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APT PSAR Blanket Safety Analyses Based on Initial Conceptual Design

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by

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Table of Contents

List of Figures

List of Tables

1 Introduction

This report is one of a series of reports that documents normal operation and accident simulations for the Accelerator Production of Tritium (APT) blanket heat removal system, [1-15]. These simulations were performed for the APT Preliminary Safety Analysis Report (PSAR). This report provides a summary of the work that is to be used as a part of revision 0 of Chapter 3 of the PSAR main body and eight supporting appendices that are also to be included in the PSAR. The blanket system contributions for the main body of the PSAR form Section 2 of this report. The summary has been slightly modified to better function as a stand alone document while appendices CB, DB, BA, BB, BC, BD, BE, BF, BG, and BD to this report are identical to those supplied to Los Alamos National Laboratory to be included in the APT PSAR. References [1-22] provide supporting material for the appendices included in the PSAR. Table 1-1 below provides a listing and description of the Appendices attached to this document. Analysis for various sections within Chapter 3 of the PSAR have not been completed and these sections are labeled with 'TBD' (to be determined).

Table 1-1. Listing of current appendices associated with the blanket system and Chapter 3 Revision 0 of the PSAR.

Appendix ID	Appendix Title
CB	A Summary of FLOWTRAN-TF and its Features Relevant to APT Blanket Analyses
DB	Thermal-Hydraulic Design Criteria for the Blanket Primary Heat Removal Systems
BA	Analyses of the Loss-of-Flow Accidents (LOFAs) in the Blanket Primary Heat Removal System
BB	Analyses of the Large-Break Loss-of-Coolant Accidents (LBLOCAs) External to the Cavity Vessel in the APT Blanket Primary Heat Removal System
BC	Analyses of the Large-Break Loss-of-Coolant Accidents (LBLOCA) Internal to the Cavity Vessel in the Blanket Primary Heat Removal System
BD	Analyses of the Small-Break Loss-of-Coolant Accidents (SBLOCA) External to the Cavity Vessel in the Blanket Primary Heat Removal System
BE	Analyses of the Small-Break Loss-of-Coolant Accidents (SBLOCA) Internal to the Cavity Vessel in the Blanket Primary Heat Removal System
BF	Analyses of the Loss-of-Heat Sink Accidents (LOHSA) in the Blanket Primary Heat Removal System
BG	Analyses of the Flow Blockage Accidents (FBA) in the Blanket Primary Heat Removal System
BH	Analyses of the Loss-of-Helium-Gas Accidents (LOHGA) Inside the Target/Blanket Building

2 Nomenclature

In the following section and in the appendices numerous acronyms are used which are defined in earlier locations within the PSAR. Since only those portions of the PSAR related to the blanket system safety analyses is presented below, the following definition of acronyms used is provided:

- A – Anticipated
- APT – Accelerator Production of Tritium
- BDBA – Beyond Design Basis Accident
- BEU – Beyond Extremely Unlikely
- DBA – Design Basis Accident
- EB – External Break
- EU – Extremely Unlikely
- FBA – Flow Blockage Accident
- HRS – Primary Heat Removal System
- ID – Identification Marker
- IB – Internal Break
- LB – Large Break
- LOCA – Loss-of-Coolant Accident
- LOFA – Loss-of-Flow Accident
- LOHGA – Loss-of-Helium Gas Accident
- LOHSA – Loss-of-Heat Sink Accident
- PSAR – Preliminary Safety Analysis Report
- RHRS – Residual Heat Removal System
- SB – Small Break
- SC – Safety Class
- SS – Safety Significant
- SSCs – Systems, Structures, and Components
- TBD – To be determined (or added later)
- T/B – Target/Blanket
- U – Unlikely

3 Chapter 3 Blanket Contribution to Main Body of APT PSAR

The original draft of the PSAR primarily contained information on safety analysis of the APT target system. In some cases, material was taken directly from the original draft PSAR and notes were added to indicate what additional information should be included to describe the blanket system as well. In other cases, entire paragraphs were added to provide information for the blanket system safety analysis. Paragraphs in the PSAR where no additional information for the blanket system was needed have been omitted. Paragraph numbering in this section corresponds to that used in the PSAR. Some of the consequence analyses referred to below are incomplete and will be finalized during later analysis efforts. For the draft PSAR, place holding letters have been inserted in place of actual numbers (e.g., XXX). Section numbers below correspond to those section numbers appropriate to the main body of Chapter 3 in the PSAR.

3.4.2.2 Target/Blanket Systems

The following summary is a narrative of the major design basis accidents for the Target/Blanket. It describes the principal events and the Target/Blanket response. It shows that for all of the design basis events the mitigation systems prevent the T/B primary radionuclide barriers from being damaged. The analyses are done assuming worst-case single-failures occur in the credited mitigating systems simultaneous with the initiating event. As a result, the spallation products in T/B modules are contained for the design basis events. Releases are limited to the activity in the coolant during a LOCA and the small inventory of tritium gas contained in the blanket if there is a double rupture of the blanket cooling system and tritium gas system.

A number of cases are evaluated to ensure that design features necessary to provide protection under all circumstances are evaluated. For each accident event sequences are presented in event trees. The salient points of each sequence is presented in a table including the event sequence number, the event sequence frequency, a summary of the analysis, the consequences, and the conclusions particularly with respect to classification SSCs.

For the target and blanket analysis a separate appendix was prepared for each accident type. These appendices cover the scenario development, the source term determination, consequences, comparison to guidelines, and a summary of safety-class SSCs and TSR controls. In addition, the appendices cover the beyond-DBAs (BDBAs) for their particular accident type. In this part of the PSAR a summary of all of the T/B DBAs and BDBAs is presented based on the information presented in the appendices.

For ease of comprehension the T/B DBAs have been divided into five DBAs for beam operations and three DBAs for retargeting operations.

3.4.2.2.1 T/B Design Basis Accidents During Beam Operation

These accidents can be grouped into LOFAs, LOCAs, LOHSAs, and beam misfocusing and misalignment accidents.

3.4.2.2.1.1 Loss of Flow Accidents (LOFA)

3.4.2.2.1.1.2 Blanket LOFA

The details of the blanket LOFA analyses are presented in Appendix BA. The discussion provided in Appendix BA is summarized in the following subsections.

Once initiated, this event can be detected by the following measurements:

- loss of electrical current to the pump,
- reduction in pump impeller speed,
- reduction in system flow,
- increase in system temperature, and
- increase in system pressure (or decrease in differential pressure).

Upon detection of the upset conditions, the following mitigative actions are taken:

1. The beam is shut down.
2. Following the beam shutdown, the RHRS pumps are started. There are two independent RHRS loops, each capable of removing the total decay heat in the blanket. The RHRS pumps are battery operated. If extended service is required, diesel generators also are available.
3. In the unlikely event that neither one of the RHRS pumps can be activated, the cavity flood is the next step in the mitigation. Independent and diverse means are available to actuate the cavity flood valves.

It is important that the upset conditions that result in a LOFA do not result in losing the detection and/or mitigation capabilities. In general, an independent power source is provided for each critical instrument train, such that the loss of site power does not disable the critical instruments. Furthermore, the detection instruments are designed to fail safe such their failure automatically results in beam shutdown. Finally, for events that result in pressurizing the cavity by causing a LOCA, the beam is automatically shut down passively without relying on the primary HRS signals for upset conditions.

Similar to the target HRS, there are two types of blanket LOFA events, those with flow coastdown and those without flow coastdown. The LOFA with flow coastdown can occur as a result of loss-of-electrical power. This LOFA is an anticipated event with an annual probability of about 0.1/yr. The mitigation for the accident is to shut down the beam and remove decay heat using the RHRS. The LOFA without a coastdown can occur as a result of a pump locked rotor, shaft break, or a valve closure. This type of event is in the unlikely frequency range. Currently, the design does not include any power actuated valves in the Primary HRS. If a pump seizes, the flow coastdown in that pump is abrupt, but because the system has more than one pump in parallel the resulting flow would be greater than 50%. Mitigation for this event is the same as for the LOFA with a coastdown.

To summarize the set of analyses for blanket only LOFAs performed to date:

- without and with beam shutdown can result in overheating of blanket modules if no further mitigative actions are taken;
- for the case with beam shutdown 5-to-7 days are available for corrective actions to be taken prior to potential overheating; and
- activation of either (or both) the RHRS or the Cavity Flood System mitigates the accident such that reuse of the blanket components is acceptable.

LOFA With Pump Coastdown

These blanket LOFAs are very similar to their corresponding target LOFAs and they are fully mitigated without damage or consequences to the workers, public, or the environment for the design basis case with beam shutdown and cooling mitgation. The mitigation cooling is provided by the RHR system or the backup Cavity Flood System.

For the unmitigated LOFA, Sequence a1, where there is no beam shutdown, the blanket modules will overheat losing their structural support and then either begin melting or slumping over. The direct consequences of melting the blanket are small as shown in Table 3.4-12. However, if the blanket structurally fails and slumps it can cause damage to the target, resulting in mechanical damage to the Inconel cladding. Under these conditions it is assumed, for a completely unmitigated LOFA in the blanket, that the source term would conservatively include all of the target tungsten. This is the result of bounding analyses and there are many reasons why the consequences would be less.

For the partially mitigated blanket LOFA, represented by Sequence a2, with beam shutdown but without RHR or cavity flood, calculations indicate that natural circulation will provide sufficient cooling so that the full heat capacity of the blanket primary HRS and of the shell sides of the blanket primary heat exchangers can be credited. This extends the time until the blanket will reach saturation conditions to approximately seven plus days, which will provide ample time for the operators to take corrective action to restore RHR or flood the cavity. However, the allowable stresses for aluminum decrease rapidly with temperature so that coupled structural and thermal analyses are required to demonstrate the level of adequacy and allowable response times available for this case. For longer times, axial heat conduction to the upper and lower thermal shields (representing sizable heat sinks) can be credited. These analyses are currently underway.

Event Sequence a3 represents the case where the beam is shutdown but the preferred mitigation using the RHR system is not available. Under this case the cavity flood would be initiated and analyses show that the cavity flood would mitigate the LOFA.

Event Sequence a4 is the preferred accident mitigation with a beam shutdown and operation of the RHRS. Parametric analyses indicate that more than adequate response time exists for shutting down the beam and activating the RHRS. Under representative response times coolant and metal temperatures within the blanket primary HRS do not exceed normal operating values.

Event Sequence a5 is the case where the beam is shutdown and RHR along with cavity flood are initiated. The cavity flood system is activated only if the RHRS becomes unsuccessful in mitigating the sequence based on monitored fluid temperatures. The actuation of cavity flood does not interfere with the cooling capability of the operating RHRS and only assists in the removal of decay heat by further blanket temperature reductions.

LOFA Without Pump Coastdown

Table 3.4-13 summarizes the results for LOFA without pump coastdown. These blanket LOFAs are very similar to their corresponding blanket LOFAs with flow coastdown and they are fully mitigated without damage or consequences to the workers, public, or the environment for the design basis case with beam shutdown and cooling mitgation. The mitigation cooling is provided by the RHR system or the backup Cavity Flood System. Whether the automatic action will include tripping the operating pump has not been determined. Once the beam is shut down one operating primary pump or one operating RHR pump will remove the decay heat.

Event sequence b1, the case of the LOFA without flow coastdown and without a beam shutdown, will have the same results as with pump coastdown: the blanket will be damaged and it is assumed that a significant fraction of the tungsten released.

For the event sequences b2, b3, b4, and b5, their analysis results are similar to their corresponding sequences under a LOFA with flow coastdown. The only differences being the shorter flow coastdown that occurs and the slight increase in temperatures early on in the events.

3.4.2.2.1.1.2.1 Scenario Development

As discussed in Section 3.3.2.3.4, multiple initiators are identified for a blanket only LOFA. These initiators are binned into two unique types of LOFA for further analyses:

- LOFA with pump coastdown; and
- LOFA without coastdown in one pump or in both pumps.

Representative event trees for these two types of LOFA are shown in Figure 3.4-13. Figure 3.4-13a corresponds to a LOFA with pump coastdown (initiated by loss-of-electrical power) and Figure 3.4-13b corresponds to a LOFA without pump coastdown (initiated by mechanical pump failure). In Figures 3.4-13 (a) and (b), the sequences are numbered starting from fully unmitigated (a1 and b1) towards the mitigated. An analytic discussion of all the sequences shown in Figure 3.4-13 is provided in the next section.

3.4.2.2.1.1.2.2 Blanket LOFA Source Term and Consequence Analyses

The analyses of the event sequences shown in Figure 3.4-13 are presented in Appendix BA. The results of the analyses and the conclusions are summarized in Tables 3.4-12 and 3.4-13.

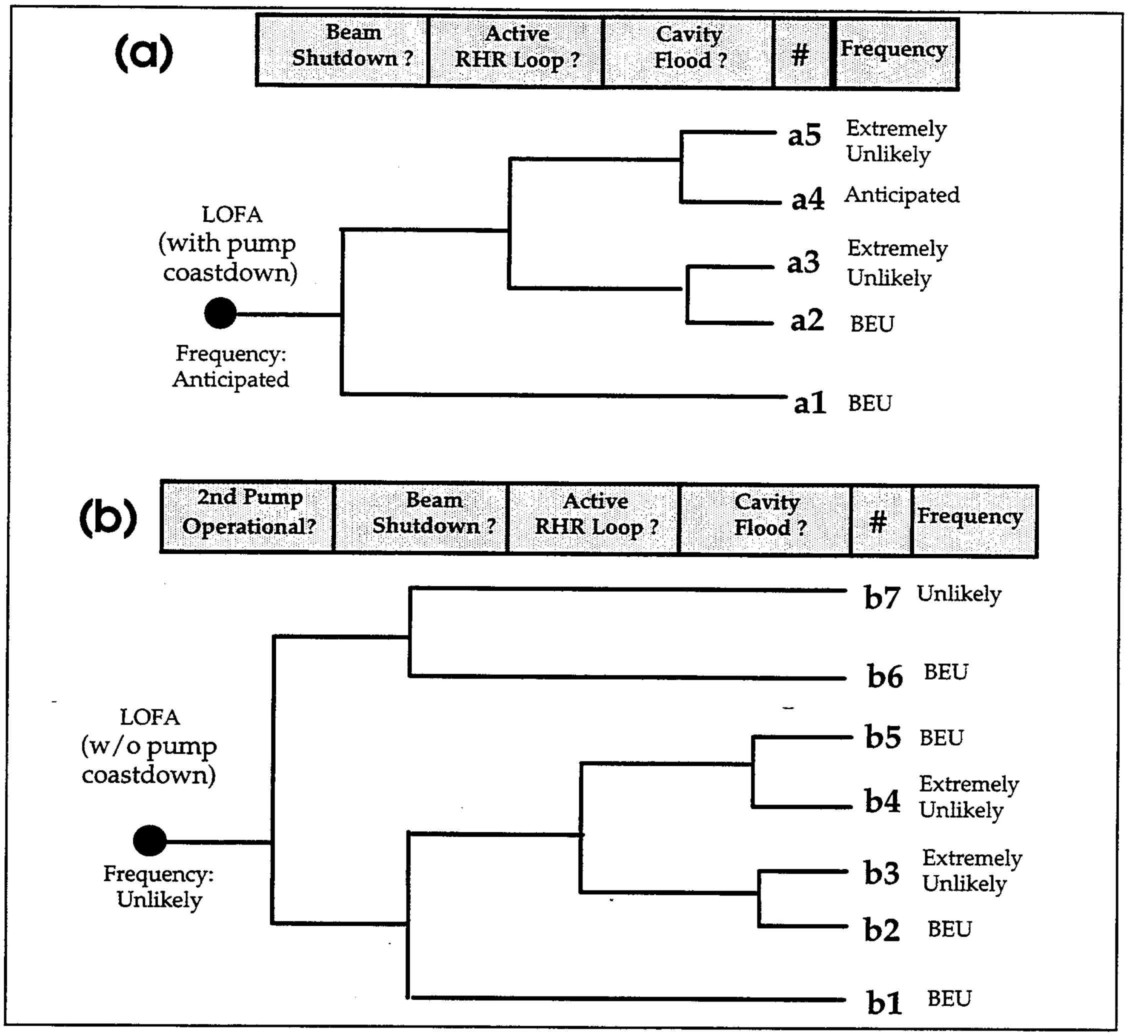

Figure 3.4-13. Blanket LOFA event trees.

Table 3.4-12. Summary of the Analyses for the Blanket LOFA Sequences with Coastdown

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
a1	BEU	**LOFA without Beam Shutdown.** For a blanket only LOFA without a beam shutdown, it is conservatively assumed that the blanket would overheat leading to severe damage and could lead to damaging neighboring target components. It is assumed that a large fraction of the tungsten inventory may oxidize and be released to the environment.	Offsite = 70 (target) = 0.24 (Blanket)	Structural failure of blanket modules lead to structure failure of target components.

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
a2	BEU	**LOFA with Beam Shutdown.** In this analysis the system transitions into natural circulation and slowly heats up to saturation. The calculation assumes the piping systems are design features. No ultimate heat sink is assumed since circulation of secondary coolant to the heat exchangers is assumed to be zero; therefore, at some point administrative actions must be taken. It takes 200 hours to reach bulk boiling in the blanket. At this point maximum aluminum temperatures are ~170 °C. The structural endurance limit for reuse of components is 150 °C for 10,000 hr. Structural analyses are being performed to determine the material limits where blanket structural failureoccurs. Alternatively, if operators depressurize the HRS so it has a lower boiling temperature after 140 hours, aluminum temperatures can be maintained below 150 °C. Additional analyses are in progress: (1) to extend the analysis time based on boil-off considerations and (2) to see if temperatures can be maintained by conduction cooling to neighboring structures within the cavity vessel.	None	The beam shutdown system performs a safety-class function. System pressure boundaries are safety-significant. Five days exist prior to the need for administrative actions (e.g., pressure relief valve opening).
a3	EU	**LOFA with Beam Shutdown and Cavity Flood.** Upon actuation of the Cavity Flood System, all blanket modules and thermal shields are submerged under subcooled water within 100 s. At 100 s, assuming that an instantaneous loss (i.e., dryout) of all module liquid inventory has occurred, bounding analysis indicates that the conductive capability of the plate-type modules maintains metal temperatures below the structural endurance limit for reuse of components (currently set to 150 °C for 10,000 hr). These analyses demonstrate in a bounding manner the effectiveness of the Cavity Flood System's mitigative capability.	None	Cavity flood performs a safety-significant function.*

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
a4	A	**LOFA with Beam Shutdown and RHRS.** This is the design basis case. Parametric analyses indicate that the beam shutdown and RHRS pump startup can be delayed as long as 30 s into the LOFA while maintaining adequate margins from incipient boiling or material structure limits. Under expected LOFA detection and RHRS actuation times, RHRs cooling will result in a negligible increase in coolant and metal temperatures beyond pre-incident normal operating temperatures.	None	RHRS system provides a safety-significant function and is the preferred mitigation strategy for a blanket only LOFA.
a5	EU	**LOFA with Beam Shutdown, RHRS and Cavity Flood.** The Cavity Flood System is activated only if the RHRS becomes unsuccessful in mitigating the event based on monitored fluid temperatures. However, the action of flooding the cavity vessel does not interfere with the cooling capability of an operating RHRS. As such, this event is bounded by sequences a3, b3, a4 and b4.	None	The cooling capability of neither the RHRS or the Cavity Flood System are diminished as a result of dual activation.

* The Cavity Flood System is being designed to safety-class standards to provide worker safety and investment/mission protection.

Table 3.4-13. Summary of the Analyses for the Blanket LOFA Sequences without Coastdown

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
b1	BEU	**LOFA without Beam Shutdown.** For a blanket only LOFA without a beam shutdown, it is conservatively assumed that the blanket would overheat leading to severe damage and could lead to damaging neighboring target components. It is assumed that a large fraction of the tungsten inventory may oxidize and be released to the environment.	Offsite ≈ 70 (target) ≈ 0.24 (Blanket)	Structural failure of blanket modules lead to structure failure of target components.

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
b6	BEU	**Single Pump Failure without Beam Shutdown.** Bounded by sequences a1 and b1. Using best-estimate calculation, 50% of total flow may be sufficient to remove the beam power without exceeding thermal onset and material temperature limits. Results of these analyses will be provided in the next PSAR revision.	Offsite << 30 (target) = 0.24 (Blanket)	The beam shutdown system performs a safety-class function
b2	BEU	**LOFA with Beam Shutdown.** The analysis and consequences for this sequence are similar to the those provided in sequence a2. Without the spare pump a shorter coastdown period occurs during this sequence resulting in a modest increase in system temperatures early on. However, at low decay powers the massive blanket structures have significant sensible heat-up times. Therefore, computed times given under the analysis of sequence a2 are only slightly shorter.	None	The beam shutdown system performs a safety-class function. System pressure boundaries are safety-significant Nearly five days exist prior to the need for administrative actions (e.g., pressure relief valve opening).
b3	EU	**LOFA with Beam Shutdown and Cavity Flood.** The analysis and consequences for this sequence are similar to the those provided in sequence a3. Without the spare pump a shorter coastdown period occurs during this sequence resulting in a modest increase in system temperatures early on. However, the bounding analysis performed for sequence a3 remains bounding for this sequence as well.	None	Cavity flood performs a safety-significant function. *
b5	EU	**LOFA with Beam Shutdown, RHRS and Cavity Flood.** The Cavity Flood System is activated only if the RHRS becomes unsuccessful in mitigating the event based on monitored fluid temperatures. However, the action of flooding the cavity vessel does not interfere with the cooling capability of an operating RHRS. As such, this event is bounded by sequences a3, b3, a4 and b4.	None	The cooling capability of neither the RHRS or the Cavity Flood System are diminished as a result of dual activation.

Seq #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
b4	EU	**LOFA with Two-pump failure with Beam Shutdown and RHRS.** The analysis and consequences for this sequence are similar to the those provided in sequence a4. Without the spare pump a shorter coastdown period occurs during this sequence resulting in a modest increase in system temperatures early on. Due to the significant allowable response times available within sequence a4, the consequences determined for sequence a4 apply for this sequence as well.	None	RHRS provides a safety-significant function and is the preferred mitigation strategy for a blanket only LOFA.
b7	U	**LOFA with Single Pump Failure with Beam Shutdown.** With a beam shutdown, a single primary HRS pump delivering more than 50% flow is more than adequate to remove the decay heat. This sequence is bounded by the sequences a4 and b4 where the RHRS delivers only 4% flow per train. The potential of HRS pump cavitation will be analyzed and address in the next PSAR revision.	None	

* The Cavity Flood System is being designed to safety-class standards to provide worker safety and investment/mission protection.

3.4.2.2.1.1.2.3 Summary of SSCs and TSR Controls

For the Blanket LOFA analyses, the credited controls are summarized in Tables 3.4-14 A and B.

Table 3.4-14A. Summary of Blanket LOFA Mitigation SSCs

SSC	Requirement or Setting	Classification
Beam Shutdown	Shut down the proton beam when signaled as shown in table 3.4-14B below.	Safety-class
Residual Heat Removal System	Provide single failure proof residual heat removal for the blanket when signaled as shown in table 3.4-14B below.	Safety-significant
Cavity Flood System	Provide a means to flood the cavity passively when initiated manually or automatically as shown in table 3.4-	Safety-significant, designed to safety-class standards

SSC	Requirement or Setting	Classification
	14B below.	

Table 3.4-14B. Setpoint Requirements for SSCs for Blanket LOFA*

	Beam Shutdown (SC, automatic)	RHRS Start-up (SS, automatic)	Cavity Flood (SS, Manual)
Pump Current	= 75% of nominal	= 75% of nominal	NA
Pump Speed	= 75% of nominal	= 75% of nominal	NA
Coolant Flow Rate	= 75% of nominal	= 75% of nominal	NA
Coolant Temp.	5°C above maximum operational temperature	5°C above maximum operational temperature	NA
RHR Flow Rate	NA	NA	= 90% of nominal after 10 min
RHR Coolant Temp.	NA	NA	5°C above maximum operational temperature after 10 min

* Due to the evolving design the setpoint requirements provided above are tentative and are subject to change in later PSAR revisions.

In the analyses summarized in this section, some assumptions are made with respect to the evolving design features and the results of the experimental program. These assumptions are listed, and a discussion of the future analyses needs is presented in Appendix BA.

3.4.2.2.1.1.3 Combined Target and Blanket LOFA

Analyses for combined target and blanket LOFAs are discussed in Appendix TBA. Note that each HRS has its on individual RHRS, while actuation of the Cavity Flood System provides mitigative benefit to both the target as well as the blanket SSCs. As discussed above under LOFAs isolated to their respective HRS (i.e., target or blanket), RHRS and Cavity Flood System are designated as *safety significant* functions. In addition, the Cavity Flood System is being designed to safety class standards (mainly for worker protection and investment/mission protection).

TBD

3.4.2.2.1.1.5 Blanket LOFA Caused by Flow Blockage

Analyses for blanket LOFAs caused by flow blockages are discussed in Appendix BG.

TBD

3.4.2.2.1.2 Loss-of-Coolant Accidents (LOCA)

3.4.2.2.1.2.3 Blanket Large-Break LOCA External to Cavity

The details of the external large-break LOCA (LBLOCA) analyses for the blanket are presented in Appendix BB. The locations of the external LBLOCAs analyzed in Appendix BB are shown in Figure 3.4-14 (labeled points A, B, C, D, and E). The discussions provided in Appendix BB are summarized in the following sections.

Once initiated, this event can be detected by the following measurement sensors:

- reduction in system pressure,
- decrease in pressurizer liquid level, and
- increase in building radiation monitoring near the break location.

