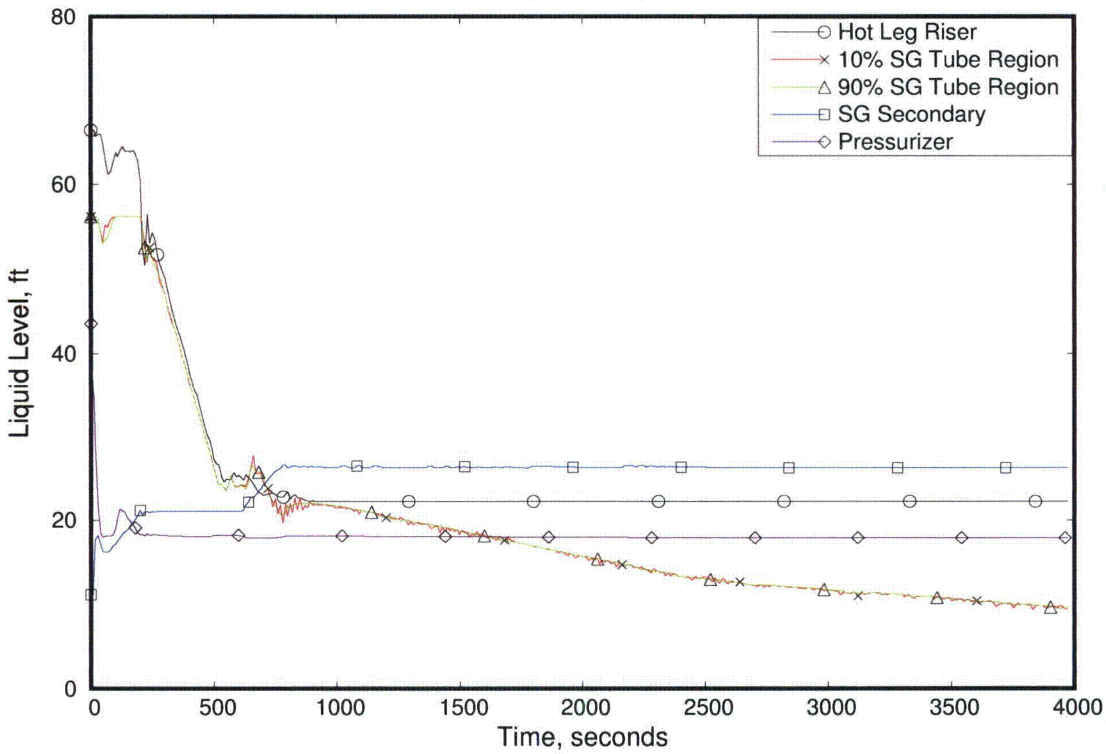


FIGURE 6 93: 0.06 ft² CLPD Break, Full Power without FCS SG B Collapsed Liquid Levels