Upon detection of the accident conditions, the following actions are designed to be taken to mitigate the consequences of this event:

1. Upon detection of low system pressure, the beam is shut down.
2. The pumps in the primary HRS are shutdown.
3. Following the beam shutdown, the RHRS primary and secondary pumps are started (typically, with about a 15 s ramp-up period). There are two independent (100%-capacity) RHR loops, each capable of removing the total decay heat from the blanket modules. The RHR pumps (i.e., primary and secondary side) are battery operated. If extended service becomes necessary, diesel generators are available.
4. In addition to the low-pressure signal, if the LOCA results in low pressurizer level, the Cavity Flood System is activated.
5. In the very unlikely event that the Cavity Flood System cannot be actuated to mitigate the initiating event, various other corrective/administrative measures can be taken (such as, replenishing through purification lines the primary HR coolant that is boiled-off).

Section 3.4.2.2.1.2.3.3 provides trip and control points for various key parameters associated with the design safety features considered in the event-tree for external LBLOCA analyses.

The location of the break, as shown in Figure 3.4-14, during an external LBLOCA results in different system responses. The system responses may be different depending on the size of broken pipe and its break location relative to other key primary HR components, such as the pressurizer and pumps. The five break locations selected for the external LBLOCA simulations are listed in Table 3.4-15. These break locations were chosen since they are believed to provide bounding locations for the present analyses.

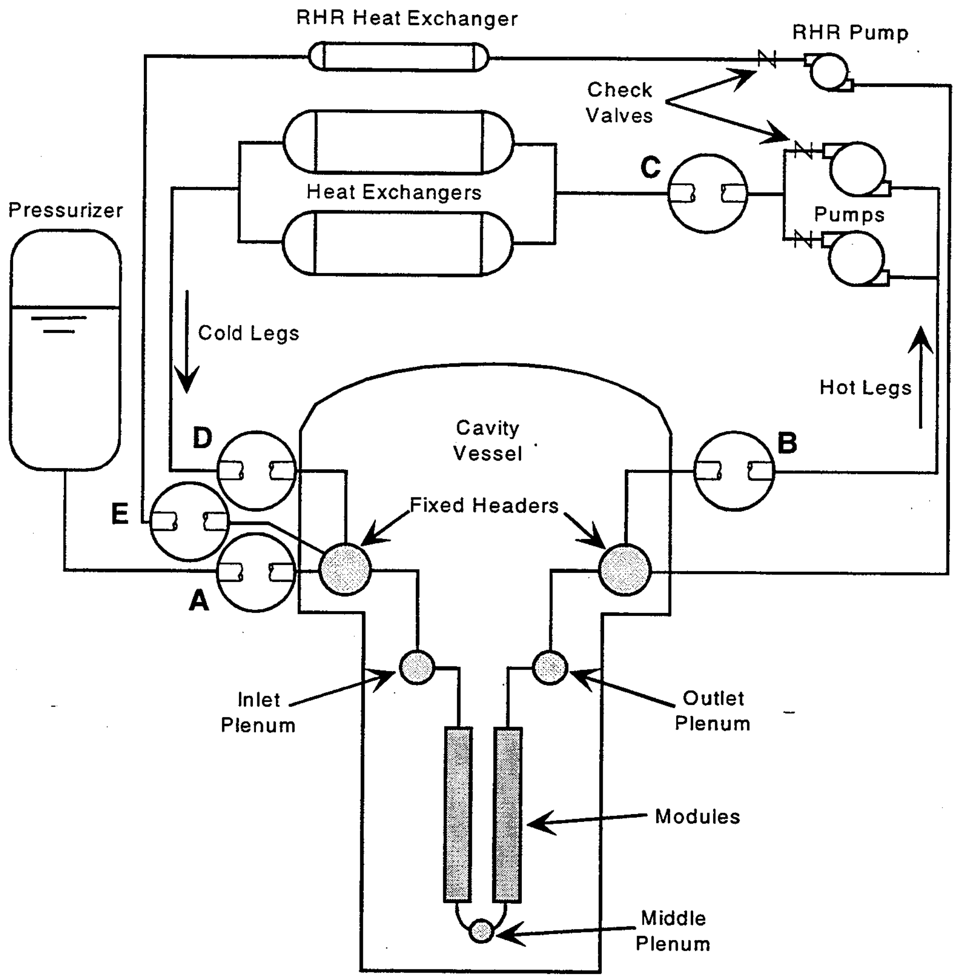

Figure 3.4-14. Schematic flow diagram for the Blanket primary HRS.

The blanket LOCAs are similar to the target LOCAs. The mitigation strategy is the same(i.e., shut down the beam and operate the RHR system). If the level in the pressurizer decreases to the low-level setpoint the cavity flood would be initiated. For the design basis events, the blanket material temperatures will be maintained below their structural endurance limit for reuse of components (~150 °C for 10,000 hr) and the consequences will be limited to the coolant activity and possibly the small amount of tritium in the helium gas system. The consequences are listed in Table 3.4-16.

The Sequence 1 unmitigated consequences for the blanket LOCA are like the blanket LOFA. The blanket source term itself is small, but failure of the blanket could damage the target cladding. Table 3.4-16, therefore, shows the unmitigated source terms from the blanket and the target individually.

For the partially mitigated external to the vessel blanket LBLOCA, represented by Sequence 2, with beam shutdown but without RHR or cavity flood, calculations indicate that boil-off of coolant inventory in isolated module units extends the time until the hottest module begins to be uncovered to approximately 22 hours. This should be ample time for the operators to take corrective action to activate RHR, flood the cavity, or provide an external source of makeup water (~1 gpm). Even though the primary HRS pumps remain operative, once pump cavitation occurs net pumping action diminishes. By increasing the rate of inventory loss, the HRS pumps reduce the available time until the blanket modules become isolated from their common fixed headers. Tripping the primary HRS pumps, Sequence 6, would push out in time the point where the heat up to saturation and the onset of bulk boiling begins. For longer times, axial heat conduction to the upper and lower thermal shields (representing sizable heat sinks) can be credited. These analyses are currently underway.

Additional analysis is required to determine if the blanket would fail if cooling were not re-established. However, these cases are bounded by the Sequence 1, the completely unmitigated results. Event Sequence 3 represents the case where the beam is shut down but the preferred mitigation using the RHRS is not available In this case, the cavity flood would be initiated. The early portion of this event sequence is similar to Sequence 2 prior to covering the blanket modules with subcooled water during the cavity flood process (i.e., the primary HRS pumps eventually cavitate). As discussed earlier, upon actuation of the Cavity Flood System, all blanket modules and thermal shields are submerged under subcooled water within 100 s. Beyond this 100 s the bounding analyses provided for Sequence a3 of a Blanket only LOFA apply. These analyses show that the cavity flood would mitigate the LBLOCA.

Event Sequence 4 represents the case of a LBLOCA with beam shutdown and activation of the RHRS. For the case of a pump discharge break (location C in Figure 3.4.14.), TRAC predicts that there is a period of time when air is entrained in the system from the break and passes through the blanket, where void fractions up to 50% result. TRAC and FLOWTRAN-TF predict that this air passes on through the blanket modules and single-phase flow conditions are re-established in the blanket and the blanket material temperatures are maintained below the structural endurance limit, as well as their normal operation limits. Throughout the event coolant conditions remain significantly subcooled.

Sequence 5 is the case where the beam is shutdown and RHR along with cavity flood are initiated. The RHRS is activated based on the rapid pressure loss in the HRS. If the level in the pressurizer decreases to the low-level setpoint the cavity flood would be initiated. The actuation of cavity flood does not interfere with the cooling capability of the operating RHRS and only assists in the removal of decay heat by further blanket temperature reductions.

Sequences 7, 8, and 9 are similar in behavior to Sequences 3, 4, and 5, respectively. The tripping of the primary HRS pumps reduce the rate of inventory loss during these events; thereby, reducing their consequences when compare to their counterparts associated with no pump trips. Within Sequence 8 there exists one unique case requiring additional consideration. The unusual aspect about this scenario is that the active RHRS does not mitigate but instead aggravates the situation. This case occurs when the break location is located on the pump discharge side of one of the RHR loops (location E in Figure 3.4-14.) while this system's RHR primary pump is also activated. The worst case single-failure assumes the remaining RHRS is inoperative. Preliminary calculations indicate that neither pump cavitation nor pump dead head conditions are reached prior to the removal of a significant fraction of the coolant inventory from the module units. The time to uncover the blanket modules by RHR pumping is beyond 950 s due to pressurizer inventory reduction. This particular sequence could be mitigated by isolating the affected RHR loop or turning off its pump. In either event, automatic operation of the Cavity Flood System when the pressurizer level decreases below the cavity flood set point will mitigate the consequences.

Table 3.4-15. Break locations of external LBLOCAs discussed in Appendix BB.

Break Location in Figure 3.4-14.	Reference Name used in Appendix BB	Pipe size for external LBLOCA simulations (ID)
A	Pressurizer surge-line break	6.065" (6" schedule 40)
B	Hot leg break	18.814" (20" schedule 40)
C	Pump discharge line break	15.000" (16" schedule 40)
D	Cold leg break	18.814" (20" schedule 40)
E	RHR cold leg break	6.065" (6" schedule 40)

3.4.2.2.1.2.3.1 Blanket LBLOCA Scenario Development

Initiating events for blanket external LBLOCAs are similar to those for the TNS, which are discussed above. Upon loss of coolant inventory due to a break of a large pipe in the blanket primary HRS external to the cavity vessel, system pressure drops rapidly and heat removal capacity of the blanket HRS suddenly decreases. The event tree shown in Figure 3.4-15 is applicable to all the external LBLOCAs, regardless of the break locations (as well as for target or blanket HRSs). The sequences are numbered starting from fully unmitigated towards the mitigated. An analytic discussion of all the sequences shown in Figure 3.4-4 are provided in the next section.

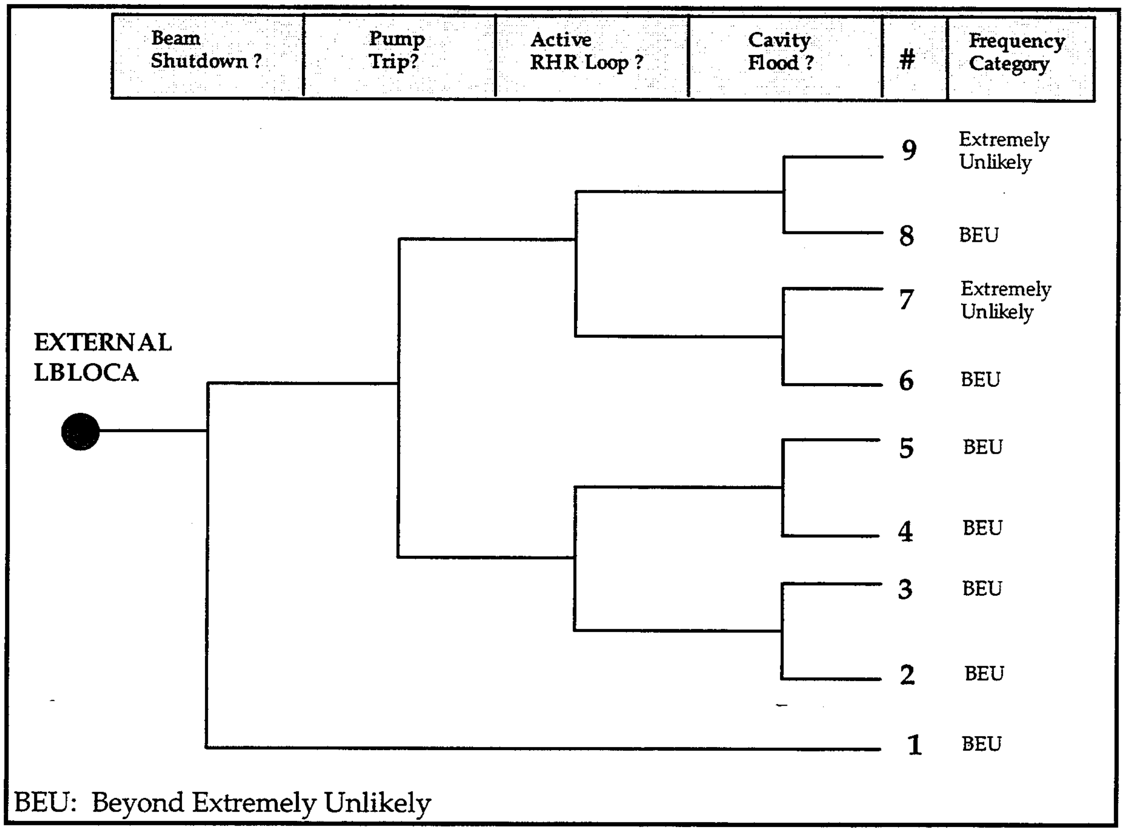

Figure 3.4-15. Event tree for an external Blanket LBLOCA.

3.4.2.2.1.2.3.2 Blanket LOCA Source Term and Consequence Analyses

The analyses of the event sequences shown in Figure 3.4-15 are presented in Appendix BB. The results of the analyses and the conclusions are summarized in Table 3.4-16.

Table 3.4-16. Summary for the Analyses for the Blanket External LBLOCA Sequences.

Seq #	Freq (yr-1)	Summary of Analyses	Conseq. (rem)	Conclusions
1	BEU	**External LOCA without Beam Shutdown.** For a blanket only LBLOCA without a beam shutdown, it is conservatively assumed that the blanket would overheat leading to severe damage and could lead to damaging neighboring target components. It is assumed that a large fraction of the tungsten inventory may oxidize and be released to the environment.	Offsite = 70 (Target) = 0.24 (Blanket)	Structural failure of blanket modules lead to structure failure of target components.

Seq #	Freq (yr-1)	Summary of Analyses	Conseq. (rem)	Conclusions
2	BEU	**LOCA with Beam Shutdown.** For this case the primary HRS pumps continue to operate until they cavitate breaking seal with no further coolant loss by pumping action. The flow coastdown provides adequate initial cooling and this period is extended out to 950 s (diminished by HRS pumping) as a result of pressurizer inventory losses. Conservatively assuming complete loss of flow to the headers beyond 950 s, adiabatic heat-up of the hottest module to saturation (~ 116°C) occurs at 4 hr. Beyond 4 hr bulk boiling within the module occurs until the top of the modules are uncovered at ~22 hr. After the modules begin to uncover they heat up further and potentially exceed their structural temperature limit of 150°C. After XX hours there is ample time for operators to take corrective action by providing ~1.0 gpm makeup water to prevent uncovering modules or to initiate cavity flood.	Offsite = 0.03 (The only source term is the activity in the coolant. See App SA.)	The beam shutdown system performs a safety-class function. Pump shutdown performs a safety-significant function in support of the RHRS function.
3	BEU	**LOCA with Beam Shutdown and Cavity Flood.** Calculations show that the pumps eventually cavitate. Upon actuation of the Cavity Flood System, all blanket modules and thermal shields are submerged under subcooled water within 100 s. After 100 s, the conductive capability of the plate-type modules maintains metal temperatures below the structural endurance limit for reuse of components (currently set to 150 °C for 10,000 hr). These analyses demonstrate in a bounding manner the effectiveness of the Cavity Flood System's mitigative capability.	Offsite = 0.03 (The only source term is the activity in the coolant. See App SA.)	Cavity flood mitigates the accident, independent of the RHRS operations. Cavity flood serves a safety-significant* function and will be built to safety-class criteria.

Seq #	Freq (yr-1)	Summary of Analyses	Conseq. (rem)	Conclusions
4	BEU	**LOCA with Beam Shutdown and RHRS but Without Pump Trip.** Throughout the event coolant conditions remain significantly subcooled. For the case of a pump discharge break, there exists a period of time when air (void fractions up to 50%) are present. Calculations predict that this air passes on through the blanket modules and single-phase flow conditions are re-established. The blanket material temperatures are maintained below the structural endurance limit, as well as their normal operation limits.	Offsite = 0.03 (The only source term is the activity in the coolant. See App SA.)	The RHRS performs a safety-significant defense-in-depth function. Pump trip is a safety-significant feature for this accident.
5	BEU	**LOCA with Beam Shutdown, RHRS and Cavity Flood but without Pump Trip.** This sequence is bounded by sequences 3 and 4 above.	Offsite = 0.03 (The only source term is the activity in the coolant. See App SA.)	The RHRS performs a safety-significant defense-in-depth function.
6	BEU	**LOCA with Beam Shutdown and Primary Pump Shutdown.** Bounded by the analysis for Sequence 2. Tripping the primary HRS pumps push out in time the point where the heat up to saturation and the onset of bulk boiling begins.	Offsite = 0.03 (The only source term is the activity in the coolant. See App SA.)	See Sequence 2.
7	EU	**LOCA with Beam and Primary Pump Shutdown and Cavity Flood.** This sequence is bounded by the analyses for Sequence 3 above.	See Sequence 3.	See Sequence 3.

Seq #	Freq (yr-1)	Summary of Analyses	Conseq. (rem)	Conclusions
8	BEU	**LOCA with Beam and Primary Pump Shutdown and RHRS.** Transient analyses discussed in Appendix BB show that RHRS is sufficient to mitigate the external LBLOCA without cavity flood. However, because all possible break locations are not analyzed (e.g. break in the RHRS line) and, considering the low probability of an external LBLOCA, cavity flood is activated upon loss-of-pressurizer inventory. Within Sequence 8 there exists one unique case requiring additional consideration. This case occurs when the break location is located on the pump discharge side of one of the RHR loops while this system's RHR primary pump is also activated. Preliminary calculations indicate that the active RHR pump removes a significant fraction of the coolant inventory from the module units. The time to uncover the blanket modules by RHR pumping is beyond 950 s due to pressurizer inventory reduction. This particular sequence could be mitigated by isolating the affected RHR loop or turning off its pump. In either event, automatic operation of the Cavity Flood System when the pressurizer level decreases below the cavity flood set point will mitigate the consequences.	Offsite = 0.03 The only source term is the activity in the coolant. See App SA.)	It is expected that cavity flood will be activated in addition to RHRS. Detection of break in an active RHRS would help mitigate conditions.

Seq #	Freq (yr-1)	Summary of Analyses	Conseq. (rem)	Conclusions
9	EU	**LOCA with Beam and Primary Pump Shutdown , RHRS and Cavity Flood.** This is the design basis case. For most break locations one of the RHRS will mitigate the external LOCAs. At least one break location in the RHRS can result in a loss of forced circulation. For these cases cavity flood is necessary and sufficient. The RHRS provides defense-in-depth and maintains material temperatures much cooler than cavity flood alone. The mitigation strategy calls for shutting down the beam and the operating primary coolant pumps if pressure decreases below the setpoint. If the break is large enough to cause a loss of pressurizer inventory below the cavity flood setpoint, then the cavity flood is initiated.	None	See Sequences 3 and 8.

3.4.2.2.1.2.3.3 Summary of SSC and TSRs for Blanket LOCA Mitigation

For the blanket external LBLOCA analyses, the credited controls are summarized in Tables 3.4-17 A and B. In the analyses summarized in this section, some assumptions are made with respect to the evolving design features and the results of the experimental program. These assumptions are listed, and a discussion of the future analysis needs is presented in Appendix BB.

Table 3.4-17A. Summary of Blanket External LBLOCA Mitigation SSCs.

SSC	Requirement or Setting	Classification
Beam Shutdown	Shut down the proton beam when signaled as shown in table 3.4-17B below.	Safety-class
Residual Heat Removal System	Provide single failure proof residual heat removal for the blanket when signaled as shown in table 3.4-17B below.	Safety-significant
Cavity Flood System	Provide a means to flood the cavity passively when initiated manually or automatically as shown in table 3.4-17B below.	Safety-significant, designed to safety-class standards
Blanket Primary Coolant Pump Shutdown During LOCAs	The blanket primary HRS pumps should be shutdown during LOCAs to prevent loss of inventory.	Safety-significant

Table 3.4-17B. Setpoint Requirements for Blanket External LBLOCA Mitigation*.

	Beam Shutdown (SC, automatic)	Pump Shutdown RHRS Start-up (SS, automatic)	Cavity Flood (SS, automatic)
Coolant Flow Rate	75% of nominal	75% of nominal	NA
Coolant Temp.	5°C above maximum operational temperature	5°C above maximum operational temperature	NA
System Pressure	90% of nominal	75% of nominal	2 atm
Pressurizer Level	90% of nominal	75% of nominal	25% of nominal

* Due to the evolving design the setpoint requirements provided above are tentative and are subject to change in later PSAR revisions.

3.4.2.2.1.2.4 Blanket Large-Break LOCA Internal to the Cavity

The analyses for these accidents have not yet been completed but the consequences are expected to be similar to the external large-break LOCAs. The internal large-break analyses will be completed (and provided in the next PSAR revision) because differences in the accident response could result in requirements that necessitate design changes for adequate mitigation.

TBD

3.4.2.2.1.2.7 Blanket Small-Break LOCA External to Cavity

TBD

3.4.2.2.1.2.8 Blanket Small-Break LOCA Internal to Cavity

TBD

3.4.2.2.1.3 Loss-of-Heat-Sink Accidents (LOHSA)

3.4.2.2.1.3.2 Blanket LOHSA

TBD

3.4.2.2.1.3.3 Combined Target and Blanket LOHSA

TBD

3.4.2.2.1.6 T/B Loss-of-Helium-Gas Accidents (LOHGA)

Inside the Target/Blanket building the loss-of-helium-gas accidents (LOHGA) occur due to ruptures in the helium supply system such as:

- external to the vessel manifolds or inlet/outlet piping penetrating through the cavity vessel wall;
- internal to the vessel manifolds or inlet/outlet piping penetrating through the cavity vessel wall;
- internal to a blanket module manifolds (or plenums) distributing helium throughout the module; and
- helium tubes internal to a blanket module receiving helium from the internal manifolds

There are two types of Target/Blanket building LOHGAs: (1) those internal to a module (i.e., internal break (IB) LOHGAs) where helium gas enters the blanket system's primary HRS coolant; and (2) those external to a module (i.e., external break (EB) LOHGAs) where helium gas does not enter the blanket system's primary HRS coolant.

3.4.2.2.1.6.1 Blanket Internal-Break LOHGA

The details of the blanket internal-break loss-of-helium-gas accident (IBLOHGA) analyses are presented in Appendix BH. There are two types of IBLOHGA events, those with the pressure-relief valve closed and those with pressure-relief valve opened. The discussion provided in Appendix BH is summarized in the following sections.

Once initiated, IBLOHGA events can be detected by the following measurements:

- increase in blanket HRS pressure,
- decrease in helium reservoir pressure,
- decrease in blanket HRS flowrate,
- increase in blanket HRS temperatures, and
- increase in monitored radiation near the rupture location.

Upon detection of the upset conditions (dependent upon the pressure-relief valve status), the following mitigative actions are taken:

1. The beam is shut down manually for pressure-relief valve closed events and automatically for pressure-relief valve stuck open events.
2. Following the beam shutdown, under pressure-relief valve closed conditions the primary pumps may remain operational. However, under pressure-relief valve opened conditions eventual system inventory losses will trip the primary pumps and the RHRS pumps will be started.

IBLOHGA with pressure relief valve closed

The IBLOHGA with pressure-relief valve closed can occur as the result of a small break or a relief valve that is stuck closed. The mitigation for the accident is to shut down the beam by manual actions once detected.

The consequences of an IBLOHGA with pressure-relief valve closed can be seen in Table 3.4-21. The unmitigated consequences of the IBLOHGA with pressure-relief valve closed and without a beam trip (Event Sequence 1) result in the entrapment of helium gas (along with tritium gas) ultimately collected in the upper regions of the blanket primary HRS heat exchangers. This gas can be potentially recovered without release to the environment. The negative impact on cooling capability as a result of noncondensible helium gas migrating through the primary HRS only slightly increases coolant temperatures. Depending upon break size, coolant pressure quickly rises to ~1.2 MPa (170 psia) within the HRS and then returns back to near normal operating values.

Event Sequence 2 by manual shut down of the beam is the preferred sequence. Details associated with specifications for retrieval of the gas from the primary HRS heat exchangers do not currently exist. The consequences of the mitigated Sequences 2, 3, 4, and 5 (corresponding to mitigative options of shutting down the beam, activating RHR and/or cavity flood) are all bounded by the consequences of Sequence 1.

IBLOHGA with pressure-relief valve opened

The IBLOHGA with pressure-relief valve opened can occur as a result of a large break or relief valve that is stuck opened. The current design specifications for the pressure setpoints to open and close the blanket primary HRS pressure-relief valve do not exist. Future analyses will be performed for IBLOHGA with pressure-relief valve opened and will be provided in the next PSAR revision. Table 3.4-22 is included as a placeholder for that tabular information. During a IBLOHGA with a stuck opened pressure-relief valve, eventually coolant inventory losses will initiate a beam shutdown followed by primary pump shutdowns and RHRS pump startups.

3.4.2.2.1.6.1.1 Blanket Internal-Break LOHGA Scenario Development.

As discussed in Section 3.3.2.3.4, multiple initiators are identified for a Blanket Internal-Break LOHGA in the T/B building.

A representative event tree for the IBLOHGA is shown in Figure 3.4-19. In Figure 3.4-19, the sequences are numbered starting from fully unmitigated towards the mitigated. An analytic discussion of all the sequences shown in Figure 3.4-19 is provided in the next section.

3.4.2.2.1.6.1.2 Blanket Internal-Break LOHGA Source Term and Consequence Analyses.

The analyses of the event sequences shown in Figure 3.4-19 are presented in Appendix BH. The results of the analyses and the conclusions are summarized in Table 3.4-20 A and B.