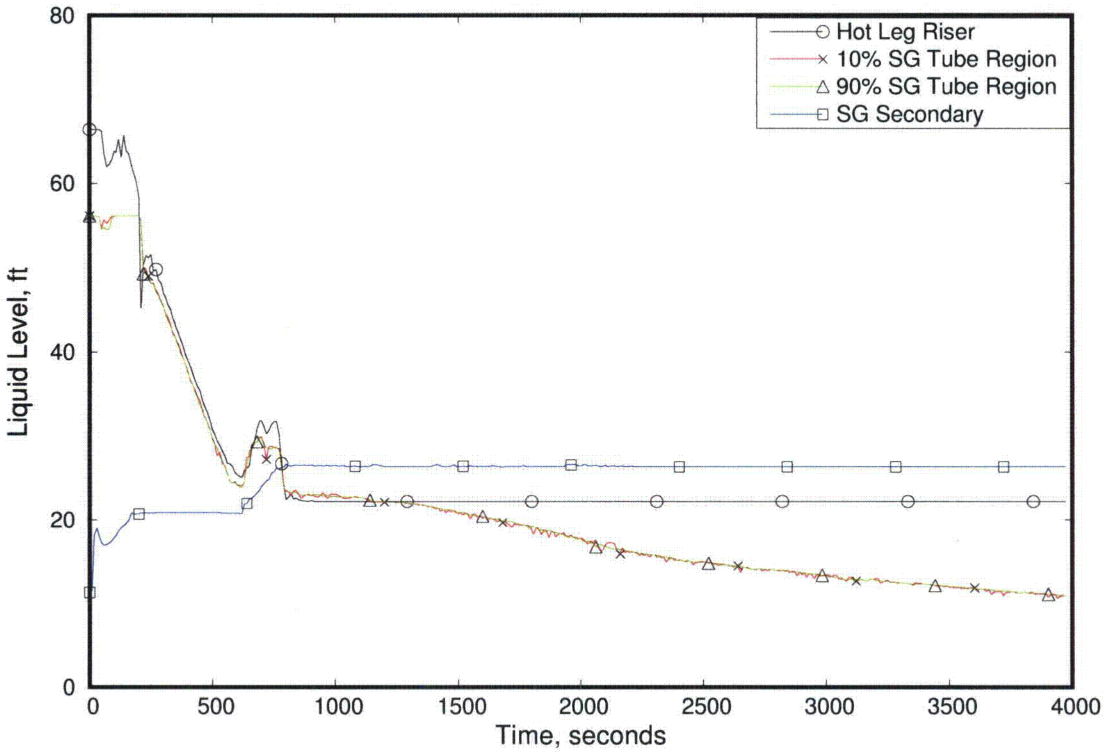


FIGURE 6 94: 0.06 ft² CLPD Break, Full Power without FCS Core Mixture Levels

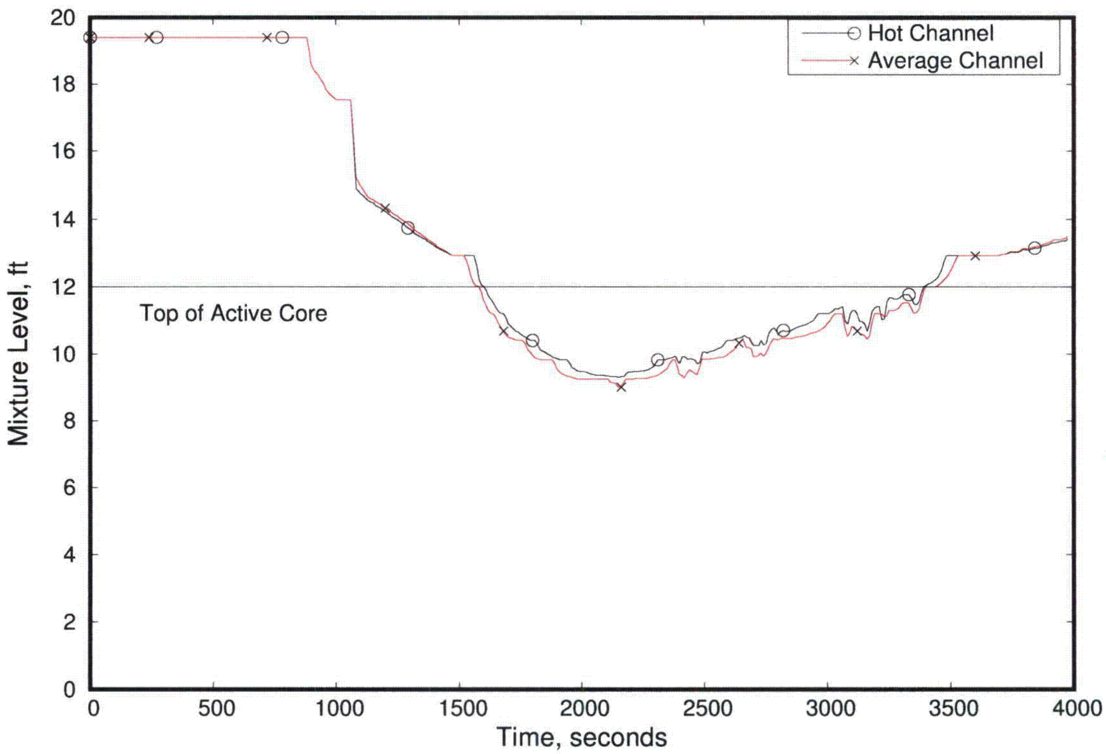


FIGURE 6–95: 0.06 ft^2 CLPD Break, Full Power without FCS Hot Channel Clad Temperatures