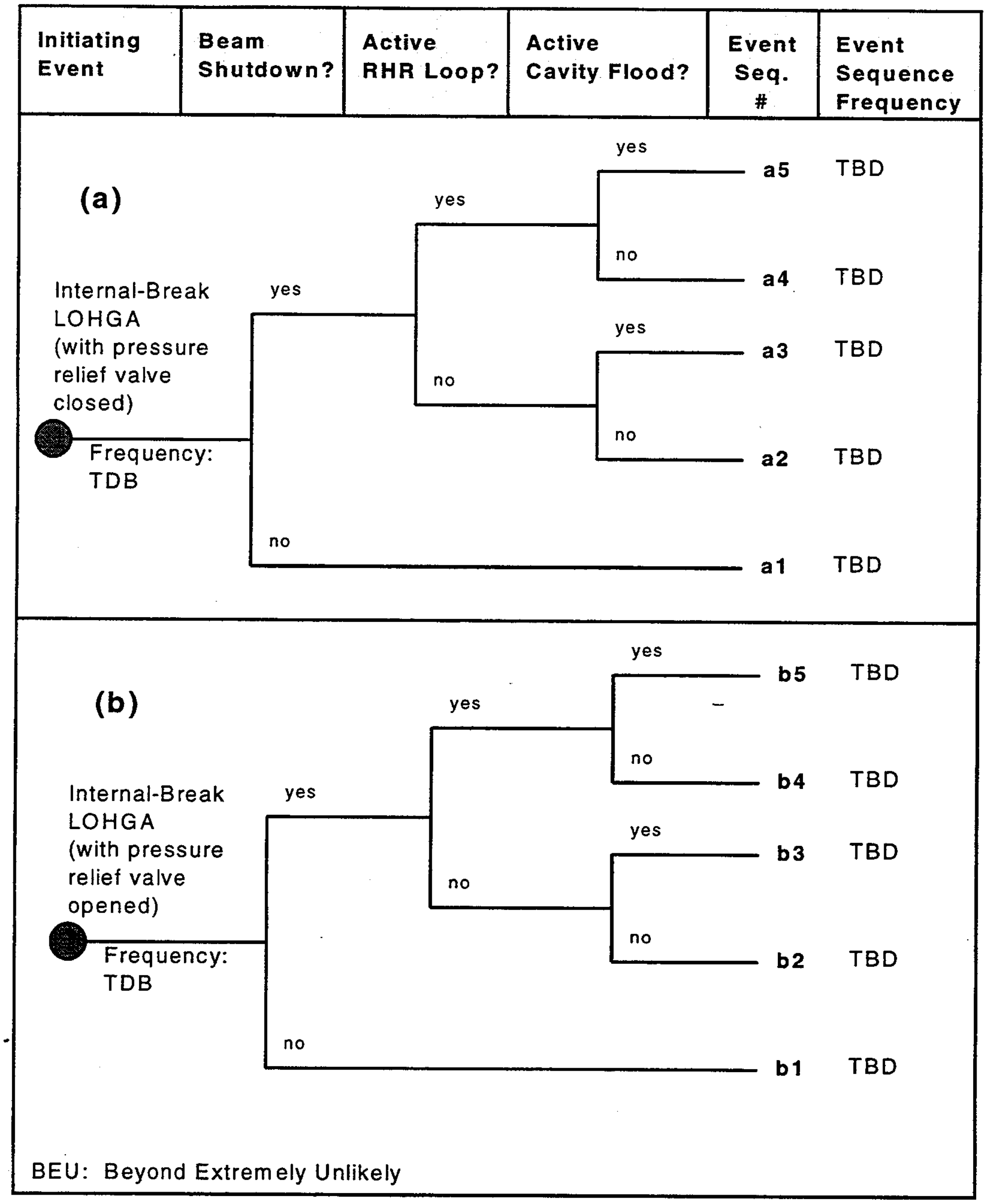

Figure 3.4-19. Blanket Internal-Break LOHGA event tree.

In the analyses summarized in this section, some assumptions are made with respect to the evolving design features and the results of the experimental program. These assumptions are listed, and a discussion of the future analyses needs is presented in Appendix BH.

Table 3.4-20A. Summary of the Analyses for the Blanket Internal-Break LOHGA Sequences with Pressure Relief Valve Closed.

Seq. #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
a1	TBD	**IBLOHGA without Beam Shutdown.** For an internal-break LOHGA with pressure relief valve closed and without a beam trip, no uncontrolled release of helium or tritium gas occurs. HRS coolant pressure quickly rises to ~170 psia and then returns to near normal operating values. A slight increase in coolant temperatures is observed.	None	Helium and tritium gas can be recovered without release to the environment.
a2	TBD	**IBLOHGA with Beam Shutdown.** Bounded by analyses for Sequence 1.	None	
a3	TBD	**IBLOHGA with Beam Shutdown and Cavity Flood.** Bounded by analyses for Sequence 1.	None	
a4	TBD	**IBLOHGA with Beam Shutdown and RHRS.** Bounded by analyses for Sequence 1.	None	
a5	TBD	**IBLOHGA with Beam Shutdown, RHRS and Cavity Flood.** Bounded by analyses for Sequence 1.	None	

Table 3.4-20B. Summary of the Analyses for the Blanket Internal-Break LOHGA Sequences with Pressure Relief Valve Opened.

Seq. #	Freq (yr^{-1})	Summary of Analyses	Conseq. (rem)	Conclusions
b1	TBD	**IBLOHGA without Beam Shutdown.** TBD	TBD	TBD
b2	TBD	**IBLOHGA with Beam Shutdown.** TBD	TBD	TBD
b3	TBD	**IBLOHGA with Beam Shutdown and Cavity Flood.** TBD	TBD	TBD
b4	TBD	**IBLOHGA with Beam Shutdown and RHRS.** TBD	TBD	TBD
b5	TBD	**IBLOHGA with Beam Shutdown, RHRS and Cavity Flood.** TBD	TBD	TBD

3.4.2.2.1.6.1.3 Summary of SSCs and TSRs for the Blanket Internal-Break LOHGA.

For the Blanket Internal-Break LOHGA analyses, the credited controls are summarized in Tables 3.4-21 A and B. For the blanket internal-break LOHGAs with pressure relief valve closed no mitigative actions were required. The helium gas (along with tritium gas) ultimately collected in the upper regions of the blanket primary HRS heat exchangers. This gas can be potentially recovered without release to the environment. For the blanket internal-break LOHGAs with pressure relief valve opened the anlayses are not complete; therefore, Tables 3.4-21 A and B are incomplete. In later revisions to the PSAR these analyses and Tables will be updated.

Table 3.4-21A. Summary of Blanket Internal-Break LOHGA Mitigation SSCs.

SSC	Requirement or Setting	Classification
Primary HRS Heat Exchanger Gas Collection System	Batch processing to remove trapped gas in HRS.	Safety-significant
TDB	TDB	TDB

Table 3.4-21B. Setpoint Requirements for SSCs for Blanket Internal-Break LOHGA.

	Beam Shutdown (SC, automatic)	RHRS Start-up (SS, automatic)	Cavity Flood (SS, Manual)
TBD	TDB	TDB	TBD

3.4.2.2.1.6.2 Blanket External-Break LOHGA

The details of the blanket external-break loss-of-helium-gas accident (EBLOHGA) analyses have not been analyzed to date. Analyses will be performed and provided in a later revision to the PSAR. It is anticipated that these events will impose no new requirements on the blanket systems.

Blanket external-break LOHGAs represent those events where helium gas does not enter the blanket system's primary HRS coolant. Their impact on blanket performance is in the loss of neutron absorbing material within the blanket modules and the subsequent impact on deposited power levels.

TBD

3.4.3 Beyond Design Accidents

3.4.3.1 Target/Blanket Beyond-Design Basis Accidents

For the analyzed DBAs, the sequences without a beam trip are the ones that result in the bounding consequences. To provide an estimate for the residual risk, LOCA , LOFA and LOHSA without a beam shutdown are selected for further analyses as the BDBA sequences in the target.

The unmitigated sequences corresponding to these accidents are discussed in Section 3.4.2.2. Based on bounding arguments for the unmitigated accident sequences without beam trip, it is assumed that the consequences would challenge or exceed the 25-rem offsite EG. Therefore, the beam shutdown is designated to perform a safety-class function. A redundant, diverse and highly reliable set of beam shutdown systems are being designed. Based on the reliability assessment provided in Appendix RA, the probability of failing to shut down the beam given a LOFA, LOCA or LOHSA is $<10^{-7}$/demand. In addition, there is a "passive" beam shutdown system that is activated by pressurizing the cavity vessel. The case where the selected accidents are allowed to progress until the activation of the passive beam trip is discussed as part of the BDBE sequence.

For the LOFA, LOCA, and LOHSA without beam trip, its is assumed that the rungs dry out shortly after the accident initiation. Under dry conditions, the rungs continue to heat up with the full power deposited by the beam. It is assumed that, no structural rung failure occurs until the rung tube reaches its melting temperature (1300 °C). At this time, the maximum temperature inside the hottest rung is ~2400°C. This is a conservative failure threshold because the rung tube is expected to fail much earlier as a result of internal pressure and the loss-of-material strength at temperatures approaching 1000 °C. Delaying the rung tube failure results in higher internal temperatures inside the rings and promotes additional sensible heat storage and tungsten vaporization. Upon failure of the rungs tubes, the cavity vessel is quickly pressurized and the passive beam shutdown is activated. The liquid that drains into the cavity vessel, quickly quenches the failed rungs, pressurizing the vessel as a result of steam production. Simultaneously, a cavity vessel failure is postulated such that the drained liquid is not contained in the vessel to filter the vaporized tungsten oxide. All the tungsten in cylinders where the Inconel clad is breached vaporizes and disperses within the cavity. The excess pressure in the cavity vessel results in a sudden release of the tungsten oxide out of the cavity vessel. For such a release, it is postulated a vent path opens from the cavity vessel to the outside during LOFA and LOHSA, which requires an additional failure. The details of the analysis are provided in Appendix TA. The resulting consequences are shown in Table 3.4-22.

Table 3.4-22. Bounding Consequences of a Beyond Design Basis LOFA, LOCA and LOHSA Sequences with Failure of Active Beam Shutdown System.

Onsite Dose (rem)	Offsite Dose (rem) (95% weather)	Offsite Dose (rem) (50% weather)
2800	9	< 1

The scenario discussed above is already in the "extremely unlikely" range. In addition to the failure of the active beam shutdown system, additional failures, such as a direct escape path to the environment, are postulated. Many bounding assumptions also are used in computing the source term. The frequency of this accident is estimated to be 10^{-8}/yr, and the consequences given in Table 3.4-22 are judged to be conservative, considering the stack up of the bounding and conservative assumptions used in obtaining the source term.

The frequency of this BDBE sequence would be even lower when the failure of the cavity system to retain the water is considered. The number is meaningless in the frequency domain but it illustrates the fact that this accident is outside the realm of credible events. One could postulate additional failures (such as the failure of the passive beam shutdown system) and potentially a less likely sequence of events than what is analyzed in Appendix TA. The analyses of such events would result in negligible additional risk and provide almost no insight into the assessment. However, the asymptotic consequences of such events would approach those listed in Section 3.4.2.2 with unmitigated consequences corresponding to 100% release of tungsten inventory.

3.4.3.1.2 Blanket DBDA

TBD

3.4.3.1.4 Target/Blanket BDBA Summary

TBD

3.4.3.2 Combined Target/Blanket BDBAs

TBD

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APPENDIX CB
A Summary of FLOWTRAN-TF and its Features Relevant to APT Blanket Analyses

1 Introduction

Detailed modeling of a single plate-type blanket module was performed as a part of the accident analyses for the Accelerator Production of Tritium (APT) blanket heat removal systems. This modeling was accomplished using a version of the FLOWTRAN-TF code modified specially for APT analyses. FLOWTRAN-TF is a transient two-fluid code that solves a conjugate heat transfer problem. The conduction solution is 3-D and the fluid dynamics in parallel passages is 1-D. Boundary conditions from the 1-D integrated system model drive the FLOWTRAN-TF detailed 3-D bin model. Results from the bin model are used to determine blanket module safety margins and their confidence levels consistent with imposed thermal/hydraulic design criteria. This appendix gives a brief description of the version of the FLOWTRAN-TF code used and the features relevant to the APT blanket analyses. Additional details are available in Refs. CB-1 and CB-2.

2 Background

The FLOWTRAN-TF code was originally developed at the Savannah River Technology Center (SRTC) to solve transient conjugate heat transfer problems associated with single or two phase flow in reactor assemblies having multiple flow channels. In the reactors, as in the APT, the multiple flow channels are connected to common inlet and outlet plenums. FLOWTRAN-TF was specifically designed to model flow in this geometry and thereby provided an excellent starting point for the development of a detailed APT bin model.

2.1 Detail Bin Code Selection

Similar to the needs for the system model, a broad range of accident scenarios covering a wide variety of different thermal/hydraulic states must be addressed with the detailed bin model. The bin model must also be numerically compatible with the system model. Since numerous simulations with the bin model will be required to quantify overall uncertainties and determine confidence levels, the bin model should be as efficient as possible. To achieve this efficiency, advantage should be taken of the unique features present in the plate-type design for the blanket modules. The key features considered in the selection process were:

- The model domain would have several 1-D discrete flow channels connected to common inlet and outlet plenums;
- The heat structure connects all discrete flow channels together within a complex arrangement that is subject to change as design improvements/optimization studies are completed;

- Each discrete flow channel has a long and narrow geometry (i.e., either annular, circular, rectangular, or trapezoidal) whose cross-sectional shape is invariant with axial position;
- System pressures range from moderate to relatively low; and
- A well established and documented source code is required if source code modifications are warranted.

Based on these considerations and those discussed below, the FLOWTRAN-TF code was selected for the detailed bin model. This code was extensively documented [Refs. CB-3, CB-4 and CB-5] and verified/validated [Ref. CB-6] as part of the K-Reactor Restart effort at the Savannah River Site (SRS). The original version of FLOWTRAN-TF handles multiple flow channels connected to common inlet and outlet plenums. FLOWTRAN-TF was specifically designed to model two-phase flow in this geometry. The code contains constitutive relations applicable to low pressure and low temperature two-component (air and water) flows in narrow channels. The original code contained fluid equations for two-dimensional flow in both the dominant axial direction and in the azimuthal direction to model flow across narrow rib gaps that were present in the reactor assemblies. FLOWTRAN-TF also contains logic to map out the complete boiling curve with the following options:

1. Diettus-Boelter or Sieder-Tate single phase heat transfer correlation;
2. Chen or Mikic-Rohsenow boiling heat transfer correlation;
3. Biasi, SRTC or Macbeth-Bowring critical heat flux correlation.

Both TRAC and FLOWTRAN-TF are based on the same set of two-component two-fluid formulations. Both codes difference these equations very similarly based on a staggered mesh arrangement where state variables are cell centered, while velocities are at the cell faces. Numerically, TRAC and FLOWTRAN-TF are very similar and no compatibility issues arise.

The principal authors of the code are still active in code development work at the SRS and several members of the original development team were available to work on the APT analyses.

3 Code Modifications

FLOWTRAN-TF solves conjugate heat transfer problems in a somewhat sequential fashion. As such, the FLOWTRAN-TF software design separates the fluid calculations from the solid heat conduction calculations. The fluid and solid calculations are interfaced through appropriate (fluid-solid interface) models. Modifications made to the original FLOWTRAN-TF code for safety analysis of the APT blanket region fall into three major categories:

1. Replacement of the original solid heat conduction subroutines with an unstructured mesh finite element based heat conduction calculation;

2. Replacement of the original lateral power distribution calculations with a simpler calculation of the deposited power within each finite element cell; and

3. Reduction of the fluid flow calculations from a two-dimensional formulation to that for one-dimensional flow by eliminating azimuthal flow equations from the code.

In addition to these major changes, a number of other modifications were made to add new or enhance existing capabilities in the code. The revised FLOWTRAN-TF code contains 124 subroutines and 4 include files. During the course of the APT blanket model development, almost every file was modified in some way. Most of the modified subroutines reflect changes made to eliminate the azimuthal fluid flow equations. Almost all of the subroutines eliminated from the original version of the FLOWTRAN-TF code were specifically designed for the azimuthal rib flow, the original cylindrical heat conduction solution and the power distribution calculation. The majority of the subroutines added to the original code are used for the finite-element heat conduction calculations.

Section 3.1 contains a discussion of the upgrades made to the fluid and interface models, while Section 3.2 contains a discussion of those upgrades made to the solid heat conduction models.

3.1 Fluid Governing Equations

The most significant modifications made to the governing fluid equations in the original code were:

1. Addition of a steady-state treatment for an oxide layer on the outer surface of the metal. This was accomplished by adjusting the surface heat transfer coefficient to an effective value that includes the thermal resistance of the surface oxide layer:

2. Including the Macbeth-Bowring critical heat flux correlation [Ref. CB-7] as a code option.

3. Utilization of the "F-factor" method to adjust the critical heat flux for a non-uniform axial heat flux profile [Ref. CB-8].

4. Including criteria checking for onset of nucleate boiling, onset of significant void formation, critical heat flux, and maximum solid temperature. Onset of nucleate boiling uses the Mikic-Rohsenow boiling correlation, onset of significant void uses the Saha-Zuber correlation, and critical heat flux is selected through input to be based on either the Macbeth-Bowring correlation, Biasi correlation, or a correlation derived from data collected at SRS on aluminum surfaces. Implementations of the Mikic-Rohsenow, Saha-Zuber, Biasi and SRS correlations in the code are unchanged from the original versions described in the FLOWTRAN-TF code manual [Ref. CB-3].

5. Adjustment of the fluid friction factor at the wall to account for heated wall effects. The adjustment is applied at each axial level and at every surface within each flow channel.

6. Restructuring the code so that the solid heat conduction calculation is performed after the fluid solution has converged and including the option to perform the heat conduction calculations on a different time frequency from the fluid calculations. Figure CB-1 shows a greatly simplified schematic diagram of the basic FLOWTRAN-TF solution algorithm.

7. Addition of a subroutine to write output data files in a format compatible with the Tecplot graphics software.

8. To simplify the code as much as possible for the APT application, the original two-dimensional fluid flow equations were reduced to their one dimensional forms in the modified version of the FLOWTRAN-TF code. Several parameters in the original two-dimensional formulation were specific for azimuthal flow across the very narrow rib gaps present in the SRS reactor assembly flow channels. Since this configuration does not apply to the APT blanket plate module, this part of the FLOWTRAN-TF coding was eliminated for greater computational efficiency. Modifying the code to strictly one-dimensional fluid flow did not reduce the code capabilities for APT calculations.

These modifications are described in more detail in Ref. CB-2 where the equations used to model items 1-5 are provided. In addition to the modifications listed above, numerous minor changes were made to improve some of the coding and to enhance the code structure.

3.2 Solid Governing Equations

The original FLOWTRAN-TF code was designed specifically for three-dimensional heat conduction in a geometry of concentric cylindrical tubes which applied to the SRS reactor assemblies. In the modified version of the code, the solid heat conduction module was replaced with a two-dimensional implicit finite element calculation using an unstructured mesh. This gave the code the capability of solving heat conduction problems in more general solid geometry and specifically in the plate-type APT blanket modules. An explicit axial heat conduction scheme using a finite difference formulation that couples adjacent axial levels allows the code to model three-dimensional conjugate heat transfer within a blanket plate.

At the level of detail required for the PSAR, the heat conduction calculation imposes a significant computational burden on the model. Therefore, an effort was made to increase the computational efficiency of these calculations by using matrix reordering, efficient solution methods, and by adopting the simplification of assuming constant metal physical properties. For the range of temperatures experienced in the safety analysis calculations, the assumption of constant metal properties is justified. Additionally, time steps for the fluid calculations are set by a Courant limit because of explicit differencing in the momentum equations. Under some flow conditions, the time step for the fluid calculations can become very small as the code attempts to converge to a solution within the specified tolerances. To avoid the excessive computational times that would occur if the solid heat conduction calculations were also performed over these very small time intervals imposed by fluid convergence constraints, the time step for the conduction calculations is specified independently of that used by the fluid. That is, solid temperatures are updated at time steps independent of the time step used for the fluid calculations. While this approach may lead to some small error in the solid temperature, the significant increase in computational efficiency warrants its use. For further details on the modifications to FLOWTRAN-TF see Ref. CB-2.

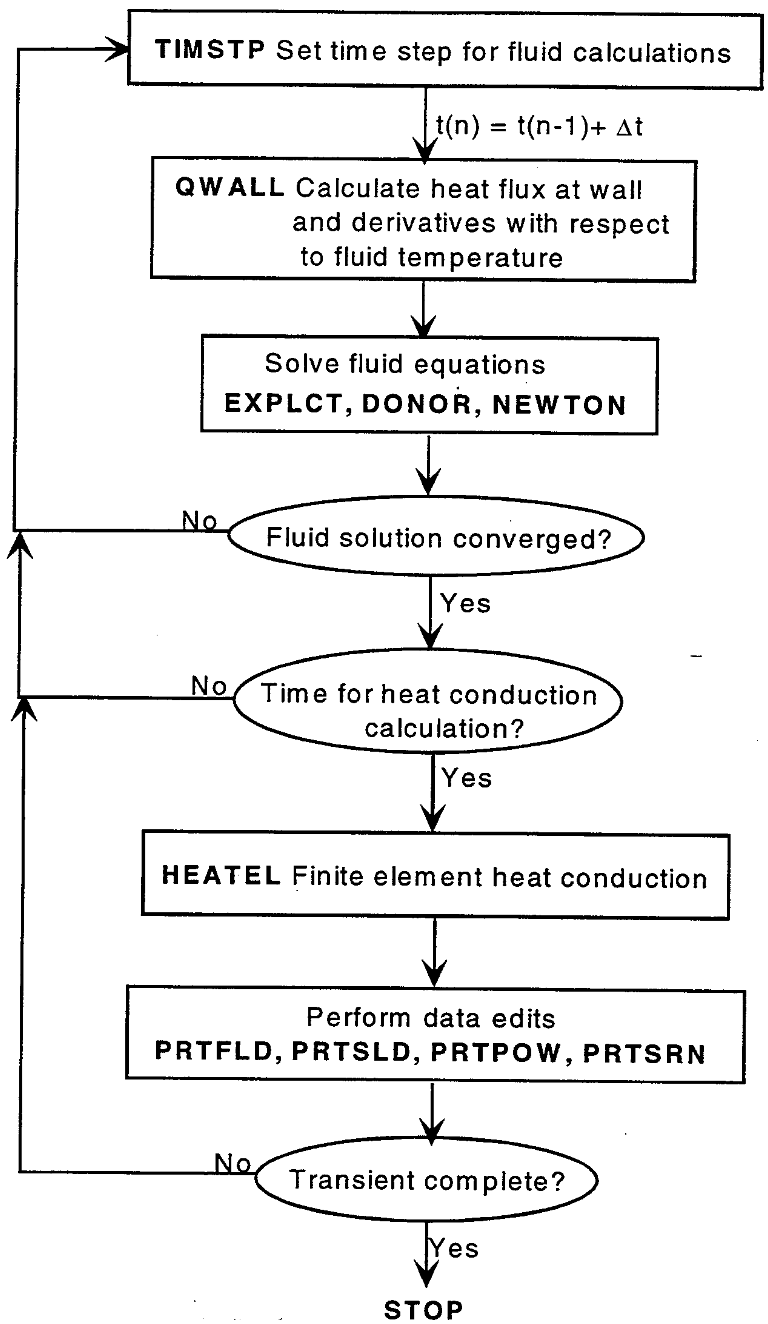


Figure CB-1 Simplified schematic diagram of FLOWTRAN-TF solution logic.

4 FLOWTRAN-TF Model of APT Blanket Plate

A closeup view of a section of module 1 (i.e., a lateral Row 1 plate-type blanket module) is shown in Fig. CB-2. Also shown in Fig. CB-2 as a dashed box is the model domain for a detailed "hot" bin model. This domain represents a lateral slice through the Row 1 section of this module. The left face of the model domain is in contact with the decoupler portion of module 1, while the right face is in contact with the cavity space residing between modules 1 and 3. The upper and lower boundaries of the bin model domain represent symmetry planes. A total of 12 discrete flow channels (actually these are half flow channels) exist within the detailed bin model. These are very long and narrow discrete flow channels joined at common inlet and outlet plenums.

Figure CB-3 shows a cross-sectional view of the finite element mesh employed in the FLOWTRAN-TF heat conduction calculations. This mesh is based on the reference 1 blanket plate-type design for a lateral Row 1 component as provided to SRTC by LANL personnel in mid October 1997 [CB-9]. The FLOWTRAN-TF blanket model includes a single metal plate and the 12 associated half flow channels. Figure CB-3 shows the 12 half flow channels surrounding the plate and the numbering convention used for the channels. Seven of the channels are trapezoidal shaped slots and five of the channels are annuli between the plate and the helium tubes. Table CB-1 gives physical dimensions of the flow channels and the fraction of fluid in each channel under normal operating conditions. Twenty levels were used to discretize the plate model in the axial direction with 673 finite element nodes at each axial level. The mesh shown in Fig. CB-3 is used at each of the axial levels. Figure CB-4 shows the full three-dimensional mesh used for the solid heat conduction calculations. Based on preliminary design information, the reference 1 plate model dimensions are ΔX = 10 cm, ΔY = 2.5 cm, and ΔZ = 278 cm. In Figure CB-4, scaling in the vertical direction is much smaller than that in the horizontal plane. Each flow channel is composed of one-dimensional fluid cells and the axial discretization is the same in both the solid and the fluid. There are a total of 240 fluid cells in the entire plate model.