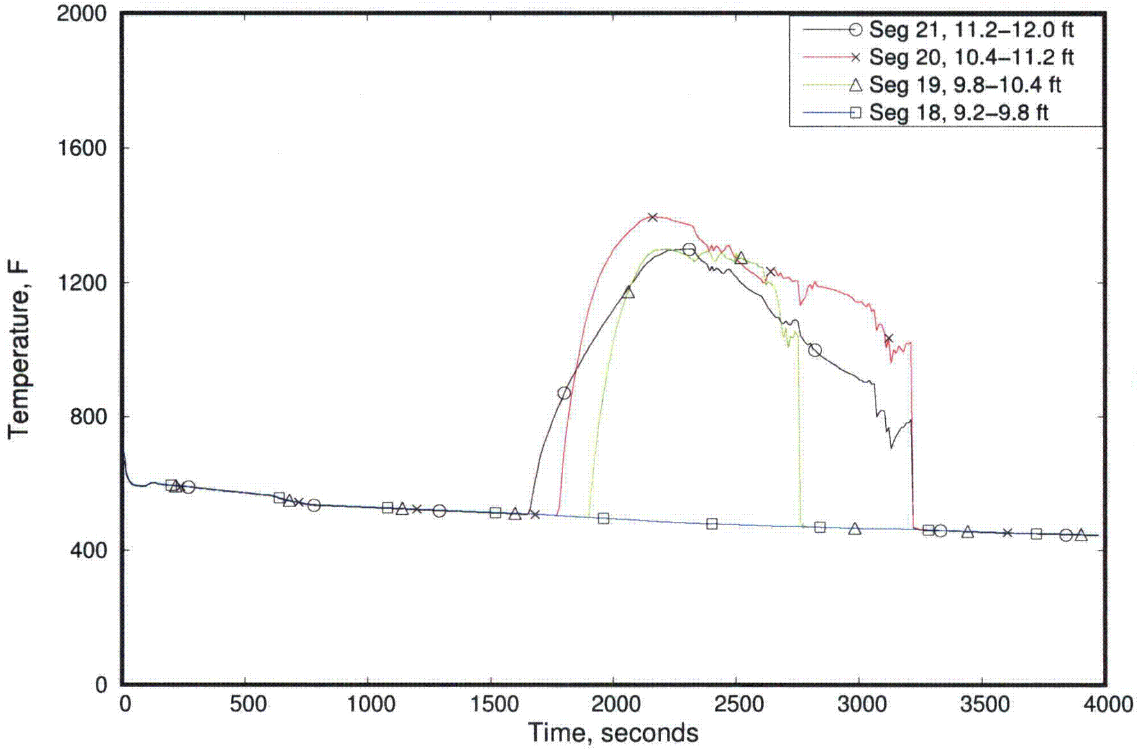


FIGURE 6–96: 0.06 ft^2 CLPD Break, Full Power without FCS Hot Channel Steam Temperatures

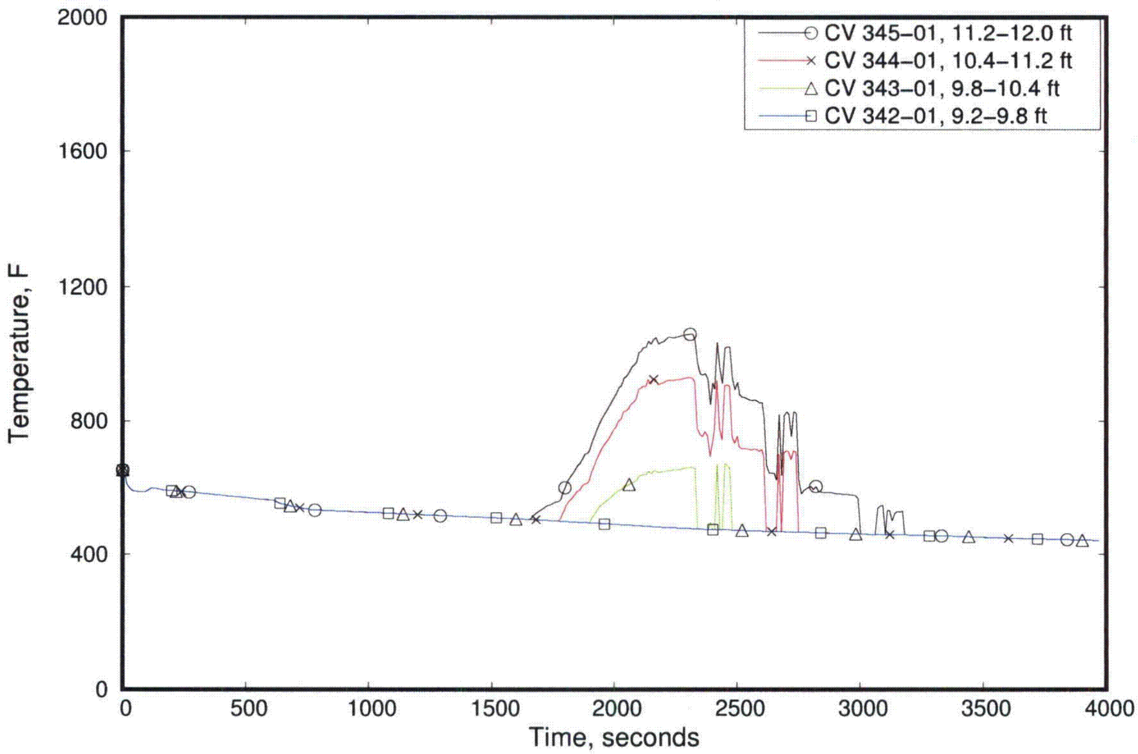


FIGURE 6–97: 0.06 ft^2 CLPD Break, Full Power without FCS Average Channel Clad Temperatures

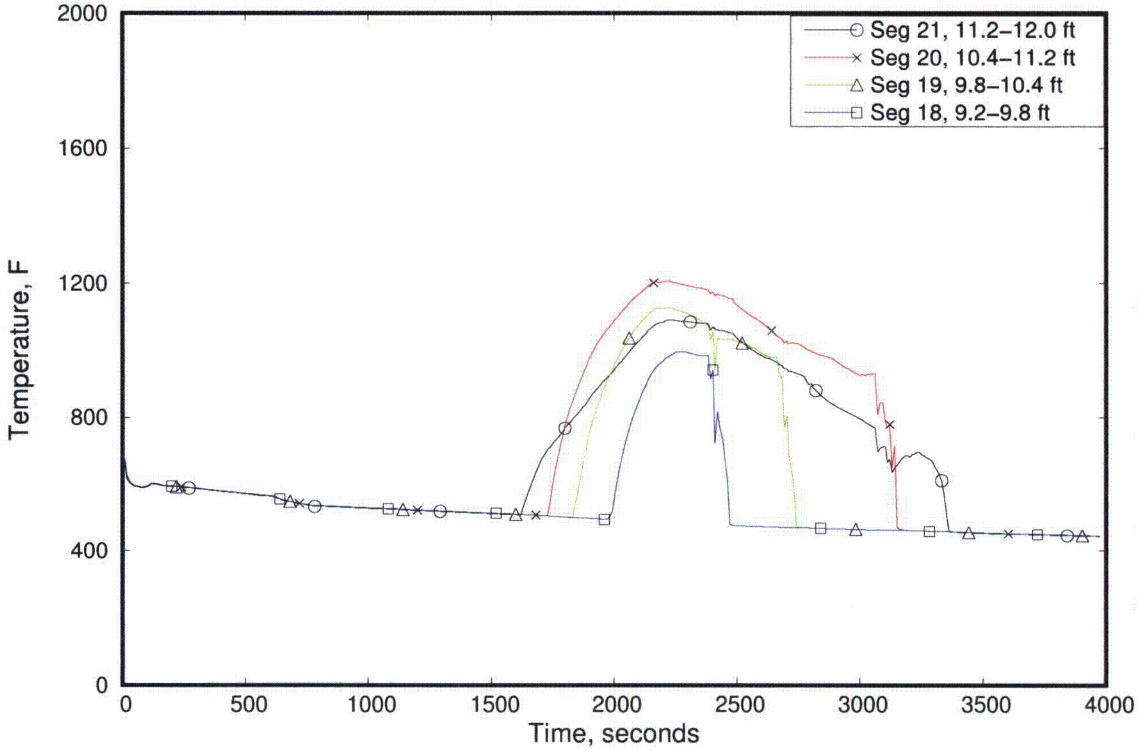


FIGURE 6–98: 0.06 ft^2 CLPD Break, Full Power without FCS Average Channel Steam Temperatures