4.1 Interfacing to System Model

The inlet, middle, and outlet plenums for each of the APT blanket modules are sized such that an approximately uniform pressure should be present within each plenum at all times. For each blanket module, hundreds of discrete flow channels connect these plenums together. Disturbances occurring within a small fraction of a module's discrete flow channels should have negligible impact on its remaining channels. Assuming that the above statements are valid, the following interface between the system model and the detailed bin model was established:

- The natural location for applying boundary conditions to a detailed bin model is at these common plenums; and
- Inlet/outlet pressure boundary conditions are chosen over the option of inlet mass flowrate/outlet pressure.

This selection allows individual flow channels to accommodate local hydraulic conditions (or disturbances such as flow instabilities) while the overall plenum-to-plenum pressure drop remains unaffected until a significant number of such flow channels become involved. Dependent upon flow direction, incoming material from a plenum advects its contents (i.e., state properties) into the bin model.

Table CB-1 Flow Channel Parameters.

Channel Number	Flow Area (cm^2)	Wetted Perimeter (cm)	Hydraulic Diameter (cm)	Flow Split
1	0.4104	1.7862	0.9191	0.099
2	0.3591	1.7298	0.8305	0.080
3	0.2552	1.4618	0.6983	0.051
4	0.1426	1.1247	0.8762	0.023
5	0.9935	3.1412	0.1557	0.286
6	0.3064	1.5919	0.5616	0.065
7	0.4398	2.6141	0.8301	0.086
8-12	0.4598	4.8277	0.3810	0.062

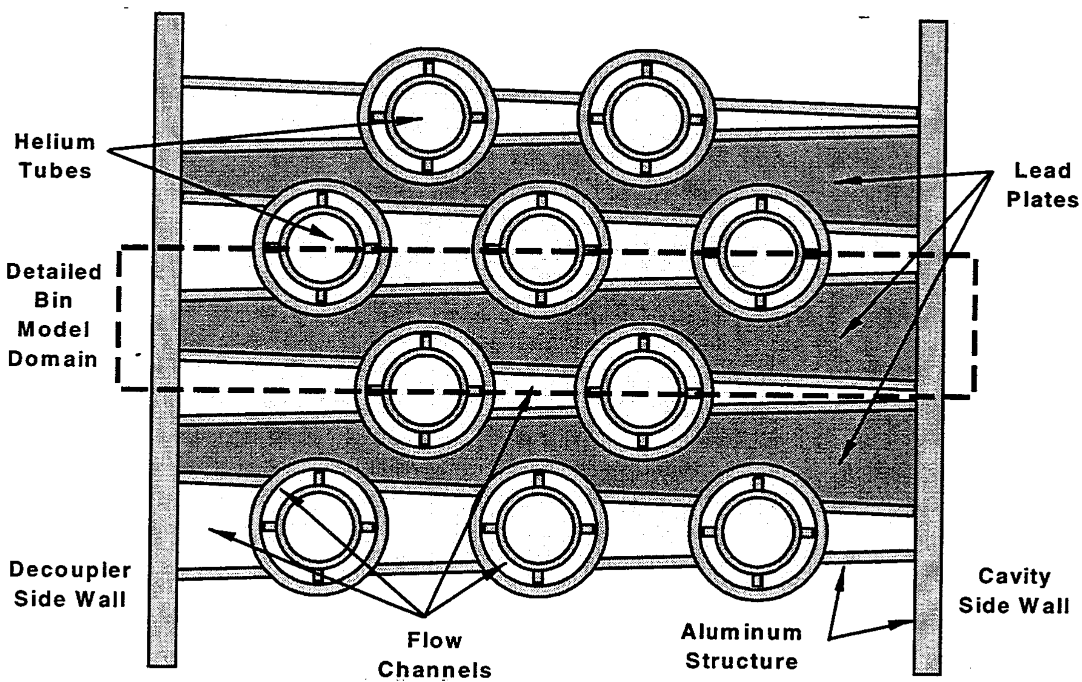


Figure CB-2 Cross-sectional view of plate-type module defining detailed bin model.

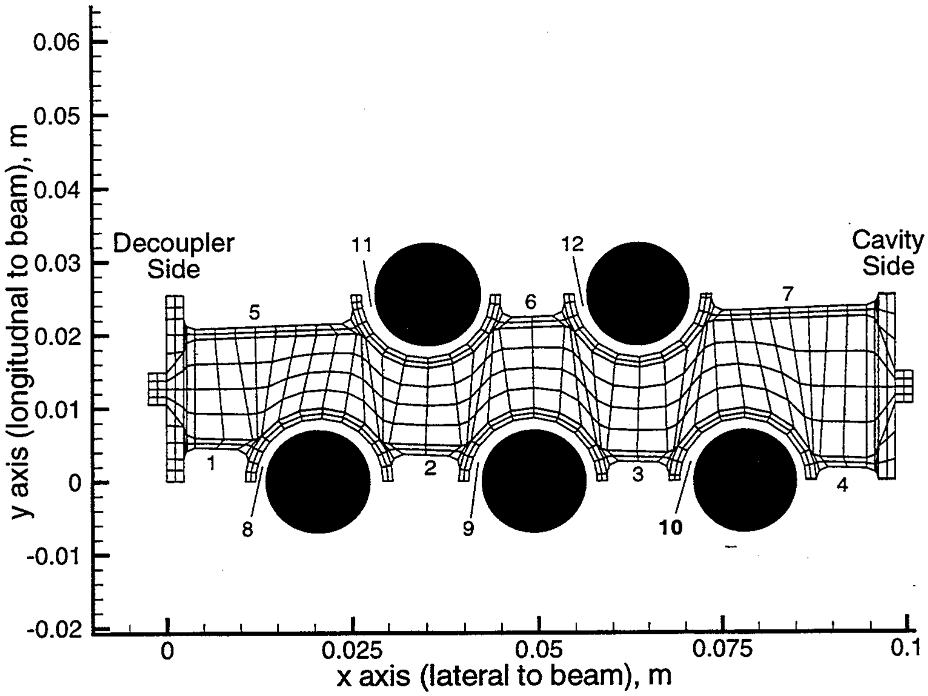


Figure CB-3 Finite element mesh of APT reference 1 blanket plate.

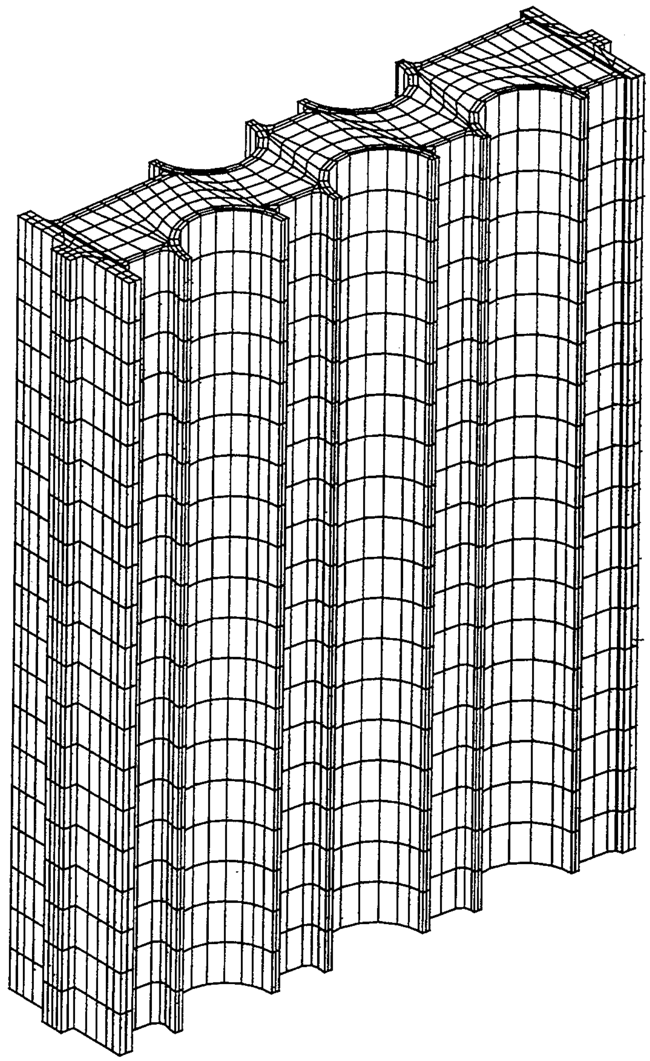


Figure CB-4 Three-dimensional mesh of APT reference 1 blanket plate.

5 Normal Operating Conditions

The FLOWTRAN-TF model simulates the thermal/hydraulic behavior of a single plate assembly and the associated coolant flow channels. The TRAC system model provides transient boundary conditions, and the FLOWTRAN-TF model simulates the fluid behavior of the discrete coolant flow channels and the conduction behavior of the lead/aluminum composite heat structure. The cross-section area mesh of the bin model is shown in Figure CB-3 along with the location and indexing used for the 12 discrete flow channels.

5.1 Model Description

The model used to simulate normal operations and in subsequent accident calculations, has 20 axial cells for both the solid structure and the flow channels. The Dittus-Boelter correlation was used to calculate surface heat transfer coefficients under single-phase flow conditions. This correlation was found to give slightly more conservative results (metal temperatures about 2 C greater) than were obtained using the possibly more accurate Sieder-Tate correlation. Figure CB-5 shows the axial power shape used in all of the calculations and its relationship to the axial mesh levels. As shown in this figure, in FLOWTRAN-TF, axial position is measured with reference to the top of the blanket module.

In all of the PSAR calculations, a 2 mil layer of aluminum oxide with a thermal conductivity of 2.16 W/m-K is assumed to be present on the outer surface of the plate. Also, a 1 mil air gap with a thermal conductivity of 0.10 W/m-K is assumed to be present between the aluminum cladding and the lead. The air gap represents a conservative model of the contact resistance between the two metal regions.

5.2 Initial Conditions

To provide a starting point for the APT blanket accident calculations for a single plate, the modified version of FLOWTRAN-TF was run until steady-state conditions were reached with normal operating boundary conditions. From the TRAC system analysis, the following pre-incident conditions were applied:

1. Inlet water temperature of 53.05 C;
2. Inlet pressure of 0.6860 MPa (99.5 psia);
3. Outlet pressure of 0.5841 MPa (48.7 psia).

Based on information supplied by LANL personnel [CB-10], the nominal pre-incident deposited power in a single lateral Row 1 blanket plate was 61.5 kW (average power density 13.15 W/cc) and the total nominal pre-incident coolant flow to the 12 half channels around the plate was 1.488 kg/s.

5.3 Solid Results

Figure CB-6 shows the FLOWTRAN-TF calculated temperature distribution on the surface of the mesh at normal operating conditions. The maximum surface temperature (also the maximum aluminum temperature) is 100.0 C on the decoupler face of the plate at the axial location where deposited power is highest. The maximum temperature in the lead is 112.8 C at the same axial location. Figure CB-7 shows the solid heat conduction mesh and temperature distribution with the upper 11 cells removed. The top horizontal plane in the cut-away view is close to the axial location where the maximum metal temperatures occur.

Note that the dimensions of the cross-sectional area shown in Figs. CB-6 and CB-7 have been greatly expanded to facilitate viewing. As noted above, the actual overall dimensions of the model section are: $\Delta X = 10$ cm, $\Delta Y = 2.5$ cm, and $\Delta Z = 278$ cm.

5.4 Fluid Results

Figure CB-8 shows temperatures and heat fluxes along the axial direction for flow channels 1 and 8 under normal operating conditions. These are the trapezoidal and annular flow channels closest to the decoupler side of the bin where the deposited power from the beam is highest. The first plot for each channel shows the fluid temperature (T_{fluid}), maximum wall temperature along the surface at each axial level (T_{wall}), and the local saturation temperature (T_{sat}). The second plot for each channel shows the operating heat flux (q_{ohf}) along with calculated values for the critical heat flux (q_{chf}), heat flux at the onset of subcooled nucleate boiling (q_{onb}), and heat flux at the onset of significant void formation (q_{osv}). The temperatures and heat fluxes are plotted on the same scale for easy comparison. Results for the other flow channels were very similar to those shown (see Ref. CB-11). At the exit of channels 4, 8, 9, 11, and 12, the operating heat flux becomes negative as heat is transferred from the liquid back into the solid. This reversal in the direction of heat transfer is a direct result of the long trailing edge of the axial power distribution curve shown in Fig. CB-5.

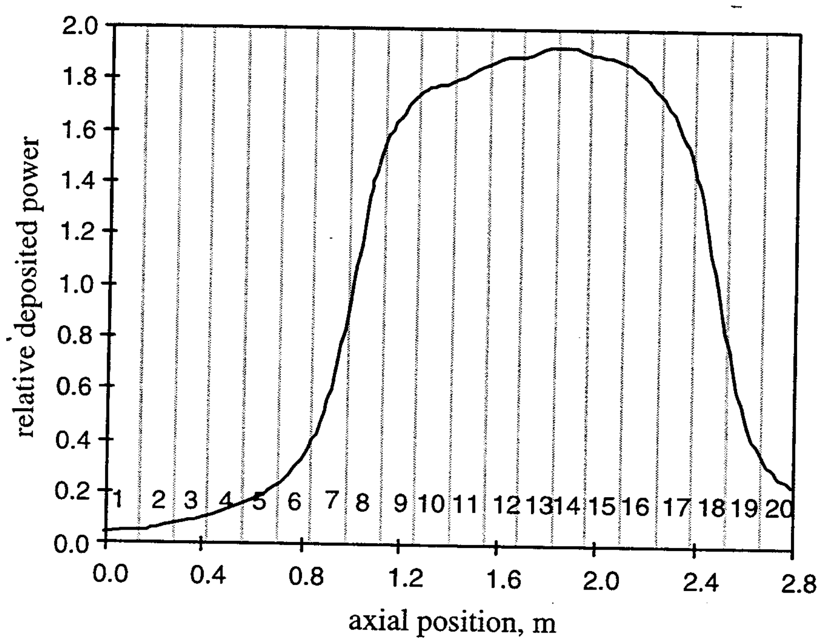


Figure CB-5 Axial power shape.

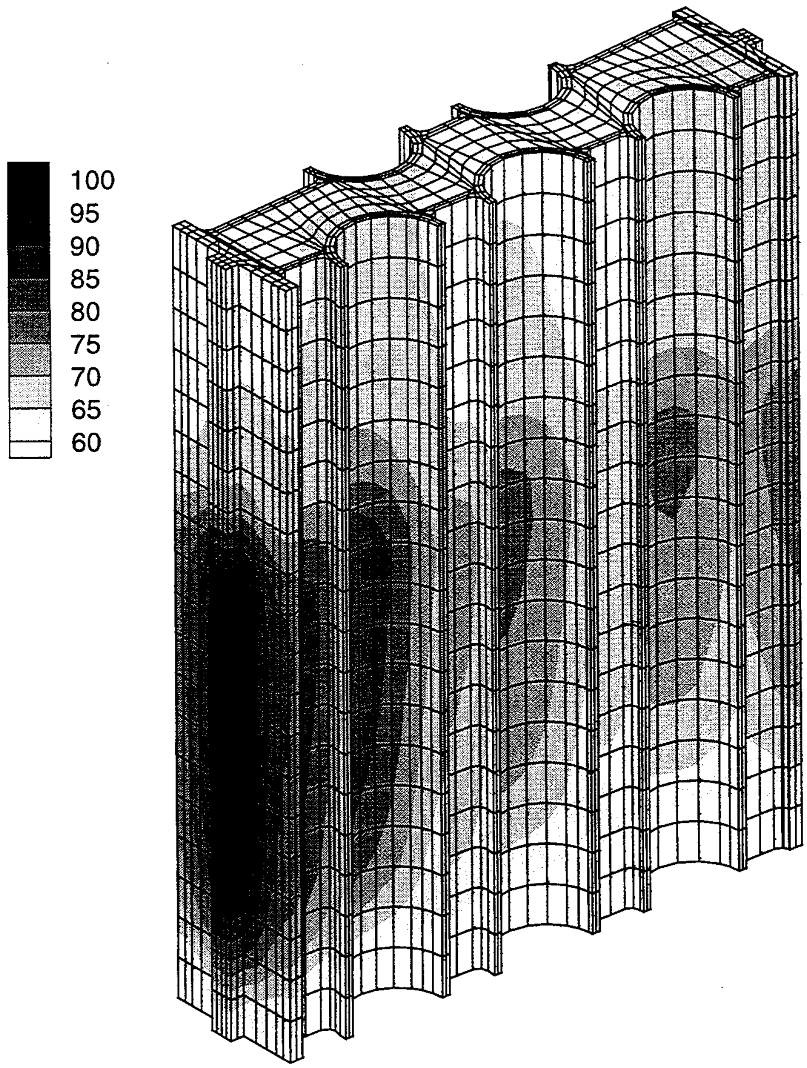


Figure CB-6 Normal operating surface temperatures.

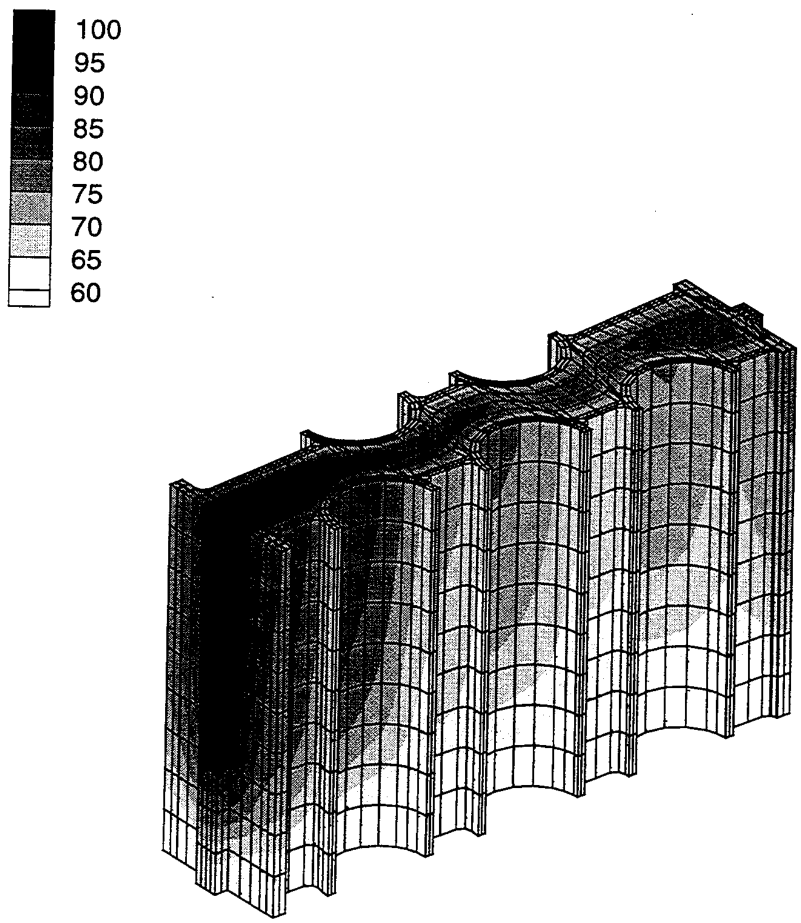
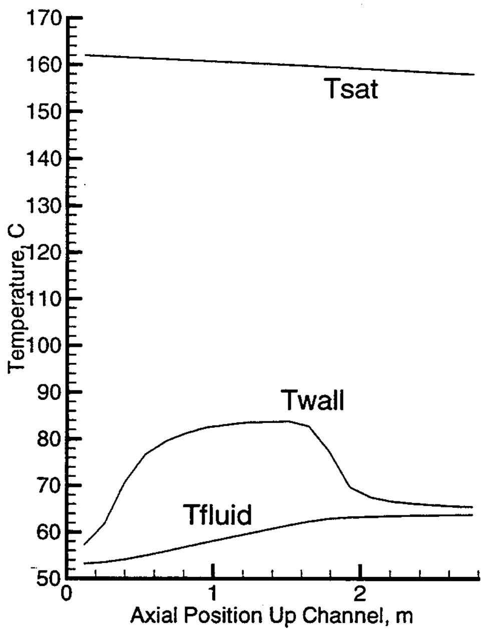
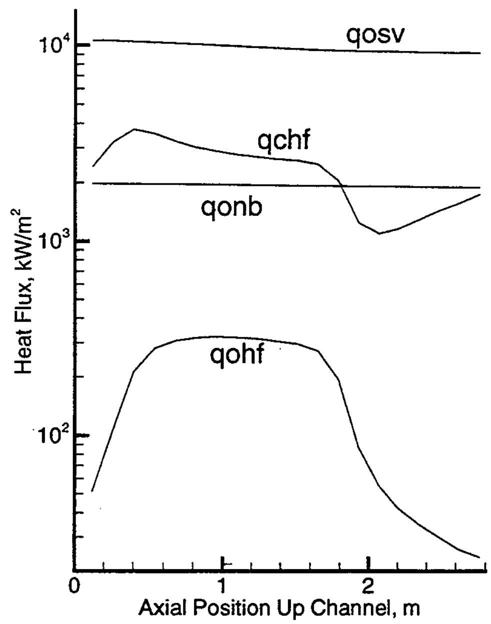


Figure CB-7 Normal operating metal temperatures, cut-away view.

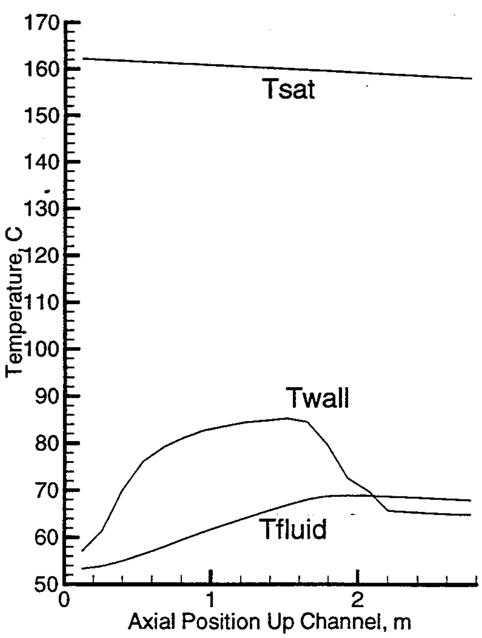
Channel 1



Channel 1



Channel 8



Channel 8

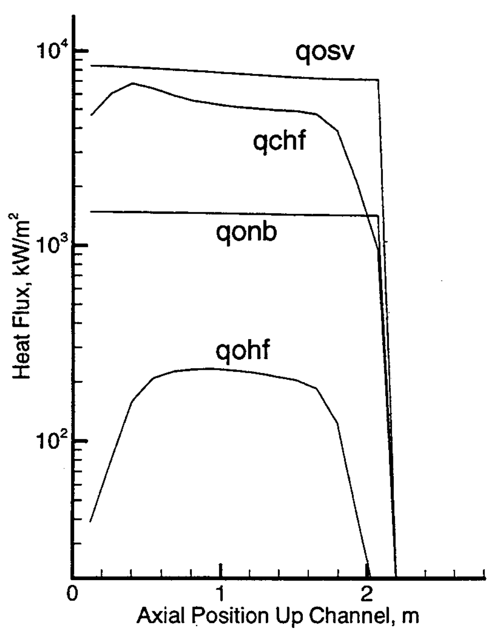


Figure CB-8 Normal operating temperatures and heat fluxes in fluid channels 1 and 8.

6 Quality Assurance

As part of the reactor restart effort at SRS, the original FLOWTRAN-TF code was subject to strict quality assurance requirements and configuration control. FLOWTRAN-TF quality assurance reference documents include:

FLOWTRAN-TF Code Development Technical and QA Plan, Rev. 0 (Flach, 1991);

FLOWTRAN-TF Software Requirements Specification, Rev. 1 (Flach, 1993); and

FLOWTRAN-TF Software Test Plan, Rev. 1 (Flach, 1993).

The results from an extensive software testing program are provided in Ref. CB-6. As previously stated, the principal changes made to the code were removal of azimuthal flow models from the fluid calculations and replacement of the power distribution and heat conduction calculations for cylindrical coordinates with a more general finite element calculation. To verify that these modifications were implemented correctly, several test cases were run with the revised code.

To verify that changes in the fluid calculations were correctly implemented, test input file test_31_01_m08.in documented in Ref. CB-6 was rerun with the modified code. This test case is a calculation to simulate data taken on air water downflow through a single annular channel. The liquid flow rate is 8 gpm with a -1 psig inlet pressure and a 12 inch head of water on the channel outlet. The modified code gave results identical to those reported for the unmodified code providing confidence that changes made to the subroutines calculating the two-phase fluid flow did not alter code performance.

The finite element coding that was used to replace the original cylindrical heat conduction calculations was written at SRTC and has been used in various applications for several years [personal communication from L. L. Hamm]. To verify that the heat conduction was operating correctly after it was implemented into the FLOWTRAN-TF code a few simple test cases that could be readily checked against analytical calculations were run. In all cases, temperature distributions calculated with the code were close to the analytical results [CB-2].

As further verification that the revised FLOWTRAN-TF code is functioning correctly, a trial calculation was made of the normal operating conditions within the reference 1 lateral Row 1 blanket plate component of the APT. Results from this calculation were then compared to those obtained at Los Alamos National Laboratory. The two sets of calculations were matched as closely as possible by using the following input parameters:

1. Total deposited power of 73.8 kW (120% normal operating power);
2. Inlet water temperature of 53.2 C; and
3. Application of the Dittus-Boelter heat transfer correlation.

FLOWTRAN-TF calculations obtained a maximum aluminum temperature of 109.4 C whereas LANL reported a value of 112 C [CB-10]. Considering that two completely different calculation techniques were used, this comparison was judged to be adequate to verify that the FLOWTRAN-TF code was performing correctly for the intended application.