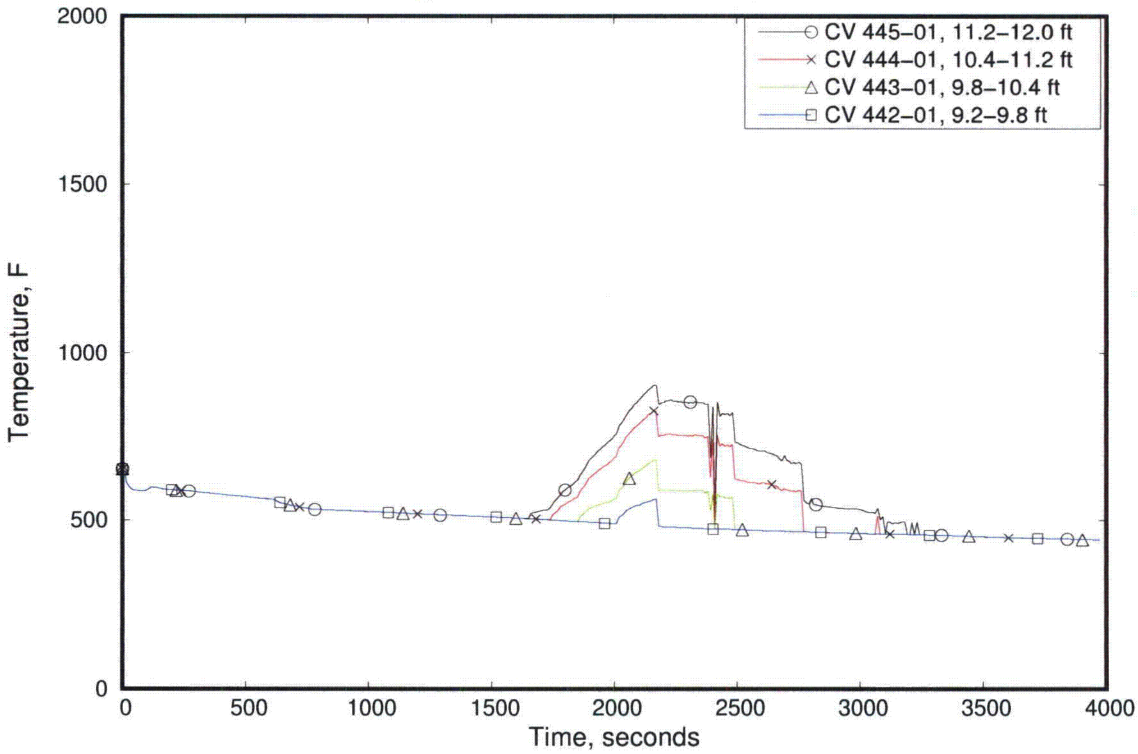


Figure 6-99: Detailed Reduced Power without FCS PCT versus Break Size

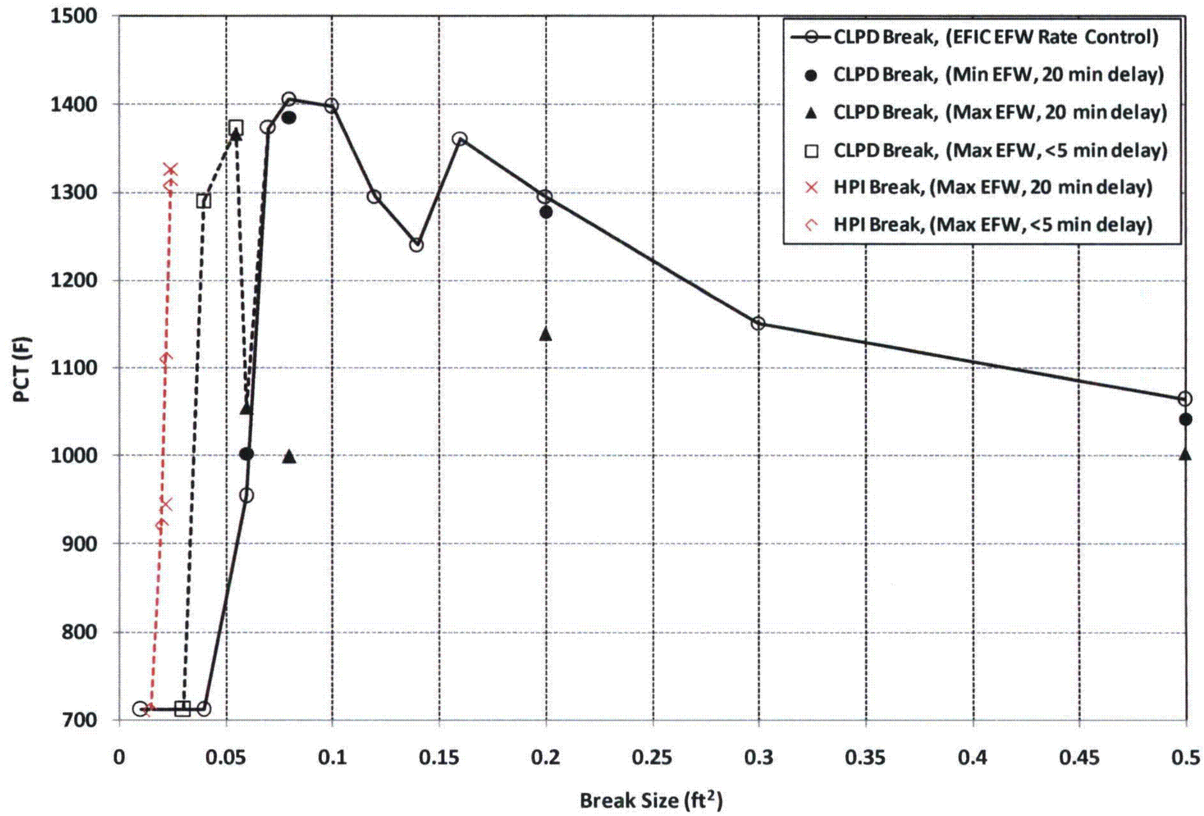
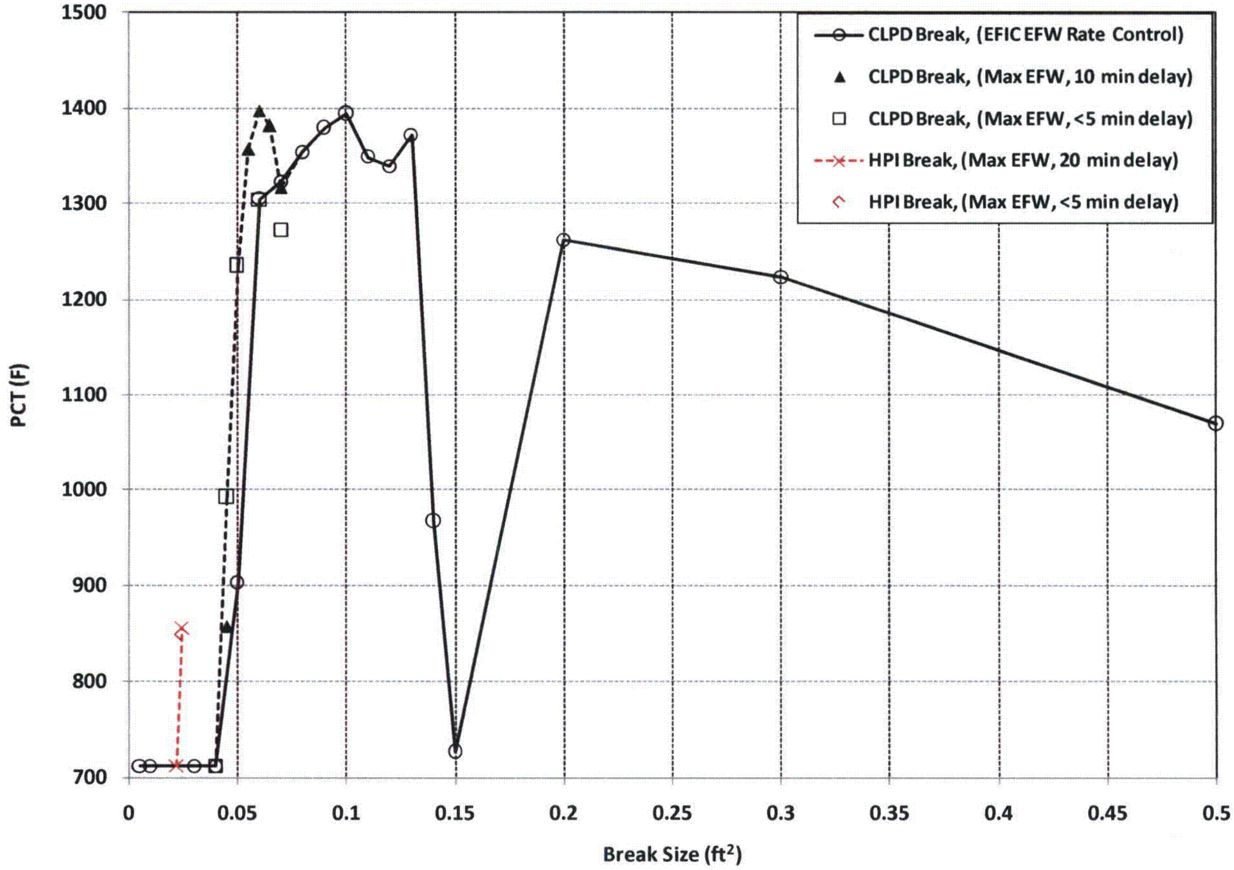