7 References

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CB-2. L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "FLOWTRAN-TF Code Modifications made for APT Blanket Safety Analyses", Westinghouse Savannah River Company, WSRC-TR-98-0056 (July 1998).

CB-3. Aleman, S. E., G. P. Flach, L. L. Hamm, S. Y. Lee and F. G. Smith, III, "FLOWTRAN-TF Software Design," Westinghouse Savannah River Company, WSRC-TR-92-532, (February, 1993).

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CB-5. Flach, G. P., S. Y. Lee and S. E. Aleman, "FLOWTRAN-TF User Guide," Westinghouse Savannah River Company, WSRC-TR-93-085, (February, 1993).

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CB-7. Collier, J. G., "Convective Boiling and Condensation", 2nd Ed., McGraw-Hill, 1981, pp. 265-267.

CB-8. ibid, pp. 275-281.

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CB-10. Kapernick, R., "Re: Problem with First Reference Plate-Type Steady-State", e-mail message from rkapernick@lanl.gov, (December 10, 1997).

CB-11. L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "Normal Operation (NO) of APT Blanket System and its Components Based on Initial Conceptual Design", Westinghouse Savannah River Company, WSRC-TR-98-0057 (July 1998).

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Appendix DB
Thermal-Hydraulic Design Criteria for the Blanket Primary Heat Removal Systems

1 Introduction

This appendix states the thermal/hydraulic design criteria imposed on the blanket system and discusses how they are to be implemented. The overall safety envelope for the blanket system and its key components is based on a defense-in-depth philosophy. Safety criteria have been established for five major event categories. Each event category contains event sequences who span a specified range of frequencies. Thermal/Hydraulic (T/H) design criteria are established that meet or exceed the stated design criteria for each event category to the specified level of confidence. Reference DB-1 discusses the thermal/hydraulic design criteria presented in this appendix and places them in the context of an overall safety envelope for the blanket system and its components.

2 Thermal/Hydraulic Design Criteria

Thermal/hydraulic design criteria are made up of two types of criteria: (1) material criteria that provide direct protection from a structural integrity viewpoint and (2) thermal onset criteria that provide indirect protection to components by restricting their thermal behavior to certain types of heat transfer and flow regimes. Since structural strength of a material is dependent upon its temperature-stress history (i.e., time-at-temperature), the material design criteria are further subdivided into a steady-state (e.g., during normal operation (NO)) and a transient class. The thermal onset criteria can also be broken up into two sets: (1) onset criteria appropriate for components with heated surfaces and (2) those components with approximately adiabatic surfaces. The various cases mentioned above are discussed in greater detail in the subsections that follow.

2.1 Material Design Criteria

Bounding material design criteria are based on the concept of maintaining a coolable geometry. Here, for computational simplicity, we conservatively meet this objective by not accepting any significant alteration of the solid structures from their nominal shapes, excluding thermal expansion and very small motions associated with lead creep (with some thermal ratcheting between operating cycles/campaigns).

Under NO conditions within the blanket modules, specific steady-state design criteria have been placed (see Ref. DB-2) on the maximum lead and aluminum (Series 6061-Type T6) metal temperatures. The limiting values for these parameters are 327.5 C and 115 C, respectively. For lead its design criterion is set to its melting point, while for aluminum its limit is established based on a material strength requirement. No adverse effects have been identified (e.g., eutectoid reactions at grain boundaries) for the presence of molten lead in direct contact with a solid aluminum cladding/housing.

Aluminum's melting point is 660 C; however, the necessary yield strength required for the aluminum cladding to remain structural sound (based on expected loadings) for extended periods of NO forces a much lower temperature limit. The 115 C temperature limit applies to aluminum material subjected to the lead loadings for extended periods of time at a given temperature level (i.e., a time-at-temperature exposure concept). The weakening or hardening effects of prolonged radiation exposure to these aluminum structures and their structural material properties have not been accounted for in the above limit. The 115 C limit ensures structural integrity such that a coolable geometry (as defined earlier) can be maintained.

Under accident conditions metal temperatures by their very nature will be time dependent. In the general transient case material design criteria now become a direct function of the event sequence being analyzed. To simplify the safety analysis efforts the following conservative de-coupling of the material criteria from the components transient behavior is used:

- Separate structural analyses are performed based on conservative stress loadings and an assumed upper temperature value that is time invariant. A parametric study is performed to create a temperature limit as a function of stress and temperature levels;
- Accident safety analyses are performed assuming that a coolable geometry exists; and
- Post-safety analysis comparison is then made to verify that metal temperature does not exceed the material design criteria over the stated allowable exposure period.

As of this writing only one structural analysis point has been established. Under the expected loadings for current plate-type blanket modules, an aluminum design criteria of 150 C for exposures not to exceed 10k hours has been determined.

Table DB-1 summarizes the currently available material design criteria tabulated for various time exposures and Figure DB-1 graphically illustrates the implementation of this information. The shaded area shown in Fig. DB-1 corresponds to the interim material design criterion for aluminum. This criterion will be updated as soon as new data becomes available. However, the interim criterion is believed to be conservative.

Table DB-1 Summary of material design criteria for various exposures times.

Exposure Time (hrs)	Material Design Criteria	Lead Temperature Limit (C)	Aluminum Temperature Limit (C)
0 - 10k	T_{Pb}^{SS}, T_{Al}^{SS}	327.5	150
10k - ∞	$T_{Pb}^{TRN}, T_{Al}^{TRN}$	327.5	115
	melting point	327.5	660

2.2 Thermal Onset Design Criteria

Conservative thermal onset criteria are based on key physical flow regime transitions or precursors that are well established/documented within the open literature. These thermal onset criteria are generally far more stringent than material design criteria. For the massive aluminum cladded lead components within the blanket modules, some of the thermal onset criteria may in fact exceed the material design criteria due to the severe constraints being placed on the maximum allowable aluminum metal temperatures.

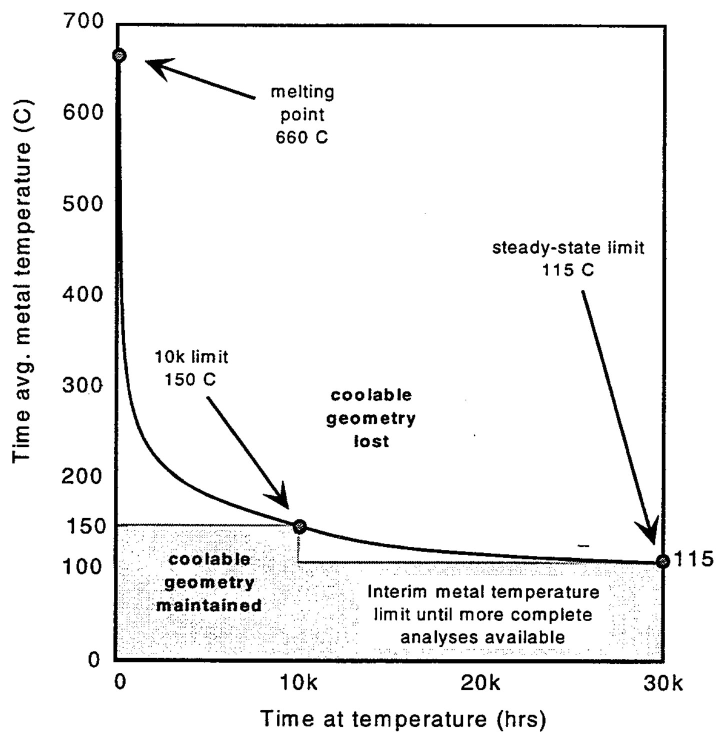

Figure DB-1 Interim aluminum material design criteria for various exposure times.

Typical candidates for thermal onset criteria are (algorithmically these criteria are computed as ratios and are check at every heated surface for every point in time):

$$R_{SUB} = \max\left(\frac{T_f - T_{in}}{T_{sat} - T_{in}}\right), \text{ liquid subcooling}$$

$$R_{SUP} = \max\left(\frac{T_w - T_{in}}{T_{sat} - T_{in}}\right), \text{ wall superheating}$$

$$R_{ONB} = \max\left(\frac{q''_{OHF}}{q''_{ONB}}\right), \text{ ONB heat flux}$$

$$R_{OSV} = \max\left(\frac{q''_{OHF}}{q''_{OSV}}\right), \text{ OSV heat flux}$$

$$R_{CHF} = \max\left(\frac{q''_{OHF}}{q''_{CHF}}\right)$$, CHF heat flux

where:

q''_{OHF} ....operating heat flux

q''_{ONB} ....heat flux at onset of subcooled nucleate boiling

q''_{OSV} ....heat flux at onset of significant void formation

q''_{CHF} ....critical heat flux

T_f ....fluid temperature

T_{in} ....fluid temperature at inlet to flow channels, (53.05 C)

T_{sat} ....local fluid saturation temperature

T_w ....wall temperature

where the maximum value corresponds to its limit spatially, as well as over the time period of the event sequence. The ratio of OHF-to-CHF is sometimes referred to as the departure from nucleate boiling ratio (DNBR). Predicted thermal onset ratios should not exceed unity. Confidence bounds are required to establish the acceptable level of probability of exceedance. All of the candidate thermal onset criteria listing above can be applied to components with heated surfaces. For unheated components only the first candidate (i.e., liquid subcooling) is appropriate. In these unheated components liquid subcooling provides an indicator as to the thermal/hydraulic margin present from local flashing and/or cavitation. Maximum fluid pressures may also be imposed but are generally considered as structural criteria.

Typically, thermal onset criteria depend upon the amount of dissolved gases present within a flowing coolant. Its impact varies greatly depending upon which criterion is considered. Within the APT blanket system it is anticipated that modest-to-significant amounts of dissolved gas (e.g., helium) will be present at all times. However, for blanket safety analysis purposes the vapor pressure curve for the flowing coolant is assumed to be that of pure light water. When dissolved gasses are present outgassing does occur at lower mixture temperatures than predicted by the pure saturation curve for water (i.e., at the mixture's bubble point for the solubility system at vapor-liquid-equilibrium). Experimental evidence suggests that under dynamic flowing conditions the rates of outgassing within the highly subcooled boiling regimes are greatly reduced such that only small measurable hydraulic impacts result up to the point of significant voiding. In other words, even though wall voidage occurs earlier due to the presence of dissolved gasses (i.e., point of ONB up to the point of OSV), its impact can reasonably be neglected.

2.3 Frequency Based Design Criteria

Based on guidance from DOE-STD-3009-94 [Ref. DB-3], Table DB-2 provides a summary of the selected design criteria for the blanket system and its components as a function of frequency category. Thermal/hydraulic design criteria are imposed of varying degrees of conservatism dependent upon the expected likelihood of the event sequences under investigation. The criteria are based on meeting very strict phenomenological limits, such as the onset-of-subcooled-nucleate (ONB) boiling, with a high degree of confidence for normal operation (NO) and anticipated operational occurrences (AOOs). The phenomenological, as well as confidence level, requirements imposed are relaxed as the likelihood of a given event sequence decreases (i.e, the concept of uniform risk or graded approach). For extremely unlikely events where it would be expected that the blanket modules would ultimately have to be replaced, the criteria are aimed at preventing excessive temperatures that could result in a significant loss in coolable geometry resulting in an un-measurable/unpredictable impact on neighboring target system ladder components and/or the rupture of the tritium bearing helium tubes.

For anticipated events (defined as events with frequencies greater than 10^{-2}/yr), meeting the ONB limit (or more conservatively the ΔT_{sup} limit) with a high degree of confidence provides a large margin of protection against frequent challenges. Furthermore, corrosive effects that can result by operating under boiling conditions for extended periods of time are prevented. For unlikely events (defined as events with frequencies ranging from 10^{-4}/yr to 10^{-2}/yr) and for extremely unlikely events (defined as events with frequencies ranging from 10^{-6}/yr to 10^{-4}/yr), meeting the OSV and CHF criteria prevent the onset of a temperature excursion triggered by either a local thermal or flow induced disturbance. Material temperature limits are imposed at varying degrees of confidence over the above frequency ranges to ensure that structural failure is prohibited.

Table DB-2 Summary of design criteria and their confidence levels for the blanket system and its components.

Event Category & Freq. Range (yr^{-1})	Confidence Levels (# Std. Dev.)	Material Design Criteria	Thermal/Hydraulic Design Criteria
Normal Operations (NO) & Operational Transients (OT) $\{10^{-1} < f\}$	3σ	T_{Pb}^{SS}, T_{Al}^{SS}	$\Delta T_{SUB}, \Delta T_{SUP}, \phi_{ONB}, \phi_{OSV}, \phi_{CHF}$
Anticipated Events $\{f < 10^{-2}\}$	3σ	$T_{Pb}^{TRN}, T_{Al}^{TRN}$	$\Delta T_{SUB}, \Delta T_{SUP}, \phi_{ONB}, \phi_{OSV}, \phi_{CHF}$
Unlikely Events $\{10^{-2} < f < 10^{-4}\}$	2σ	$T_{Pb}^{TRN}, T_{Al}^{TRN}$	ϕ_{OSV}, ϕ_{CHF}
Extremely Unlikely Events $\{10^{-4} < f < 10^{-6}\}$	1σ	$T_{Pb}^{TRN}, T_{Al}^{TRN}$	ϕ_{OSV}, ϕ_{CHF}
Beyond Extremely Unlikely Events $\{f < 10^{-6}\}$	**Best Estimate**	$T_{Pb}^{TRN}, T_{Al}^{TRN}$	**N.A.**

The following is a listing of the definitions used for each parameter employed in Table DB-2:

q''_{ONB} ....heat flux at onset of subcooled nucleate boiling
q''_{OSV} ....heat flux at onset of significant void formation
q''_{CHF} ....critical heat flux
ΔT_{SUB} ....fluid subcooling
ΔT_{SUP} ....wall superheat

T_{Pb}^{SS} .... lead steady-state temperature limit (infinite time of exposure)

T_{Al}^{SS} .... aluminum steady-state temperature limit (infinite time of exposure)

T_{Pb}^{TRN} .... lead temperature limit for a specified time of exposure

T_{Al}^{TRN} .... aluminum temperature limit for a specified time of exposure

σ .... estimated overall standard deviation

The implementation of the thermal-hydraulic design criteria provided in Table DB-2 is further discussed in a later section.

3 Safety Margins and Uncertainty Approach

Safety margins represent the net difference between a measured parameter (such as a local fluid temperature) and the parameter's stated thermal/hydraulic design criterion limit. Uncertainties in safety margins must address modeling uncertainties and measurement uncertainties associated with the parameter, as well as uncertainties associated with the thermal/hydraulic design criterion itself. Figure DB-2 illustrates graphically how a safety margin is calculated based on uncertainties associated with the model results and with the design criterion.

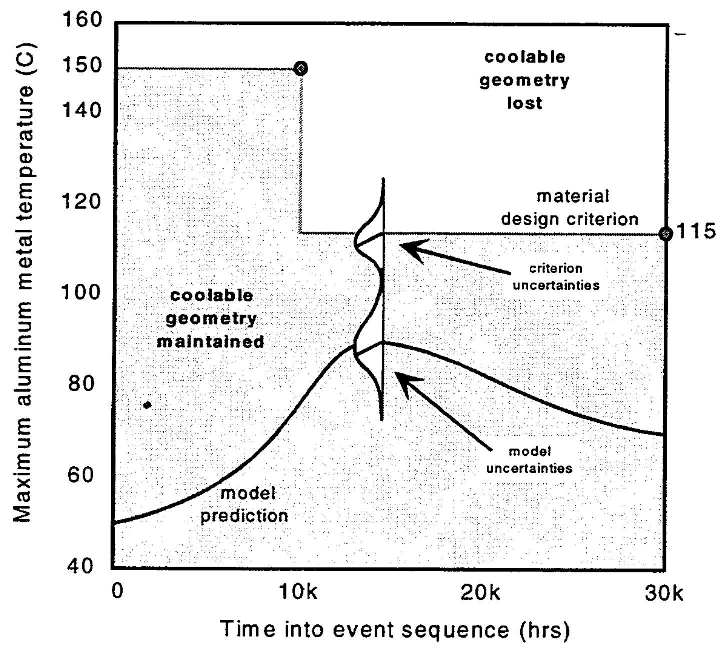

Figure DB-2 Safety margin with quantified uncertainties.

In computing an overall safety margin from exceeding the thermal/hydraulic design criteria mentioned above, a modified "best estimate plus uncertainty" approach has been chosen. A pure "best estimate plus uncertainty" approach would require that all modeling parameters and associated boundary conditions be statistically varied about their mean values. However, due to the separated modeling approach chosen, certain model and boundary condition parameters are set to either their upper or lower statistical bounds. The confidence levels in determining their bounds coincide with the levels established in Table DB-2.

As such, the computed overall safety margins are the result of a combination of a best estimate plus uncertainty limits methodology with certain key parameters conservatively set. No explicit credit is taken for bounded parameters when computing confidence levels.

Uncertainties associated with predicted model results (e.g., a maximum metal temperature within a given module) are obtained through sensitivity studies where response surface analyses are applied. In many cases the range of values used for a given input parameter will be based on engineering judgment. Wherever possible these parameter ranges will be supported by available databases or separate analyses.

4 References

DB-1 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Safety Analysis Methodology," Westinghouse Savannah River Company, WSRC-TR-0052 (May 1998).

DB-2 "APT Conceptual Design Report," Los Alamos National Laboratory report, LA-UR-97-1329 (April 1997).

DB-3 DOE Standard, "Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports,", DOE-STD-3009-94, (July, 1994).

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Appendix BA
Analyses of the Loss-of-Flow Accidents (LOFAs) in the Blanket Primary Heat Removal System

1 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal systems (HR) identified the loss-of-flow accident (LOFA) as a design basis accident (DBA). As discussed in Appendix CD, multiple initiating events are identified for a LOFA in the blanket systems. The initiating events are summarized in Table BA-1 and binned into one of three unique cases for detailed analyses.

Table BA-1 Discussion of Initiators for LOFA.

Initiator	Discussion	Analysis Bin
Loss-of-power	• Loss of electrical power to blanket pumps • Loss of electrical power to detection instruments must be addressed.	LOFA with coastdown
Facility fire	• Loss of electrical power to the blanket pumps caused by fire. • Loss of detection capabilities must be addressed. • Beam shutdown upon detection of facility fire.	LOFA with coastdown
Seismic Event	• Discussed separately in Appendix TBD	See Appendix TBD
Flood	• Loss of electrical power to the pumps as a result of flooded pump pits. • Automatic beam shutdown upon detection of facility flood. • Loss of detection capabilities must be addressed.	LOFA with coastdown
Pump electrical system failure	• Loss of electrical power to a pump (e.g. broken cable). • Extremely unlikely to happen in both pumps simultaneously unless caused by an external event.	LOFA with coastdown
External Event: Helicopter crash	• Mechanical damage to both pumps. • Loss of detection capabilities must be addressed. • Beam shutdown upon detection of large-scale external events.	LOFA without coastdown
Mechanical Pump Failure - Locked rotor - Shaft break	• Extremely unlikely to happen in both pumps simultaneously. • No impact on detection instruments unless the mechanical failure is caused by an external event.	LOFA without coastdown
Spurious valve closure	• If pump isolation valve is closed, one pump is lost. • If a valve in the main loop is closed, both pumps are lost. • All the valves in the main loop must be locked open during beam operations.	LOFA without coastdown
Debris in the HR systems	• Partial or complete flow blockage in the HR systems. • Collection of debris within narrow flow passages. • Inline debris filter specification must be established.	See Appendix BG

Table BA-1 shows that the initiators can be binned into one of the following three cases of LOFA:

1. LOFA with pump coastdown where the flow in the loops reduces gradually due to flywheel inertia as each pump coasts down;

2. LOFA without pump coastdown where the flow through one pump or both pumps is lost instantaneously; or
3. LOFA initiated by the unwanted collection of debris resulting in partial or complete flow blockage to local flow passages within the primary HR piping or modules.

The objective of this appendix is to provide a summary of the analyses performed for the event sequences of the first two types of LOFAs described above. The event sequences are discussed in the following sections. The third type of LOFAs (i.e., resulting from flow blockages) described above form a special class of LOFAs and are discussed separately in Appendix BG.

A schematic flow diagram of the blanket primary HR system is shown in Fig. BA-1. Pumps labeled 1 and 2 in Fig. BA-1 are online during normal operation and are physically identical. Due to piping differences however, these two pumps are flowing at slightly different mass flowrates. Each pump has separate drive trains (i.e., shaft, electric motor, and flywheel) but are coupled hydraulically. A common AC power supply is provided to both pumps.

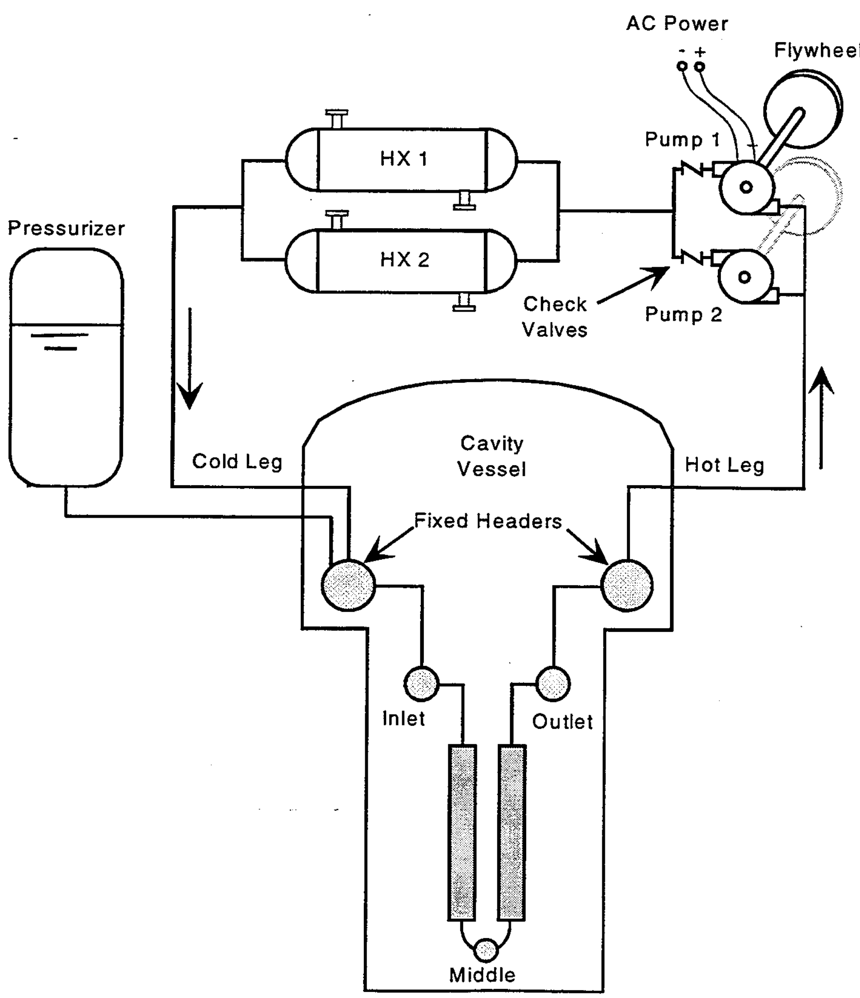


Figure BA-1 Schematic flow diagram for the blanket primary HR system.

Analyses associated with simultaneous LOFAs in both the tungsten neutron source (TNS) and blanket primary HR systems is discussed in Appendix TBA. This appendix focuses on LOFAs within the blanket HR systems only.

2 LOFA with Pump Coastdown

In analyzing a LOFA with pump coastdown, upon loss-of-power, it is assumed that forced circulation flows through the primary, secondary, and tertiary loops of the blanket HR piping systems are lost. The event-tree for a LOFA initiated by a power failure is shown in Fig. BA-2. The initiating event frequency for this accident is dominated by the loss-of-electrical power to the HR pumps in the blanket primary coolant loop. The initiator frequency is estimated to be in the anticipated frequency range. Event sequence 4 represents the design mitigation strategy for handling a LOFA initiated by a power failure and it is considered an anticipated event. The four remaining event sequences have lower likelihood of occurrences.

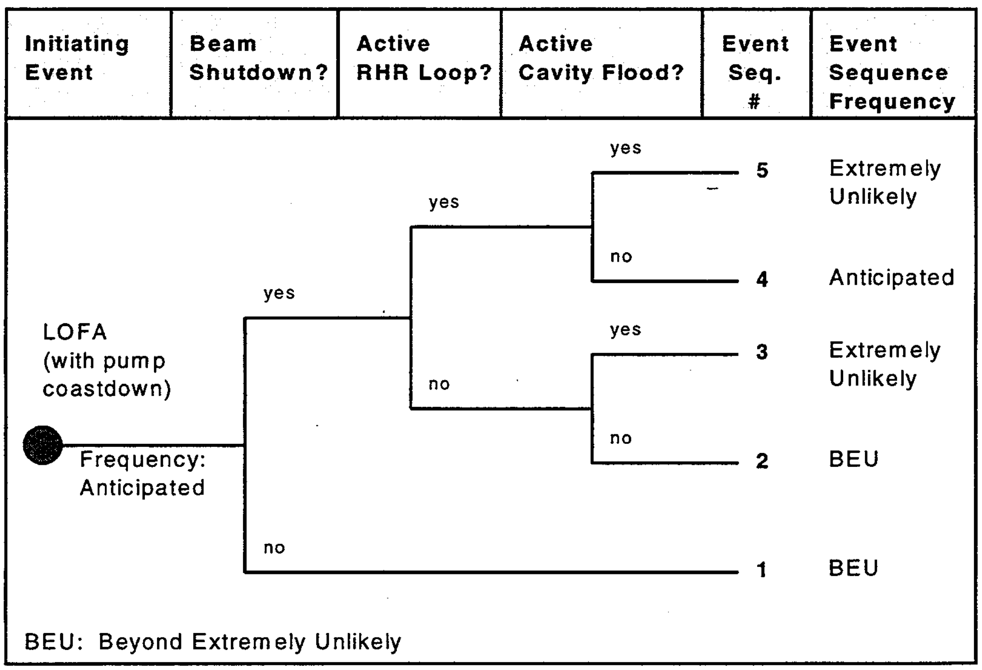


Figure BA-2 Event-tree for LOFAs initiated by loss-of-power to blanket HR pumps.

Once initiated, this event can be detected based on the following system measurements:

- loss of electrical current to the HR pumps (primary, secondary, or tertiary);
- reduction in pump impeller speeds;
- reduction in system flow computed from pressure drop across pumps or other components;
- increase in fixed header temperatures; or

- increase in fixed header pressures.

Upon detection of the upset conditions, the following mitigative actions are taken:

1. The beam is shutdown. The primary beam shutdown system is based upon the above measurements in the HR systems. The reliability of the primary beam shutdown system is discussed in Appendix RA. Based on this discussion, the frequency of failure to shutdown the beam given a LOFA with coastdown is in the Beyond Extremely Unlikely (BEU) range. In addition, there is a back-up beam shutdown system that is automatically activated upon pressurizing the cavity vessel. If a LOFA progresses to a point where a failure in the pressure boundary of the HR system occurs inside the cavity, the back-up system shuts the beam down.
2. Following the beam shutdown, the Residual Heat Removal (RHR) system primary and secondary pumps are started. There are two independent (100% capacity) RHR loops each being capable of removing the total decay heat from the blanket modules. The RHR pumps (i.e., primary and secondary side) are battery operated. If extended service becomes necessary, diesel generators are available for continued use of these RHR pumps. Failing to activate either one of the RHR primary pumps is believed to be extremely unlikely unless the initiating event results in a complete facility blackout (large facility fire). This case is discussed in Appendix TBA along with combined target and blanket LOFAs. The reliability of the RHR systems is discussed in Appendix RB.
3. In the unlikely event that neither one of the primary RHR pumps (one per loop) can be activated, as a backup the cavity flood system can be actuated to mitigate the initiating event. Independent and diverse means are available to actuate the cavity flood valves. As discussed later, after beam shutdown, there is ample time to actuate the cavity flood before a blanket LOFA progresses to a point where radiological source term generation becomes an issue or loss in coolable geometry occurs. Thus, the frequency of an event sequence where there is a need for cavity flood actuation combined with a failing to actuate the cavity flood after a blanket LOFA is in the BEU frequency range. The reliability of the cavity flood system is discussed in Appendix RB.

It is important that the upset conditions that result in a LOFA do not result in losing key detection and/or mitigation capabilities. Some of the initiating events discussed in Table BA-1 may challenge the detection and control instruments. In general, an independent power source is provided for each critical instrument train. Furthermore, the detection instrument are designed to fail safe such that their failure automatically results in beam shutdown. Finally, for the external events (such as a large facility fire) or natural phenomena hazards (e.g., seismic and flood), the beam is shutdown without relying on the primary HR signals for upset conditions.

In Fig. BA-2, event sequences are numbered starting from fully unmitigated (Event Sequence 1) towards the various mitigated event sequences. Event sequences numbered 3 and 4 in Fig. BA-2 are the DBA event sequences. The remaining event sequences are in the beyond-design-basis accident (BDBA) category. Brief discussions covering all the event sequences shown in Fig. BA-2 are provided. More detailed discussions for particular event sequences are provided within the cited references.

2.1 LOFA without a Beam Shutdown (Event Sequence 1 in Figure BA-2)

This event sequence represents the completely unmitigated LOFA. In the HA, it was recognized that during a TNS LOFA without a beam shutdown, a potential exists to release a significant fraction of the tungsten inventory and some of its spallation products (i.e., tungsten can be oxidized at high temperatures [see Appendix SA]). On the other hand, within the blanket modules, lead and mercury (i.e., one of the spallation side products) were considered as potential source terms. Due to the very low vapor pressures for molten lead and mercury, release mechanisms are limited as discussed in Appendix SB. Given these release mechanisms, the blanket modules themselves will contribute a negligible amount to the overall off-site consequences resulting from this unmitigated event sequence. However, the loss in coolable geometry associated with the blanket modules can result in a potential detrimental impact in the cooling capability of neighboring target ladders. Uncontrolled and unwanted excessive movement (e.g., slumping over) of the massive blanket modules could occur during this scenario; thus, jeopardizing the neighboring target ladders.

Since the tritium bearing helium tubes are closely distributed throughout the blanket modules, slumping of the blanket modules would most likely rupture numerous helium tubes, and perhaps helium manifolds, resulting in the release of gaseous tritium product. At any particular point in the operation of the APT facility, tritium inventory is kept low due to the online batch extraction process being employed for tritium gas recovery.

2.1.1 Unmitigated LOFA Analysis

There are three components that would contribute to a release from the blanket. The activity in the coolant which will be controlled by the purification system during operation. The tritium gas in the helium system inside the blanket and spallation products that could be released from the lead in the blanket if the lead melts. This source term is limited by the low vapor pressure of the spallation products in the lead.

Conservative analyses based on the diffusion and vapor pressure properties of molten lead in the blanket indicate that 2% of the mercury inventory will be released (See Appendix SB). The radiological consequences of this release have been calculated and the results are presented in Appendix CC.

In the coolant it is assumed that the entire gaseous radionuclide inventory, plus a limited fraction of other isotopes contained within the coolant of the blanket primary HR system, would be released. However, the release from the coolant contributes negligibly to the consequences as shown in Table BA-2. It is also assumed that the entire tritium inventory contained within the Target/Blanket building is also released to the environment and its consequences are also shown in Table BA-2.

In Table BA-1, the onsite and off-site consequences are obtained using the unit-dose calculations provided in Appendix CC. The unit-dose calculations corresponding to the following assumptions are used in computing the consequences:

- The release occurs rapidly (in less than 1 hour) such that meandering effects are not credited;
- The release to the environment occurs very early into the decay chain (< 10 seconds);
- The release occurs at ground level without initial momentum or buoyancy;

- Consequences are bounding for 95% of the weather conditions for the bounding year (1987), (Appendix CC); and
- Deposition velocity was selected as zero which was the bounding case calculated in Appendix CC.

Table BA-2 Consequences of a blanket LOFA without a beam shutdown for site 2.

Material	Quantity	Onsite Dose (rem)	Off-Site Dose (rem)
Mercury	2%	17	0.06
Coolant*	100% of coolant	12	0.028
Tritium*	94 g	23	0.07
Total*		52	0.16

* This is the total release from only the primary blanket coolant systems (HR, RHR, modules, fixed headers, and pressurizer systems). For this scenario, the release from the window and target systems must also be added to compute the total consequences. Note that the mercury and tritium results are partitioned from Appendix CC, Table 7.2.

Consequently, the dose estimates given in Table BA-2 are very conservative and provide an upper bound. The totals provided in Table BA-2 do not exceed the guidelines. The 2% release fraction for the mercury inventory is a conservative bound, since the following aspects that would reduce this release fraction are ignored:

- Condensation of mercury vapor onto colder surfaces;
- Potential partial filtering provided by the HEPA filters; and
- Only a fraction of the release would go through the stack, which would reduce the onsite consequences with negligible impact on the off-site consequences (see Appendix CC).

Assuming the release of the entire tritium inventory within the Target/Blanket building is also conservative because helium headers are separate for each module.

Based purely on the conservative exposure assessment above, the beam shutdown would not in-and-of-itself be required to be designated a *safety-class* function. However, the potential loss of coolable geometry in the blanket modules could result in a impact on the neighboring target ladders. To ensure that no unwanted side-effects occur, the beam shutdown is designated a *safety-class* function. A redundant, diverse and highly reliable set of beam shutdown systems are being designed. The reliability of the beam shutdown systems is discussed in Appendix RA.

2.1.2 Analysis of the Beyond Design-Basis LOFA Event Sequence

Since the beam shutdown system is designed to perform a safety class function, and given the level of reliability associated with this design, event sequences without beam shutdown fall within the beyond extremely unlikely (BEU) frequency range.

Analyses under this set of conditions are not complete and will be provided in the next PSAR revision.

2.2 LOFA with a Beam Shutdown (Event Sequence 2 in Figure BA-2)

For this scenario, it is assumed that the trip signal to shutdown the beam is initiated based on a 5% reduction in pump pressure drop on either primary HR pumps. Signal detection occurs within tenths of a second following the initiating event. The trip signal is activated approximately 0.2 seconds after the initiating event occurs. A conservative 1 second time delay to account for signal processing is assumed (i.e., best estimate values range within 0.1 to 0.2 second delays). The actual beam shutdown begins to occur at approximately 1.2 seconds after the initiating event occurs. Blanket deposited power drops rapidly. For example, power levels are approximately 1 to 3% of their pre-shutdown levels within 1 second. The primary RHR pumps and the cavity flood system are assumed to not be initiated for this scenario.

After a beam shutdown, no other available mitigation options are activated. This scenario was simulated using the integrated 1-D TRAC system model described in Ref. BA-2. The details of the TRAC calculations are provided in Ref. BA-3. A transient single-phase natural convection model of the blanket HRS, described in Ref. BA-4, was used to extend the accident simulation in time beyond that of the TRAC model. Calculations were carried out to the point where the onset of bulk boiling occurs.

2.2.1 Discussion of TRAC model results

The transient behavior of the blanket system was predicted using the integrated system model out to approximately 5600 seconds into the LOFA (i.e., slightly over 1.5 hours). By this point in time quasi-steady-state behavior has been achieved. The natural convection model described in Ref. BA-4 was then used to extend the simulation out to 200 hours (beyond 8 days). This strategy was chosen based on the belief that simulation times on the order of days are unrealistic using the integrated system model and that the predictive capability of TRAC to accurately model the natural circulation patterns diminishes as the temperature driving forces diminish. Also, under natural circulation various blanket modules experience mixed convection conditions where buoyancy opposed and assisted flows are important.

The TRAC calculations detailed in Ref. BA-3 conservatively set the flowrate on the secondary side to zero at time zero. In reality a flow decay similar to the primary HR flow decay occurs (i.e., negligible flow beyond approximately 100 seconds into the transient). However, credit was taken for the thermal sink capacity of the light water trapped on the shell side of the primary HR heat exchangers. The heat capacity of water residing within the shell side of the primary heat exchangers represents a sizable portion of the total available heat capacity of the composite system (i.e., blanket module metal, module water, HR primary water, shell side water). Selected output from Ref. BA-3 of TRAC results is shown in Figs. BA-3 through BA-6. The following are important observations from the TRAC simulation:

- The initial primary HR loop mass flowrate of 1569 kg/s drops to a natural circulation value of approximately 13 kg/s in the first 2 minutes, as the pumps coast down.
- Quasi-steady-state natural circulation with a mass flowrate of approximately 13 kg/s is established after approximately 35 minutes (2100 seconds). Thereafter, the flowrate very slowly drops due to a reduction in the blanket module decay powers that drive the circulation.

- Due to the presence of a check valve within the RHR primary loop, RHR flow remains stagnant.
- The fluid temperature difference between the inlet and outlet headers is 4°0 C at 2000 seconds and 3.5°C by 5600 seconds with an overall system heat-up rate of approximately 2°C per hour. The heat up is due to the assumption that there is no flow in the secondary heat removal system. Figure BA-5 shows the fluid saturation temperatures at the fixed headers. The saturation temperatures are approximately 170°C at the heated surfaces in the blanket bins.
- The module mass flowrates remain positive (i.e., no flow reversals are observed) as shown in Fig. BA-6. At these very low decay power levels metal temperatures remain only a few degrees above their local free stream coolant temperatures.

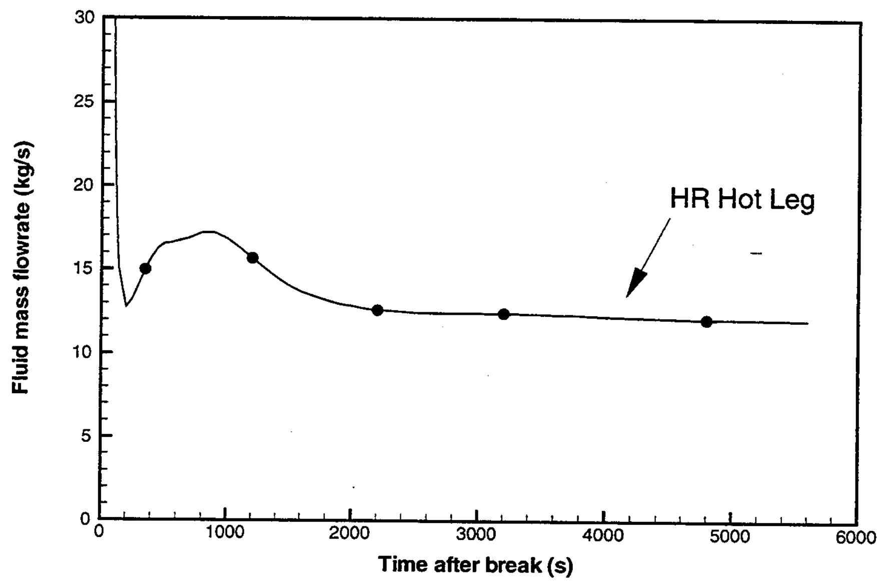


Figure BA-3 Primary HR mass flowrate for LOFA with a beam shutdown.

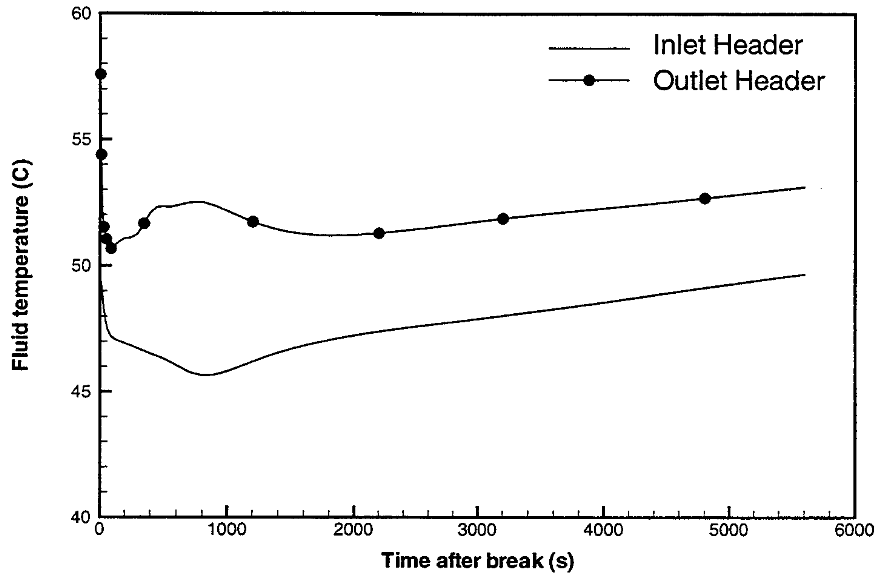


Figure BA-4 Fixed inlet/outlet header fluid temperatures for LOFA with a beam shutdown.

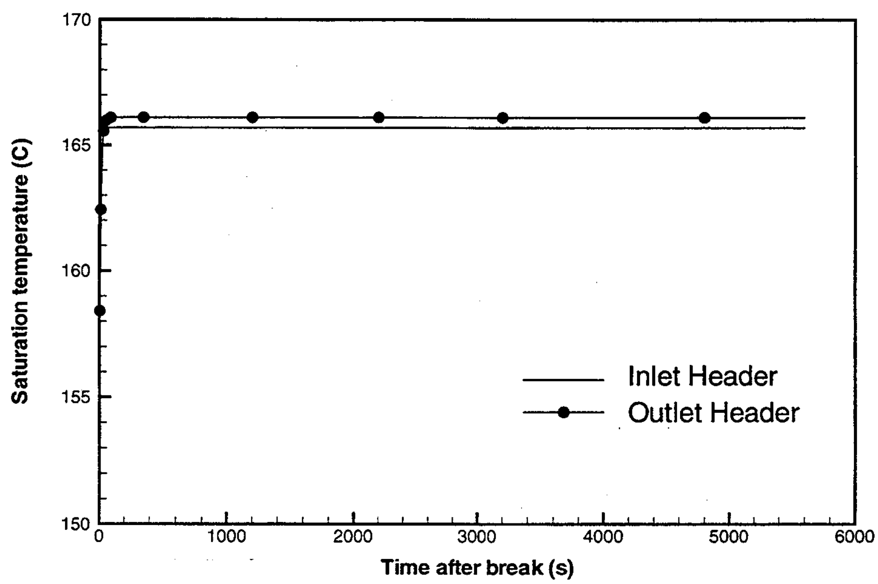


Figure BA-5 Fixed inlet/outlet header saturation temperatures for LOFA with a beam shutdown.

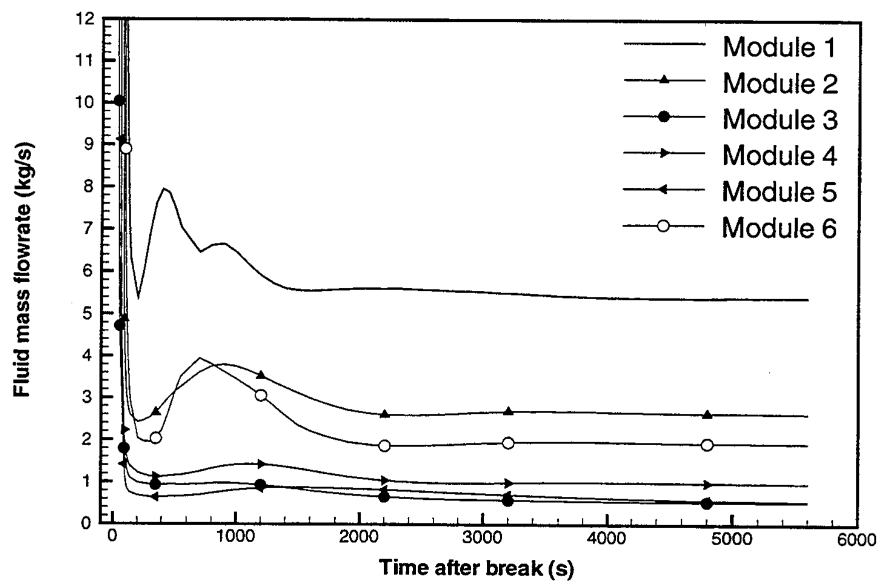


Figure BA-6 Individual module inlet mass flowrates for LOFA with a beam shutdown.

2.2.2 Discussion of the Natural Circulation Model and Results

A single-phase transient natural convection model of the blanket primary heat removal system was developed to determine the duration of effective passive cooling of the blanket during a LOFA, provided in Ref. BA-4. The blanket modules are modeled by a flow network with three parallel legs between the inlet and outlet fixed headers. One leg models the lateral row-one modules, another leg models the rest of the vertical modules, and the third leg models the horizontal modules. A fourth leg models the external portion of the HRS that contains the heat exchangers. The heat sink for this flow network is the fluid and metal on the shell sides of the heat exchangers. The shell side fluid is stagnant so it continually heats up, and there is no steady-state solution for the network flowrates. Figure BA-7 shows the flowrates within the network, while Fig. BA-8 shows the metal temperatures in the modules. The fluid and metal in a section of a module are lumped as single masses in the energy equations, and therefore the fluid and metal are assumed to be at the same temperature. This simulation starts at one hour into the LOFA. The initial system mass flowrate is predicted to be less than 6 kg/s while the TRAC model predicts a flowrate of approximately 13.0 kg/s. The reason for this discrepancy has not been determined as yet. It could be a function of the module lumping strategies in the two models. This flow resistance discrepancy should have a small impact on the temperature results due to the heat transfer limited shell side of the heat exchanger; however, efforts to resolve this difference are ongoing and should be resolved for the next PSAR revision.

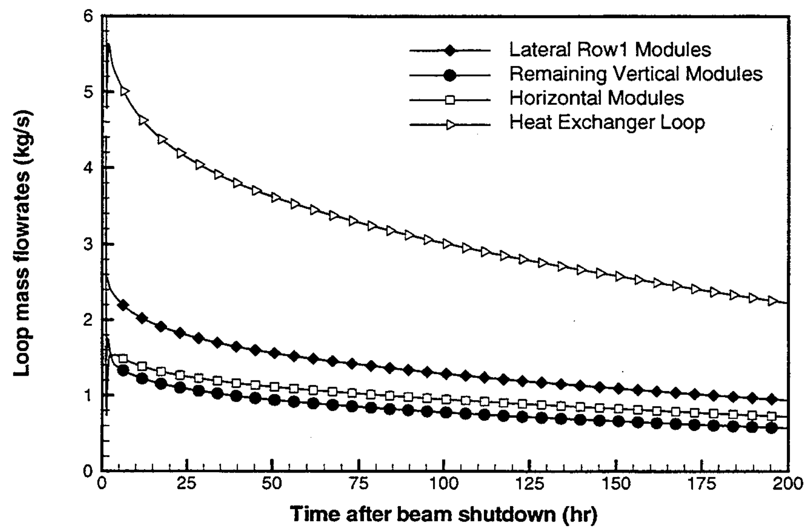


Figure BA-7 Blanket HRS natural circulation flowrates for a LOFA initiated by loss-of-power to the blanket HRS pumps and with beam shutdown.

The blanket modules reach the fluid saturation temperature of ~170°C in approximately 8 days. The model results for times subsequent to the fluid reaching saturation are meaningless since boiling would occur and the system would pressurize, (phenomena not considered in this single-phase model). A separate analysis is required for system behavior beyond the point where the fluid reaches saturation. Preliminary analyses indicate that the blanket aluminum structures may maintain their load carrying capability for more than 100 hours at 200°C under certain assumed set of stress conditions. These calculations suggest that the blanket structures may maintain their coolable geometries up to 200°C without significant deformations. Whether the modules could exceed this material temperature limit of 200°C during bulk boiling is dependent on the pressurizer relief valve set point. Once the system dries out, metal temperatures will rise above 200°C if no corrective actions are taken. However, given the magnitude of water present within the blanket modules the time required to reach this excursive situation is well in excess of 8 days. These analyses of post saturation system behavior have not been completed, but it will be performed for the next PSAR revision.

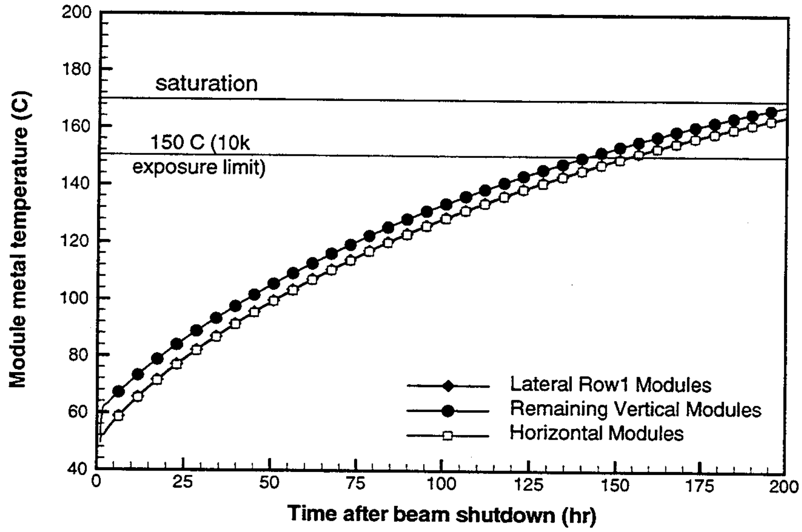


Figure BA-8 Blanket module temperatures for a LOFA initiated by loss-of-power to the blanket HRS pumps and with beam shutdown.

The following are important observations concerning the long term system response to an unmitigated LOFA:

- The system takes ~8 days for the modules to reach the saturation temperature of 170°C. This is sufficient time for the problem to be identified and mitigating measures such as restoring power to the pumps to be taken.
- A saturation temperature of 170°C corresponds to a pressure in the modules of 115 psia, and a saturation temperature of 200°C corresponds to a pressure of 226 psia. Setting the pressurizer relief valve set point such that the pressure in the modules remains below 226 psia would ensure that the modules remain below the material temperature limit of 200°C during the boil-off phase of the accident.
- The mass of fluid in the pressurizer has been neglected. This represents a sizable fraction of the total system inventory. The pressurizer is connected to the inlet header by a surge line and it is at a higher elevation. While the actual mixing rate could be difficult to quantify, it is inconceivable that there would be no mixing between the hot fluid in the inlet header and cold fluid in the pressurizer. Inclusion of this heat sink in the model would significantly extend the time required to reach saturation.
- At the very low decay power levels eight plus days after beam shutdown (i.e., approximately 0.2% or less), boil-off rates will significantly extend the corrective action period prior to experiencing the onset of temperature excursions within the blanket module materials.

2.2.3 Summary and Conclusions

Without taking any corrective measures, the above results indicate that peak metal temperatures for lead and aluminum within the bins of the blanket modules remain below the fluid saturation temperature for approximately 8 days. Current thermal/hydraulic design criteria impose transient metal temperature limits on lead and aluminum of 327.5°C and 150°C, respectively, based on a limit for no more than a 10k hour exposure (see Appendix DB). Work is currently in progress to raise the aluminum limit higher. According to the ASME code, material allowable stress is a function of the load condition. For once in a lifetime events for equipment that will not be reused, the allowable stress may be increased by a factor of 2.4. Stress analyses are being performed assuming 200°C under specified loading conditions. These results will be presented in next PSAR revision.