Figure 6-100: Detailed Full Power without FCS PCT versus Break Size



7.0 RELAP5/MOD2-B&W EM SER RESTRICTIONS

The NRC Safety Evaluation Report (SER) on BAW-10192P-A [1] contained eleven restrictions related to the use of the RELAP5/MOD2-B&W EM. Compliance with these eleven restrictions described in [22] was confirmed in [2 and 3] as summarized in this section. There are no restrictions pertaining to LOCA associated with the use of the M5 cladding material.

1. *The LOCA methodology should include any NRC restrictions placed on the individual codes used in the evaluation model (EM).*

Response: For LBLOCA analyses, the RELAP5/MOD2-B&W (includes BEACH), the REFLOD3B and CONTEMPT codes are utilized. For SBLOCA analyses, only the RELAP5/MOD2-B&W and CONTEMPT (for CFT analyses only) codes are utilized. Sections 2.2 through 2.5 of [22] detail the NRC restrictions placed on the codes used in the BWNT LOCA EM. All items were in compliance the NRC restriction based on the review performed according to the latest revision of [22].

2. *The guidelines, code options, and prescribed input specified in Tables 9-1 and 9-2 in both Volume I and Volume II of BAW-10192-P should be used in LBLOCA and SBLOCA evaluation model applications, respectively.*

Response: Table 9-1 in Volume I (LBLOCA) of BAW-10192P-A is verified via use of Table 4 in [22]. Compliance to the Table 4 restrictions for the LBLOCA analyses is listed in [2]. Table 9-2 in Volume II (SBLOCA) of BAW-10192P-A is verified via use of Table 6 in [22]. Compliance to the Table 6 restriction for the SBLOCA analyses is listed in [3]. These tables also include inputs and restrictions placed on the individual codes that make up the BWNT LOCA EM as discussed in detail in [22].

3. *The limiting linear heat rate for LOCA limits is determined by the power level and the product of the axial and radial peaking factors. An appropriate axial peaking factor for use in determining LOCA limits is one that is representative of the fuel and core design and that may occur over the core lifetime. The radial peaking factor is then set to obtain the limiting linear heat rate. For this demonstration, calculations were performed with the axial peak of 1.7. The general approach is acceptable for demonstrating the LOCA limits methodology. However, as future fuel or core designs evolve, the basic approaches that were used to establish these conclusions may change. AREVA must revalidate the acceptability of the evaluation model peaking methods if: (1) significant changes are found in the core elevation at which the minimum core LOCA margin is predicted or (2) the core maneuvering analyses radial and axial peaks that approach the LOCA LHR limits differ appreciably from those used to demonstrate Appendix K compliance.*

Response: This restriction is related only to LBLOCAs. The axial and radial peaks used in the LBLOCA analyses [2] were similar with an axial peaking factor of 1.7 for all elevations and linear heat rates analyzed. The restriction states that AREVA must revalidate the acceptability of the evaluation model peaking methods if: (1) significant changes are found in the core elevation at which the minimum core LOCA margin is predicted or (2) the core maneuvering analyses radial and axial peaks that approach the LOCA LHR limit differ appreciably from those used to demonstrate Appendix K compliance.

Several layers of screening criteria needed to show compliance with the BWNT LOCA EM restriction on peaking are detailed in [50]. The effect of the axial peaking factor on the LOCA transient is from two blowdown affects and one reflood effect [50, Section 3]; CHF timing, elevation of dryout during core flow reversal, and reflood carryout rate. The method described in [50] was based on B9/B10 fuel rod analyses. It was confirmed in [51] that the method remained applicable to the B11 fuel rod design, which has a different fuel and clad diameters and fuel assembly flow area compared to the B9/B10 fuel rod design. Since very similar trends were seen for both the B9/B10 (BWC CHF correlation) and the B11 (BWCMV correlation), it can be concluded that the CHF correlation does not impact the trend. The CHF timing is set by the initial enthalpy distribution in the channel and local fuel pin power distribution. This is confirmed by the similarities of the comparisons between the BHTP and BWC CHF correlations in a sensitivity study in [52, Rev 04]. Therefore, the methods provided are valid for any current or past Mark-B fuel type (including but not limited to Mark-B4Z, Mark-B8, Mark-B9, Mark-B10, Mark-B11, and Mark-B12), including the Mark-B-HTP, that is ruptured-node limited or has similar ruptured- or unruptured-node PCTs predicted with the BWNT LOCA EM.

Four criteria were developed in [50] from which to show compliance or to define a LOCA linear heat rate (LHR) limit penalty. These four criteria are summarized below.

1. The fuel burnup must be compared to the LOCA LHR limits versus burnup. If the burnup is on the PCT-limited portion of the LOCA limit curve (≤ 40,000 MWd/mtU), then proceed to Step 2. If the burnup range is on the pin-pressure-limited portion of the curve (> 40,000 MWd/mtU), the restriction is met without any other conditions. That is, no axial peaking checks or linear heat rate limit adjustments are needed for pin pressure limited LHRs.

2. If the burnup is on the PCT-limited portion of the curve, then the power distribution analysis LOCA margins must be checked at all core elevations. If there is less than 5% LOCA margin, proceed to Step 3. If there is more than 5% margin, the restriction is met and no further checks are needed because the PCT at the maximum power distribution LHR will be lower than the BWNT LOCA EM PCT.

3. If the burnup is on the PCT-limited portion of the curve and there is less than 5% LOCA margin, then variations in the augmented peaking factor versus the 1.7 axial used in the LOCA analyses must be considered. The axial peak must be 1.65 or greater for 0 to 4 ft power peak elevations, 1.7 + 0.05 for 4 to 8 ft elevations, and 1.75 or less for 8 to 12 ft elevations. If these axial peaks are in compliance, the restriction is met and no further checks are needed. If they are not met, then proceed to Step 4 for the LOCA LHR limit reductions.

4. If the burnup is on the PCT-limited portion of the curve, there is less than 5% LOCA margin, and the axial peak is not in compliance, then the power distribution analysis must assign a LOCA LHR limit penalty to ensure that the BWNT LOCA EM PCT (based on the given LHR and APF of 1.7) is not underpredicted. The LHR limit penalty compensates for the known deviation between the augmented axial peak and the required peak. The LHR limit reductions, ΔLHR, are core elevation dependent:

   $\Delta LHR_{0\text{ to }4\text{ ft}} = \min \{ 0.0, [(APF_{\text{power distribution analysis augmented peak}} - 1.65) * 1.5 \text{ kW/ft}] \}$,

   $\Delta LHR_{4\text{ to }8\text{ ft}} = \min \{ 0.0, [(1.75 - APF_{\text{power distribution analysis augmented peak}}) * 4.0 \text{ kW/ft}] \}$

   $+ \min \{ 0.0, [(APF_{\text{power distribution analysis augmented peak}} - 1.65) * 1.5 \text{ kW}] \}$,

   and

   $\Delta LHR_{8\text{ to }12\text{ ft}} = \min \{ 0.0, [(1.75 - APF_{\text{power distribution analysis augmented peak}}) * 4.0 \text{ kW/ft}] \}$.

4. The mechanistic ECCS bypass model is acceptable for cold leg transition (0.75 ft^2 to 2.0 ft^2) and hot leg break calculations. The nonmechanistic ECCS bypass model must be used in the large cold leg break (2.0 ft^2) methodology since the demonstration calculations and sensitivities were run with this model.

Response: As outlined in BAW-10192P-A Volumes I and II, different bypass models are used for large break and small break analyses. The nonmechanistic ECCS bypass model is used in large break analyses (≥ 2.0 ft^2). The mechanistic ECCS bypass model is used for cold leg transition (0.5 ft^2 to 2.0 ft^2), hot leg, and all smaller sized cold leg breaks. As presented in Sections 4.2 and A.6.3 of Volume II of the EM [1], the minimum break size range for cold leg transition breaks is determined based on those breaks that show initial clad DNB. The largest break size that did not undergo DNB was the 0.50 ft^2 for the Mark-B-HTP CR-3 with ROTSGs at the EPU power level. Therefore, the analyses of break sizes larger than 0.50 ft^2 up to 2 ft^2 are included in the LBLOCA transition break range.

5. *Time-in-life LOCA limits must be determined with, or shown to be bounded by, a specific application of the NRC-approved evaluation model.*

Response: Time-in-life cases were explicitly examined for the LBLOCA analyses. Conditions appropriate to the specific time in life were used in the hot channel, while the BOL parameters were maintained in the average channel.

Time-in-life calculations for SBLOCA applications, which use a conservative composite set of reactivity parameter bounding for all TILs, are not required unless the fuel pin heatup is sufficient to cause cladding rupture. For the EPU analyses, AREVA used a method to explicitly examine times in life and the likelihood of rupture and its effect on the PCT for each case. The method used three supplemental pins with a plastic weighted heating ramp rate option, BOL fuel temperatures, and BOL initial oxide thicknesses. The hot channel is set to the pin pressure limit at EOL. The three supplemental pins use pin pressures consistent with BOL and two pressures roughly uniformly distributed between the BOL and EOL values. Clad rupture at cladding temperatures less than approximately 1600 F allows increased cooling because of the clad surface area increase. At these temperatures the metal-water reaction is not significant, therefore rupture is a beneficial event that if avoided will produce higher PCTs. For higher cladding temperatures where the metal-water reaction contributes to the peak clad temperature, the pin pressure variation will ensure that clad rupture is obtained at the most limiting time during the transient. To maximize the cladding temperatures, the BOL fuel stored energy and BOL oxide thicknesses are used. While these assertions are based on studies performed with Zr-4 cladding, they are equally applicable to M5 cladding, because the rupture behavior and metal-water reaction are not significantly different between the cladding materials.