In these accident simulations, credit was taken only for the *safety class* beam shutdown system. While the analyses are not complete, it is evident that no margin exists to prevent the loss of coolable geometry unless some sort of corrective measures are taken. The time period within which corrective action must be taken is very long (200 hours just to reach the saturation temperature) and it is unrealistic to assume that the accident would be allowed to progress longer than a week without additional administrative measures, such as:

- restoring AC power to the facility;
- bringing in temporary power supplies to operate the RHR and secondary HR systems or cavity flood systems;
- replenishing primary HR coolant that is boiled-off through purification lines (only a few gpm would be required); or
- reducing system pressure using controls to the pressurizer gas supply system. Reducing system pressure to atmospheric would allow the onset of bulk boiling to occur at approximately 120°C; thus, maintaining a coolable blanket geometry. This action would require the replenishing of primary HR coolant.

In conclusion, the consequences for this event sequence, if no corrective action is taken, are similar to those for event sequence 1, as shown in Table BA-1. Based purely on the conservative exposure assessment given, the RHR or cavity flood systems would not in-and-of-themselves be required to be designated *safety-class* functions. However, during a complete facility loss-of-power the potential loss-of-coolable blanket module geometries could result in an impact to their neighboring target ladders. Details addressing this combined target and blanket LOFA are discussed in Appendix TBA.

Based on considerations to be discussed under event sequence 4, the RHR system becomes the preferred choice for mitigation. The RHR system is designed for operation in standard shutdown modes. The cavity flood system can fully mitigate this accident as is shown in the discussion of event sequence 3. The RHR is preferred over the cavity flood because there is much less involved in returning to normal operation following such an accident.

2.3 LOFA with Beam Shutdown and Cavity Flood (Event Sequence 3 in Figure BA-2)

This is a DBE sequence with a frequency estimated in the extremely unlikely range. The preferred mitigation option for a LOFA is the use of the blanket RHR system(s). The cavity flood system is activated only if neither RHR system successfully mitigates the event sequence by reducing coolant temperatures to or below their pre-incident values. The primary function for the cavity flood system is to mitigate the consequences resulting from internal (as well as external) loss-of-coolant accidents (LOCAs) within the target and blanket primary HR systems. The primary signals that activate the cavity flood are: (1) the system pressure; (2) the pressurizer level, and (3) liquid inventory on the floor of the cavity vessel. During the early phase of a LOFA, no liquid inventory is lost and the system pressure either remains constant or increases due to the approach to near hydrostatic conditions within the blanket modules. The pressurizer level remains nearly stationary until coolant inventory is lost (e.g., loss through the pressure relief valve). Inventory loss occurs as a result of net-steam production, which can only occur very late into the transient under low decay heat conditions. Therefore, it is extremely unlikely that the cavity flood option will be inadvertently actuated or needed to mitigate a LOFA, unless the LOFA progresses to a point where the coolant loop is breached and a LOCA is initiated. For the blanket systems the cavity flood system's cooling capability for receiving decay heat from the modules provides a defense-in-depth strategy.

As demonstrated in Ref. BA-5, the plate-type blanket design is very robust from a thermal perspective. The main feature of the plate-type design is its continuous heat structure at the bin level with discrete one-dimensional flow channels (of simple well known shapes) dispersed throughout the heat structure. For the highest powered modules (i.e., front/back lateral and downstream row-1/decoupler modules) the horizontal conduction path lengths are kept to a minimum by allowing each plate component to be in direct contact with neighboring cavity vessel spaces.

Results from Ref. BA-5 (and further discussed in Ref. BA-6) indicate that the plate-type design modules can by heat conduction alone transfer all of their decay heat to neighboring flooded cavity spaces (typically, small rectangular gaps on the order of one to one and a half inches wide). An evaluation model (EM) was developed based on several conservative assumptions (see Ref. BA-5) to demonstrate the robust capability of the cavity flood system. This EM consists of a three-dimensional finite element conduction model of a section of a plate-type component driven by conservative boundary conditions. A summary of this EM and its key results are discussed below.

As provided in Ref. BA-3, flywheel inertia extends the period of forced convective flow out beyond 100 seconds after beam shutdown. As shown in Fig. BA-4, between 100 and 2000 seconds the primary coolant system transitions into natural circulation (in a mixed convection mode). Beyond 2000 seconds, single-phase natural circulation persists until saturation conditions are reached approximately 200 hours later (see Fig. BA-8). However, in the EM it is assumed at 100 seconds that successful transition to natural circulation is not achieved and that a complete loss of liquid coolant inventory (i.e., dryout conditions) results in one or more of the module units. Figure BA-9 illustrates the relative elevations of various key cavity vessel components. As shown in Fig. BA-10, upon actuation of the cavity flood system all modules are covered with subcooled water in less than 100 seconds and by 800 seconds the tops of the fixed headers are covered.

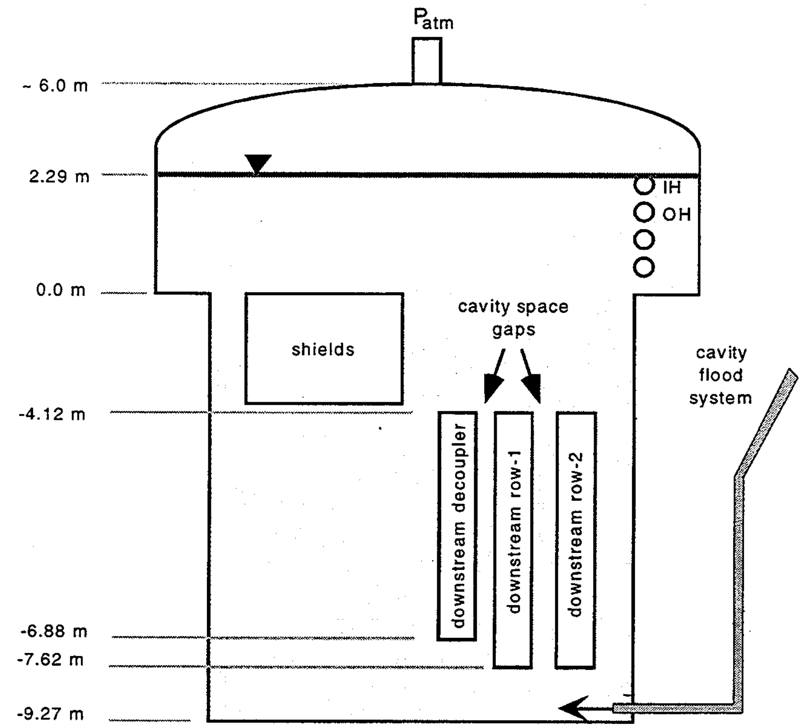


Figure BA-9 Vertical cross-sectional view of Target/Blanket vessel highlighting the elevation of key cavity vessel components.

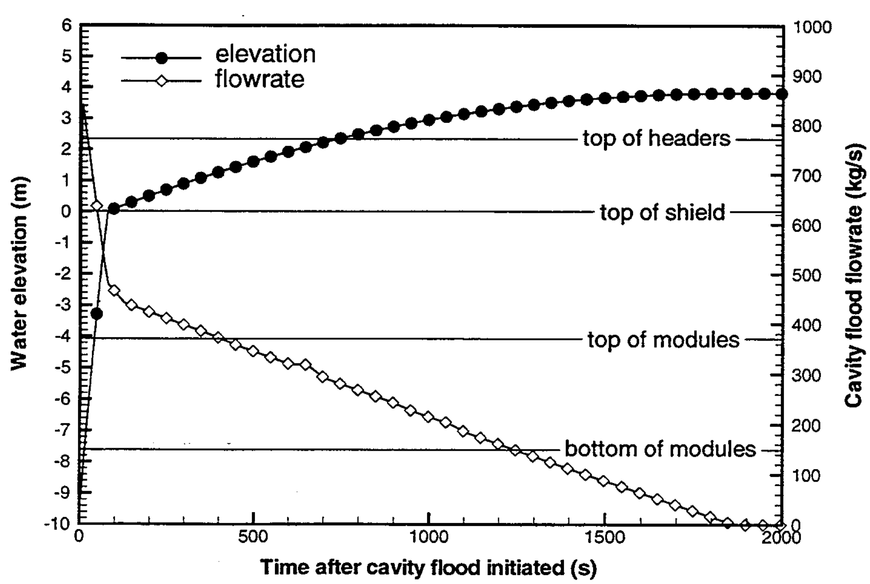


Figure BA-10 Timing associated with covering certain key cavity vessel components once a cavity flood actuation has been initiated.

For conservatism the component with the highest power density is considered (i.e., the downstream Row-1 component). A plan view of the model's mesh and boundary locations are provided in Fig. BA-11. Bounding fluid heat transfer conditions along the surfaces of the plate in contact with the cavity space are set based on the following assumptions:

- The hydrostatic pressure profile within the cavity space is computed based on the maximum level of water achievable. This maximizes the saturation temperature and extends the region where low single-phase heat transfer is present.
- The mixed convection heat transfer coefficient within the cavity spaces (i.e., gaps) is limited to the laminar value for the largest expected gap widths of one inch.
- The boiling heat transfer coefficient within these gaps is set to the pool boiling value corresponding to a wall superheat of 10 C.
- The onset of subcooled nucleate boiling is delayed until a value of 15 C wall superheat has been reached.
- Initial metal temperatures are set to 100 C. Actual conditions should correspond to 50-60 C, however, the final results are reasonably insensitive to this value.
- Adiabatic boundary conditions are applied at the top and bottom of the plate component thermally separating it from neighboring solid structures (i.e., potential heat sinks).

Also, under the assumed complete dryout conditions it is further assumed that adiabatic boundaries exist between the plate and the fluid within the discrete flow channels.

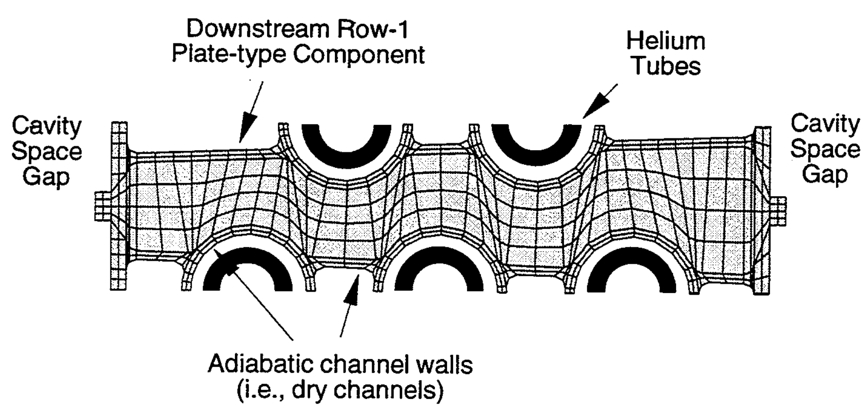


Figure BA-11 Plan view of downstream Row-1 plate-type component highlighting thermal boundary conditions used.

Results of maximum aluminum/lead metal temperature based on the above EM are shown in Fig. BA-12. As illustrated in Fig. BA-12 for early times, the maximum metal temperature exceeds the steady-state design criteria of 115 C, but then drops below this limit beyond approximately 80 hours. At no time during this event sequence does the maximum metal temperature exceed its 10k hour exposure design criteria of 150 C.

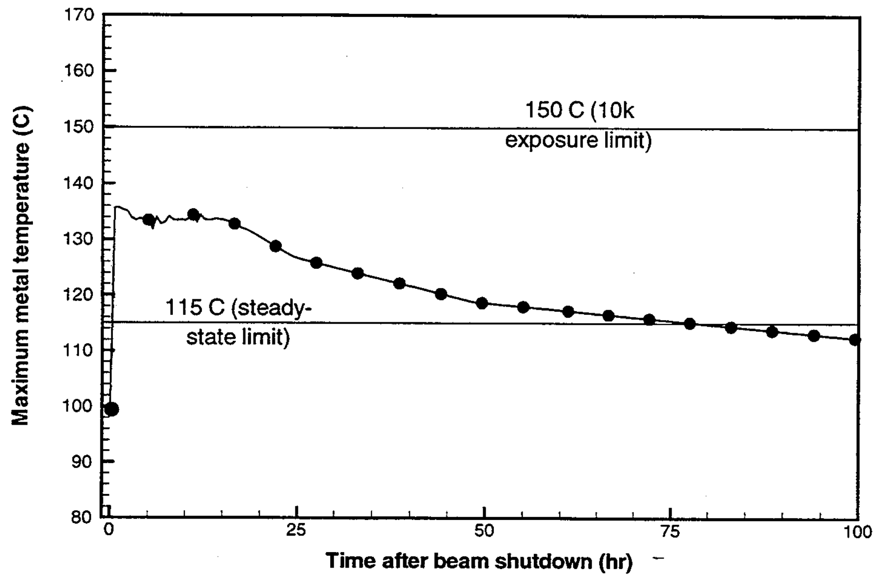


Figure BA-12 Downstream Row-1 plate-type maximum metal temperature response to channel dryout conditions initiated at 100 seconds after beam shutdown.

In this analysis, credit is taken for the cavity flood system and a beam shutdown. It is assumed that the cavity flood system successfully floods the cavity vessel within stated timing and dumps all decay heat received. For this particular analysis the cavity flood system becomes the only ultimate heat sink available. To ensure that the heat transfer rates predicted were achievable, a separate study was performed (see Ref. BA-7) to determine the maximum amount of power that can be transferred from the bin wall over to the cavity space without experiencing a counter-current-flow limitation (CCFL) within the flow gaps. The current spacing (i.e., one inch maximum and one half inch minimum) between neighboring blanket modules can accommodate all expected power loads without a CCFL phenomenon occurring. No credit is taken for the various conduction paths available to the surrounding building structures and ground. No credit is taken for any natural circulation patterns that may exists within the primary HR loop or the physical time required for inventory leakage or boil-off.

Based on single-phase natural circulation the analyses provided in Section 2.2 indicate that, during a LOFA, there is ample time (i.e., on the order of 4 to 8 days) to activate the cavity flood system. For dryout times greater than 100 seconds, the conservative analyses discussed above indicate that the cavity flood system is quite capable of preventing metal temperatures within the blanket aluminum/lead components from exceeding design limits where coolable geometries are no longer achievable. By maintaining metal temperatures below the 10 K hour 150 C material temperature limit ensures that reuse of these blanket components is acceptable. As such, the cavity flood system is defined as a *safety significant* function being designed to safety class standards (mainly for worker safety and investment protection). The control associated with the activation of the cavity flood upon loss of pressurizer inventory is a *safety significant* control. For a LOFA only, there is no loss of inventory; therefore, as a defense-in-depth control the cavity flood system is activated if:

- forced circulation in the HR or RHR loops cannot be established within 125 hours after the initiation of the LOFA; and/or
- the RHR heat exchanger inlet temperature cannot be stabilized at or below 90 C after 2 hours of RHR flow initiation.

Because of the extended duration for the necessary response, a manual cavity flood activation option would be appropriate as a defense-in-depth with regard to LOFA mitigation.

For LOFAs where cavity flood mitigates the event, the ability of the cavity vessel to retain the water is credited. Also the beam window must be capable of withstanding the full hydrostatic pressure under cavity flood. Based on these considerations, integrity of the cavity vessel and beam window are designated to perform *safety-significant* functions

2.4 LOFA with Beam Shutdown and Active RHR (Event Sequence 4 in Fig. BA-2)

This is the DBA for a blanket LOFA within the anticipated frequency. Activation of the RHR system is the preferred mitigation strategy for addressing a LOFA initiated by loss-of-power. A number of TRAC/FLOWTRAN-TF simulations were performed for this event sequence (Ref. BA-8). The integrated 1-D lumped TRAC system model used for these simulations is described in Ref. BA-2. The detailed 3-D FLOWTRAN-TF bin model used for these simulations is described in Ref. BA-9. The methodology employed and code-to-code interfacing are addressed in Ref. BA-5. In general, the calculations used best-estimate values for input parameters. At this time no quantification of confidence levels or uncertainties is attempted. Further uncertainty analyses along with verification of the lumping strategies are planned as future calculations to be provided in the next PSAR revision.

The initiating event represents a loss-of-power to the primary, secondary, and tertiary pumps within the blanket HR systems. For the LOFA scenario, it is assumed that the trip signal to shutdown the beam is initiated based on a 5% reduction in pump pressure drop on either of the primary HR pumps. Signal detection occurs within a few tenths of a second following the initiating event. The trip signal is activated approximately 0.2 seconds after the initiating event occurs. For the base case analysis a conservative 1 second time delay to account for signal processing is assumed (i.e., best estimate values range within 0.1 to 0.2 second delays). For other supporting cases the time delay becomes a parameter that is varied over a wide range. Actual beam shutdown begins to occur at approximately 1.2 seconds after the initiating event occurs in the simulations.

The primary RHR pumps are activated at approximately 0.2 seconds and have an approximate 15 second ramp up period to reach full capacity. As our worst case failure, one of the two RHR pumps is assumed to fail. Full capacity of an individual RHR primary pump is set to 4% of the pre-incident primary HR flowrate. The accident simulation lasted for 600 seconds, long enough for the severe transients to die out, and for temperatures, pressures, and flows to stabilize at acceptable values. Results from the simulation are summarized in Figs. BA-13, BA-14 and BA-15.

Figure BA-13 shows mass flowrates in the pressurizer surge line, primary HR cold leg, and primary RHR loop during the LOFA scenario. In the HR loop, coolant flow drops from the normal operating value of 1569 kg/sec relatively quickly during the first 90 seconds of the accident. Beyond 90 seconds, there is still a small flow in the loop driven by natural circulation. The RHR system is activated and reaches full flow of 62 kg/sec (4% of the normal operation HR flow) about 20 seconds into the accident. There is negligible flow in the pressurizer surge line during the LOFA transient.

Figure BA-14 shows transient pressures in the fixed inlet and outlet headers. Pressure at the outlet header increases approaching a hydrostatic limit as flow is lost since the system loops remain intact and full of water. The blanket gas within the pressurizer establishes the long term system pressures based on its pre-incident inventory. After about 60 seconds of elapsed time, the header pressures are essentially constant. There is no void formation anywhere within the loops or blanket modules during the LOFA scenario.

Figure BA-15 shows fluid temperature at the inlet and outlet headers during the LOFA transient. Upon the loss-of-power initiating event, mass flowrate within the secondary (i.e., shell) side of the primary heat exchangers (HXs) decays to near zero following a decay curve similar to that for the primary loop. The pre-incident inlet temperature to the shell side of the primary HXs was 43 C. As beam power drops, the temperature at the outlet header falls from 58 C to about 50 C. Temperature at the inlet header is relatively constant throughout the transient. Over the first 40 seconds, the inlet temperature falls about 2 C and then increases to reach a constant value of about 48.5 C late in the accident. The initial fluid temperatures within the stationary RHR system were set to 40 C (i.e., the maximum expected annual building temperature) with an inlet temperature to the shell side of the primary RHR HX of 40 C as well.

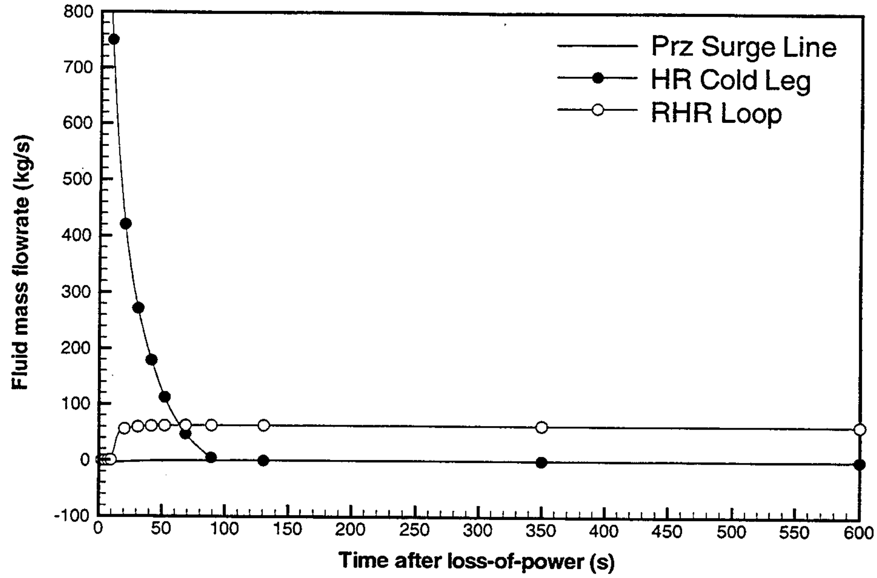


Figure BA-13 Primary HR, RHR, and pressurizer liquid mass flowrates during a LOFA with beam shutdown and active RHR.

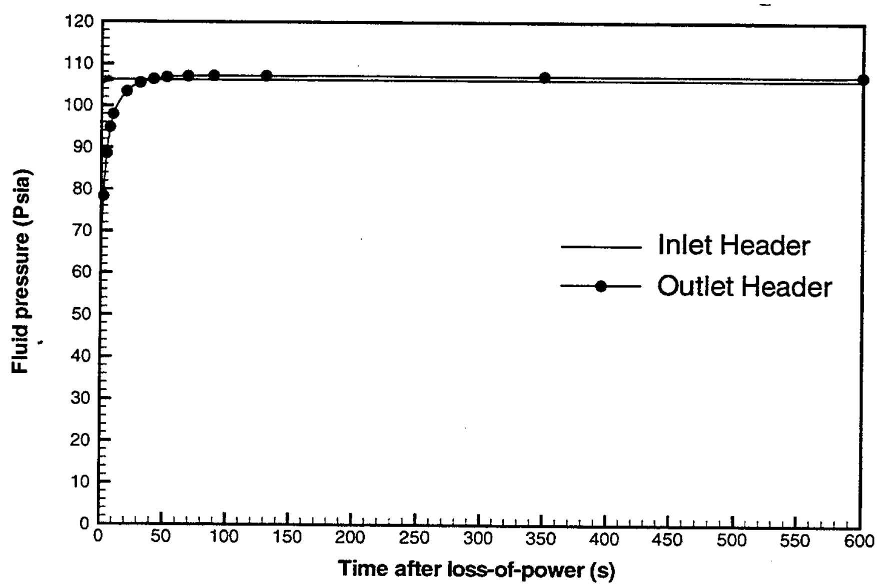


Figure BA-14 Fixed inlet and outlet fluid pressures during a LOFA with beam shutdown and active RHR.

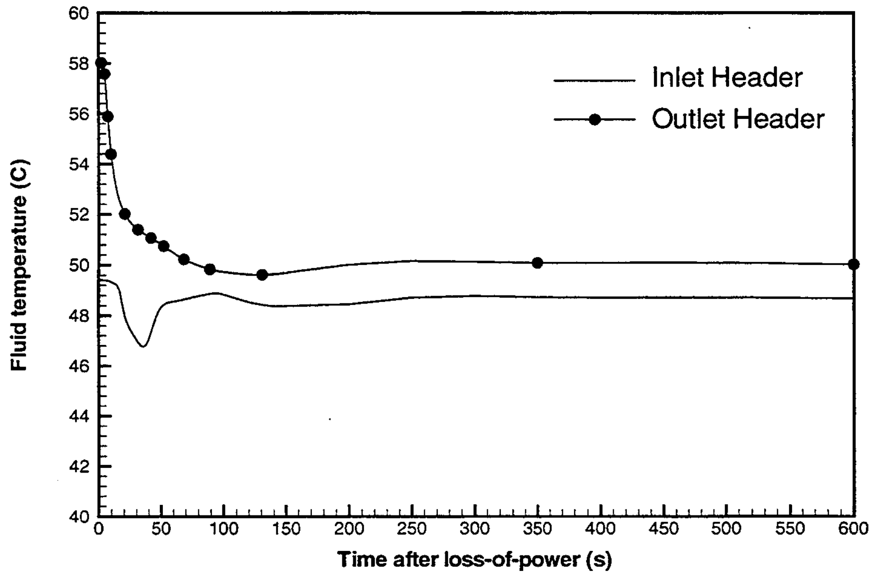


Figure BA-15 Fixed inlet and outlet fluid temperatures during a LOFA with beam shutdown and active RHR.

A summary of the results from the FLOWTRAN-TF model of a module 1 plate-type assembly are presented in Figs. BA-16 and BA-17. Figure BA-16 shows the transient peak aluminum clad and lead temperatures, along with their specified material design criteria. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1, is 112.8 C in the lead plate. This is well below the lead melting point of 327.5 C. The peak aluminum temperature is about 100 C, which is below the long term exposure temperature limit of 115 C. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the beam. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially pre-incident values. Actually, maximum metal temperatures would be reached 1 second after the start of the accident when the beam trips (i.e., in general maximum metal temperatures correspond roughly with the point in time when the beam begins to shut down). However, the thermal inertia of the solid is such that this brief time delay is negligible.

It is clear from the peak aluminum temperatures that the channel surface temperatures are substantially below local saturation conditions. To further illustrate the safety margins, operating surface heat fluxes (q_{ohf}) were compared to the heat fluxes predicted for onset of nucleate boiling (q_{onb}), onset of significant void formation (q_{osv}), and the critical heat flux (q_{chf}). Fig. BA-15 shows transient axial peak operating surface heat fluxes and local values for the three boiling heat flux limits for channels 1 and 8. Also shown are plots of the wall, fluid, and saturation temperatures. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, while channel 8 is the adjacent annular flow channel. The large margins between the operating heat flux and the boiling limits are readily apparent. Similar results were obtained for the other ten flow channels.