A pure TIL calculation (with TIL-specific reactivity inputs, fuel stored energy, pin pressure, and cladding oxide thickness consistent with the TIL that produces the worst rupture time) would be performed if the composite case is judged to be overly conservative. The consistent case would also use the plastic-weighted normalized heating ramp rate to predict the fuel pin swell and rupture performance.

6. *LOCA limits for three pump operation must be established for each class of plants by application of the methodology described in this report. An acceptable approach is to demonstrate that three pump operation is bounded by four pump LHR limits.*

Response: A LBLOCA analysis of three operating RCPs at a core power of 80 percent full power was performed to demonstrate that three-pump operation is bounded by four-pump LHR limits. The hot channel three-pump peak LHR limit is set equivalent to the 100 percent power 4-pump LHR limit. Because this analysis is performed at a power level less than 95 percent, a positive MTC of +1 pcm/F is considered. The analysis showed that the consequences of the 4 RCP full-power LOCA LHR limit analyses bound those during 3 RCP operation; therefore, the 4 RCP operation LHR limits remain valid for the 3 RCP operation. See Section 5.2.4 for additional details.

Three-pump SBLOCA analyses are not performed, because the core power is reduced but the ECCS capacity remains at the 100 percent full power levels. Therefore, four-pump full-power SBLOCA PCTs will bound the PCTs for similar three-pump partial power cases.

7. *The limiting ECCS configuration, including minimum versus maximum ECCS, must be determined for each plant or class of plants using this methodology.*

Response: This restriction is primarily related to LBLOCAs and is not applicable to the SBLOCA analyses. The limiting LBLOCA ECCS configuration is a single ECCS train for CLPD breaks. For this application, the minimum containment pressure derived from a maximum ECCS flow configuration that was applied to the LBLOCA PCT analyses with minimum ECCS injection. This composite approach conservatively considers the worst containment pressure with the minimum ECCS refill capacity to ensure that LBLOCA calculated consequences are bounding for any combination of available ECCS pumps.

In addition to the LBLOCA analyses, a minimum containment pressure analysis using the guidance for LBLOCA applications was performed specifically for use in the SBLOCA CFT line break analyses [3].

8. *For the small break model, the hot channel radial peaking factor to be used should correspond to that of the hottest rod in the core, and not to the radial peaking factor of the 12 hottest bundles.*

Response: There are twelve assemblies modeled in the hot bundle, and each pin is peaked to the hot pin radial value.

9. *The constant discharge coefficient model (discharge coefficient = 1.0) referred to as the "High or Low Break Voiding Normalized Value," should be used for all small break analyses. The model which changes the discharge coefficient as a function of void fraction, i.e., the "Intermediate Break Voiding Normalized Value," should not be used unless the transient is analyzed with both discharge models and the intermediate void method produces the more conservative result.*

Response: This restriction is related only to SBLOCA analyses. A constant discharge coefficient is used for SBLOCA analyses. Verification of this input is performed for each SBLOCA analysis.

10. *For a specific application of the AREVA small break LOCA methodology, the break size which yields the local maximum PCT must be identified. In light of the different possible behaviors of the local maximum, AREVA should justify its choice of break sizes in each application to assure that either there is no local maximum or the size yielding the maximum local PCT has been found. Break sizes down to 0.01 ft2 should be considered.*

Response: This restriction is related only to SBLOCA analyses. The SBLOCA break spectrum (down to 0.005 ft^2 [3]) is performed to determine the local maximum PCT. The break sizes analyzed are chosen to ensure that the local peak has been appropriately defined. The full spectrum of break sizes performed for the Mark-B-HTP fuel at EPU conditions covers this requirement.

11. *B&W-designed plants have internal reactor vessel vent valves (RVVVs) that provide a path for core steam venting directly to the cold legs. The BWNT LOCA evaluation model credits the RVVV steam flow with the loop steam venting for LBLOCA analyses. The possibility exists for a cold leg pump suction to clear during blowdown and then reform during reflood before the evaluation model analyses predict average core quench. Since the REFLOD3B code cannot predict this reformation of the loop seal, AREVA is required to run the RELAP5/MOD2-B&W system model until the whole core quench, to confirm that the loop seal does not reform. This demonstration should be performed at least once for each plant type (raised loop and lowered loop) and be judged applicable for all LBLOCA break sizes.*

Response: This restriction is related only to LBLOCA analyses. This verification analysis was performed using the RELAP5 system model for the 177-FA LL plant design in [53]. The results of that analysis confirmed that a loop seal does not reform prior to whole core quench. Since these results were obtained using the 177-FA LL model, it can be concluded that Restriction #11 of the evaluation model is met for the CR-3 plant.

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*References marked by asterisk (*) are maintained and controlled by Progress Energy. Per AREVA NP procedures, use of these references is allowed in safety-grade calculations with the approval of the project manager. The Project Manager's approval on the signature page authorizes the use of these documents.