Notice that the CHF limits are predicted to be lower than the OSV limits. These plots misleadingly imply that CHF would be encountered before OSV if the inlet subcoolings and flowrates in the channels were reduced; while in reality the limits would cross as they were approached and OSV would be reached prior to CHF.

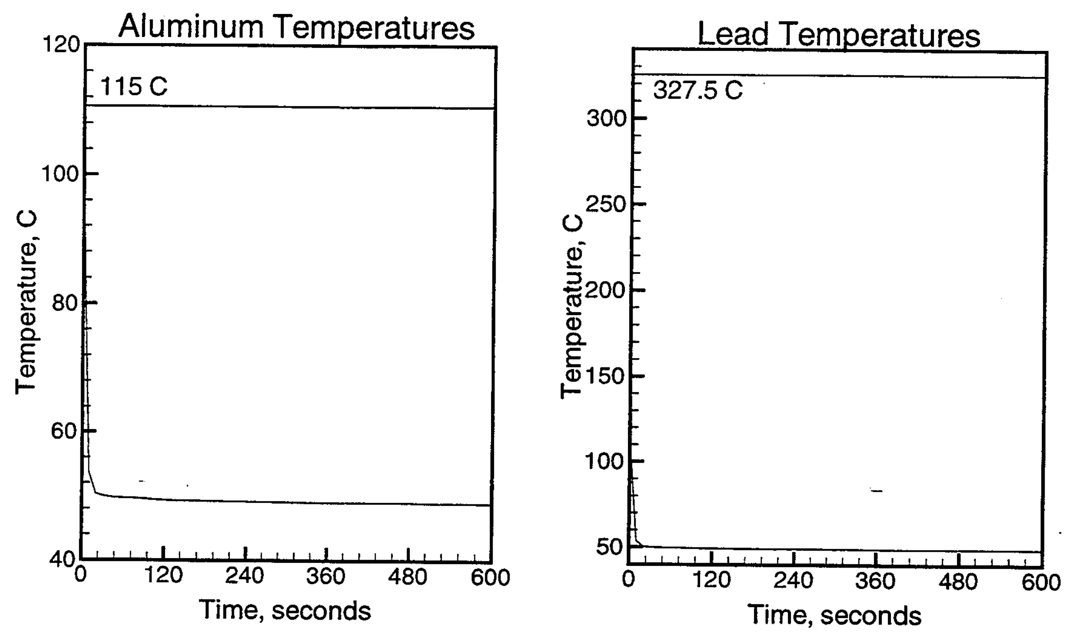
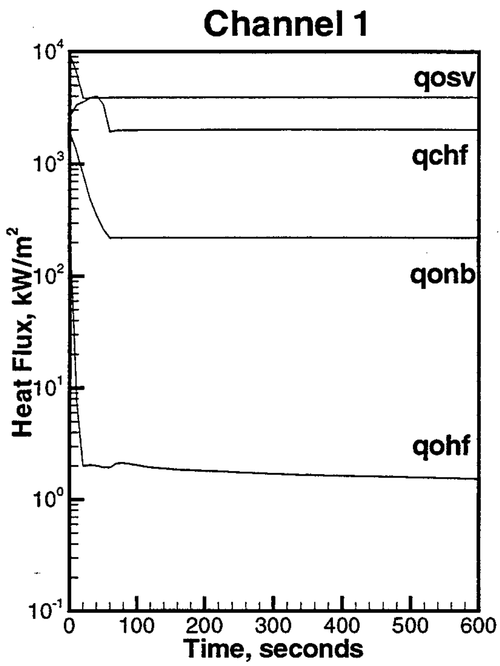
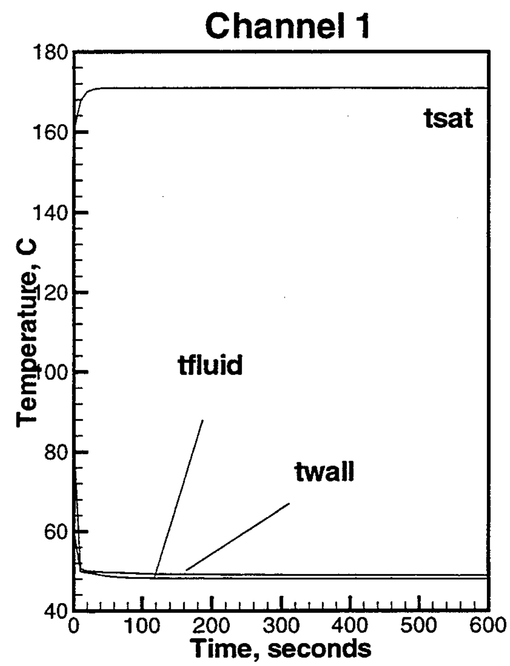
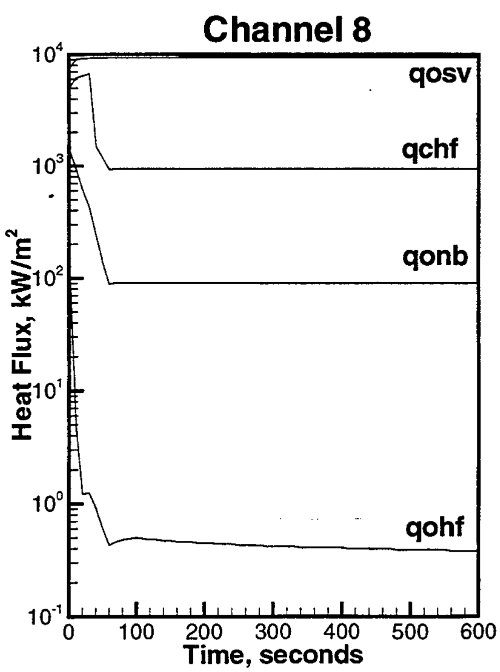


Figure BA-16 Maximum metal temperatures in module 1.


Channel 1
qosv
qchf
qonb
qohf
Heat Flux, kW/m2
Time, seconds


Channel 1
tsat
tfluid
twall
Temperature, C
Time, seconds


Channel 8
qosv
qchf
qonb
qohf
Heat Flux, kW/m2
Time, seconds

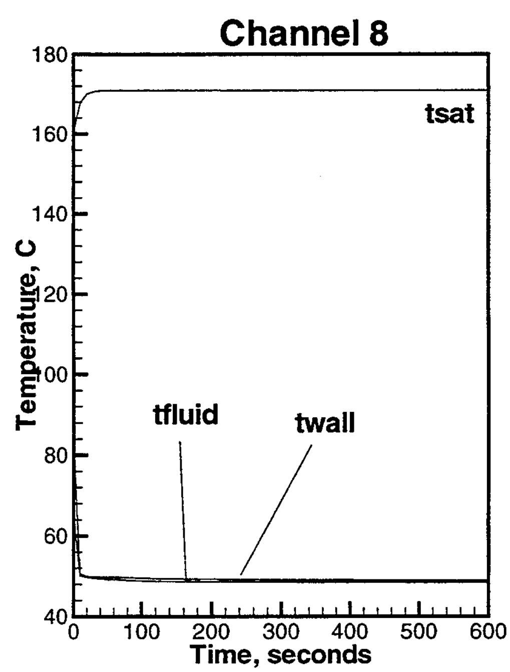

Channel 8
tsat
tfluid
twall
Temperature, C
Time, seconds

Figure BA-17 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

On a module-by-module basis, the steady-state material and thermal onset criteria for LOFA can be compared to results from the FLOWTRAN-TF detailed bin model. The bin model results for the reference 1 plate-type module are tabulated in Table BA-3 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 were not available at the time of the analysis; as plate-type designs for the remaining modules become available similar analyses will be performed and provided in the next PSAR revision). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BA-3. Note that these are generally more stringent than the imposed design criteria chosen.

Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BA-3 represent essentially best estimate values. Quantification of overall uncertainties and their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined and the results will be provided in the next PSAR revision.

Table BA-3 FLOWTRAN-TF model results under LOFA conditions.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio	Max ONB Ratio	Max OSV Ratio	Max CHF Ratio
1	112.8	100.0	0.301	0.150	0.165	0.032	0.150
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD	TBD	TBD	TBD

The quickest signal indicating a LOFA would be loss of pump current, this signal is almost instantaneous and the beam can be shut down in less than 200 ms after the signal. As expected, the TRAC results provided in Ref. BA-8 shows that if the beam is shut down in 0.2 seconds into the transient and the RHR pumps are started 1.0 seconds into the transient, the system remains coolable throughout the transient and reaches a highly subcooled end-state.

In Ref. BA-8, a parametric study was performed to investigate the impact in the delay time in shutting down the beam, starting the RHR pumps, and the level of RHR pump flow. Delayed beam-shutdown and RHR pump start-up cases also were investigated to address the issue of single-failure to detect the loss of pump current. The results in Ref. BA-8 show that the beam shutdown and the RHR pump startup can be delayed for as along as 30 seconds into the transient while maintaining adequate margin to incipient boiling. As shown in Fig. BA-13, at t = 30 seconds into the transient, the flow in the primary loop reduces by about 80% which is easily detectable. Figure BA-13 shows the flowrate in the RHR loop as well. As shown in this figure, the flow in the RHR loop reaches the design value in 20 seconds after the RHR pump is started.

Simulations performed using the TRAC system model and the FLOWTRAN-TF detailed bin model show that the APT blanket modules maintain a coolable geometry during this LOFA scenario. Blanket conditions during this LOFA scenario fall within all specified thermal/hydraulic design criteria. No onsite or off-site impact to people or the environment would occur as a result of a LOFA with a beam shutdown and an active RHR system.

As discussed previously, the radioactive material releases during a LOFA are negligible even without the RHR system(s), given a safety class beam shutdown system. Based purely on the LOFA analyses, the RHR systems would be considered a as defense-in-depth feature. Actuation of RHR maintains metal temperatures below the 10 K hour 150 C material temperature limit ensuring that reuse of these blanket components is acceptable. However, if a LOFA is allowed to progress for a long time without active cooling by the RHR systems or cavity flood system, then overheating of blanket modules may occur resulting in unacceptable deformation of structural components (and their ultimate replacement required). As such, the RHR systems are defined as a *safety significant* function (mainly for worker safety and investment protection considerations).

2.5 LOFA with Beam Shutdown, Active RHR and Cavity Flood (Event Sequence 5 in Fig. BA-2)

As discussed under Section 2.4, the desired mitigation strategy for a LOFA is to remove the blanket modules decay heat with the RHR system(s) after the beam is shutdown. Signal detection for example by a loss in electrical power or a 5% pump pressure drop occurs within tenths of a second. The beam is shutdown immediately following a signal detection, but due to the massive thermal inertia contained within the blanket modules delay times of tens of seconds are acceptable. The RHR system(s) is actuated upon receiving a signal that a LOFA has been initiated within the HR systems as well.

During the earlier portion of the HR pump coastdown phase, the RHR pumps are ramped up to full capacity. Initially, upon a beam shutdown fluid temperatures begin to drop due to the existing (but dropping much slower than the decay power curve) primary HR system flowrate. For approximately 40 to 50 seconds small temperature swings are observed. At approximately 100 seconds after the initiating event fluid temperatures equilibrate to values at or below their pre-incident values.

The cavity flood system is activated only if the RHR system(s) becomes unsuccessful in mitigating the event based on monitored fluid temperatures. The use of the RHR system(s) along with cavity flood is not a design choice and can happen accidentally. The inadvertent actuation of the cavity flood system when monitored parameters indicate that RHR is successful places this event sequence in the extremely unlikely category. The actuation of cavity flood does not interfere with the cooling capability of the operating RHR system(s) and only assists in the removal of decay heat by further blanket temperature reductions. The conductive capability of the plate-type blanket modules to dump all of their decay heat to their neighboring cavity spaces when flooded has been demonstrated in Ref. BA-5 and summarized in Section 2.3. This conductive feature adds to the overall heat removal capability already present. As such, this event sequence is bounded by the event sequences 3 and 4 and has no consequences.

3 LOFA without Pump Coastdown

The distinct feature of a blanket LOFA initiated by a mechanical pump failure is that there is no coastdown period associated with flywheel inertia. During a mechanical pump failure, it is conservatively assumed that rotation of the impeller blades stop instantaneously. Very rapid de-acceleration occurs with the failed pump acting as a simple momentum sink. However, unless the same failure occurs simultaneously in both 50% capacity pumps, one of the pumps (referred to here as the spare pump in the subsequent discussions) will continue to run after the failure of the first pump (noting that some of the original hydraulic load handled by the failed pump is quickly shifted over to the operating spare pump). Simultaneous mechanical failure of both pumps is extremely unlikely, but is considered as a BDBA. The event tree for LOFAs that are initiated by mechanical pump failure(s) is shown in Fig. BA-16. Similar behavior is observed for spurious valve closures within a given pump leg. However, in the spurious valve closure case neither forward or backward flow can occur through the affected pump.

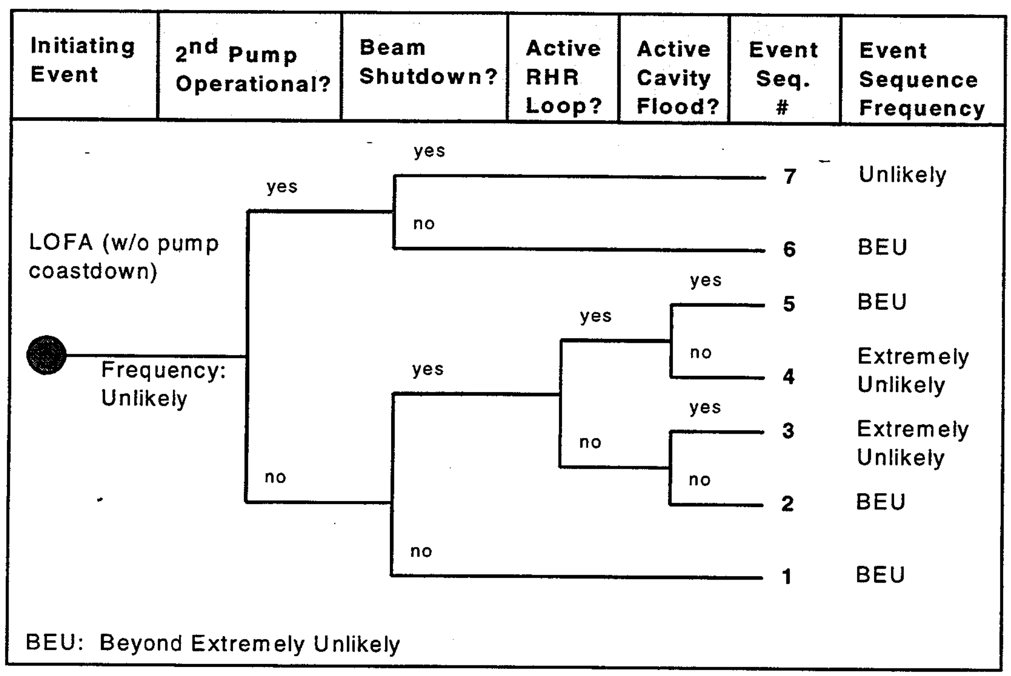


Figure BA-18 Event-tree for LOFAs initiated by mechanical pump failure(s).

3.1 LOFA without a Beam Shutdown or Spare Pump (Event Sequence 1 in Fig. BA-18)

Given a safety class beam shutdown, this event sequence is in the beyond extremely unlikely range. Nonetheless, the consequences are bounded by the analyses provided in Section 2.1. No specific beyond design basis analyses are performed for this case since the frequency of such an event is outside the realm of credible events. However, the arguments made for the BDBE for a LOFA with pump coastdown (Section 2.1) are applicable to this case as well.

3.2 LOFA without a Spare Pump and with a Beam Shutdown (Event Sequence 2 in Figure BA-18)

The accident analysis for this scenario is similar to the analysis provided in Section 2.2 for the LOFA with a beam shutdown. Based on the analysis provided in Ref. BA-3, the consequences of this event sequence are similar to the consequences given in Section 2.2. Compared to the scenario in Section 2.2, with the shorter primary HR flow coastdown duration during this event sequence a modest increase in system temperatures occur earlier on. However, at these very low decay powers sensible heat-up times remain significant. The frequency of this event is in the beyond extremely unlikely range.

3.3 LOFA without a Spare Pump, with a Beam Shutdown and Cavity Flood (Event Sequence 3 in Figure BA-18)

The accident analysis for this scenario is similar to the analysis provided in Section 2.3 for the LOFA with beam shutdown and cavity flood. Their are no consequences associated with this event sequence similar to the results given in Section 2.3. Similar to the previous case, the impact of earlier flow coastdown has negligible impact on the time to onset of bulk boiling. The frequency of this event is in the extremely unlikely range.

3.4 LOFA without a Spare Pump, with a Beam Shutdown and Active RHR (Event Sequence 4 in Figure BA-18)

The accident analysis for this scenario is similar to the analysis provided in Section 2.4 for the LOFA with beam shutdown and active RHR. Similar to the results given in Section 2.4, there are no consequences associated with this event sequence. The analyses provided in Ref. BA-8 show that if the beam is shutdown 40 to 50 seconds into the transient and the primary RHR pumps reach full 4% design capacity within 70 seconds into the transient, RHR maintains a coolable blanket geometry. Compared to the scenario in Section 2.4, with the shorter primary HR flow coastdown duration during this event sequence a modest increase in system temperatures occur earlier on. However, significant thermal margins exist to easily accommodate these increases.

3.5 LOFA without a Spare Pump, with a Beam Shutdown, Active RHR and Cavity Flood (Event Sequence 5 in Figure BA-18)

The accident sequence is bounded by the analyses provided in Sections 3.3 and 3.4 above; therefore, no consequences are associated with this event sequence. This event sequence is in the beyond extremely unlikely frequency range.

3.6 LOFA with a Spare Pump and without a Beam Shutdown (Event Sequence 6 in Figure BA-18)

This event sequence is in the beyond extremely unlikely frequency range. The consequences of this sequence are bounded by the consequences presented in Sections 2.1 and 3.1. It is anticipated that during reduced flow safety margins may still exists during the event sequence. Future analyses are necessary to confirm the above conclusion speculation and will be provided in the next PSAR revision.

3.7 LOFA with a Spare Pump and with a Beam Shutdown (Event Sequence 7 in Figure BA-18)

This is the DBA event sequence which is in the unlikely frequency range. As long as the beam is shutdown, the remaining plus 50% coolant flow in the primary HR system loop is more than sufficient to remove the decay heat (especially when compared to the 4% primary RHR coolant flow assumed in Sections 3.4 and 2.4 above). This event sequence is bounded by the analyses provided in Sections 3.4 and 2.4 above; therefore, no consequences are associated with this event sequence.

6 Summary and Conclusions

In this appendix, results were presented for the accident analyses of blanket only LOFAs with and without pump coastdown. For results addressing combined target and blanket LOFAs see Appendix TBA. For results addressing LOFAs associated with partial or complete flow blockages within the blanket system see Appendix BG.

Table BA-4 provides a summary of the predicted onsite and off-site consequences for every event sequence analyzed. These results show that, no radioactive material releases to the environment occur for DBA scenarios. Zero release is associated with the maintaining of a coolable blanket geometry throughout each event sequence.

For many of the BDBA event sequences maximum metal temperatures do not every exceed their material limits such that replacement of blanket modules would be necessary as a post-incident cleanup activity. For the BDBA event sequences, those event sequences without a beam shutdown, or without either an active intact RHR or cavity flood system with no corrective action for several days, could result in the loss of a coolable blanket geometry. For the case where there is a failure to shutdown the beam the blanket would be severely damaged and the releasable inventory could be released. The bounding onsite and off-site consequences corresponding to the total release are shown in Table BA-4. This total release represents 2% of the mercury inventory, the entire tritium inventory (i.e., gaseous tritium in the helium system and the tritiated water in the activated primary coolant, assumed to be in the oxide form), and the activity in the coolant including 100% of the noble gases, and a fraction of the other isotopes (see Appendix CC).

Table BA-4 Summary of consequences for each event sequence analyzed.

Analysis Bin	Event Sequence (id)	Event Sequence Category	Onsite Dose (rem)	Off-Site Dose (rem)
LOFA with pump coastdown	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	DBA	none	none
	4	DBA	none	none
	5	DBA	none	none
LOFA without pump coastdown	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	DBA	none	none
	4	DBA	none	none
	5	BDBA	none	none
	6	BDBA	none	none
	7	DBA	none	none

6.1 Credited SSCs

For the LOFA analyses, the following SSCs are credited:

- Primary and back-up beam shutdown is determined to serve a safety class function;
- RHR pump(s) activation is determined to be a safety significant function;
- Manual cavity flood based on extended inability to restore forced circulation to the blanket is determined to be a defense-in-depth function; even though, the cavity flood is a safety significant system it is being deigned to safety class standards.
- The cavity vessel and the beam window are determined to serve safety significant functions.

6.2 Summary of Control Logic and TSRs

The quantitative set of control logic for blanket LOFA mitigation and the associated parameters are summarized in Table BA-5. This table is provided as an input for the development of the TSRs. Table BA-5 shows the signals based on the primary loop and cavity vessel measurements. For a LOFA, the cavity flood is automatically activated based on the RHR loop measurements. The cavity flood is manually activated after a maximum waiting time of 15 minutes if either one of the following conditions occurs:

- Total RHR flow (considering both RHR systems) is less than 4% of the normal operating flowrate; or
- The RHR loop heat exchanger inlet temperature(s) exceeds TBD.

Table BA-5 Shutdown and Startup Set-Points for Blanket LOFA Mitigation.

Signal	Beam Shutdown	RHR Start	Comment
PRIMARY LOOP			
Pumps (each)			

-Current or Voltage	75%	NA	Fastest LOFA indication
-Speed	75%	NA	Fastest LOFA indication
Flow Rate			
- Pump Exit	75%	75%	~60% used in the BE analysis
- Pump Inlet	75%	75%	Not used in the current analysis
Pressure			
- Pump Inlet	90% or 110%	150%	Not used in the current analysis Less conservative then current analysis
Temperature			
- HX Inlet	80°C	85°C	Not used in the analysis. Slowest LOFA indication
- HX Exit	55°C	60°C	Not used in the analysis. Slowest LOFA indication.
CAVITY VESSEL			
- Pressure	25 torr	NA	Used in the BDBE sequence

6.3 Discussion of Conservative Analysis Assumptions and Future Plans for Analyses and Experiments

In the LOFA analyses, all the consequence calculations are performed conservatively. In the quantification of the control points, in general, best-estimate analyses (TRAC and FLOWTRAN-TF) are used.

The following are some of the planned future analyses to supplement the results presented in this appendix:

- Assessment of the TRAC/FLOWTRAN-TF lumping strategies by additional component analyses driven by the boundary and initial conditions obtained from systems analyses. Note that the LOFA is a slow transient and the lumping strategy based on quasi-steady calculations is probably adequate. Nonetheless, this must be demonstrated by a few transient component and sub-system analyses.
- Verification of TRAC/FLOWTRAN-TF constitutive packages for low flow conditions using representative separate effects data.
- Under natural circulation conditions a mixed convection regime is present where buoyancy opposed and assisted flow occurs. The impact on constitutive models within the analysis tools must be address.
- Under near low flow RHR conditions the potential redistribution of flow between modules and among flow channels within a given modules must be further studied to verify assumed lumping strategies.
- Verification of TRAC to FLOWTRAN-TF interfacing.
- Sensitivity analyses to support quantification of safety margins and uncertainties.
- Verification and validation of the various analysis tools must be performed to re-certify their results within the APT project QA requirements.

7 References

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BA-2 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Model Based on Initial Conceptual Design - Integrated 1-D TRAC System Model," Westinghouse Savannah River Company, WSRC-TR-98-0053 (July 1998).

BA-3 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Flow Accident (LOFA) Analyses Based on Initial Conceptual Design - Case 2: with Beam Shutdown only," Westinghouse Savannah River Company, WSRC-TR-98-0085 (July 1998).

BA-4 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "Natural Circulation in the Blanket Heat Removal System during a Loss-of-Pumping Accident (LOFA) Based on Initial Conceptual Design," Westinghouse Savannah River Company, WSRC-TR-98-00207 (July 1998).

BA-5 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Internally Dry Flooded Cavity Accident (IDFCA) Based on Initial Plate-Type Design - Demonstration of Bin Heat Conduction Capability," Westinghouse Savannah River Company, WSRC-TR-98-0064 (July 1998).

BA-6 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Safety Analysis Methodology," Westinghouse Savannah River Company, WSRC-TR-98-0052 (May 1998).

BA-7 S. Y. Lee and L. L. Hamm, "APT Blanket Safety Analysis: Counter Current Flow Limitation for Cavity Spaces," Westinghouse Savannah River Company, WSRC-TR-98-0086 (July 1998).

BA-8 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Flow Accident (LOFA) Analyses Based on Initial Conceptual Design - Case 1: with Beam Shutdown and Active RHR," Westinghouse Savannah River Company, WSRC-TR-98-0058 (July 1998).

BA-9 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket Detailed Bin Model Based on Initial Plate-Type Design - 3-D FLOWTRAN-TF Model," Westinghouse Savannah River Company, WSRC-TR-98-0055 (July 1998).

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Appendix BB
Analyses of the Large-Break Loss-of-Coolant Accidents (LBLOCAs) External to the Cavity Vessel in the APT Blanket Primary Heat Removal System

1 Introduction

The hazard analysis (HA) performed for the blanket primary heat removal (HR) systems identified the loss-of-coolant accident (LOCA) external to the cavity vessel as a design basis accident (DBA).

The LOCAs are typically categorized as either large-break (LB), intermediate-break (IB), or small-break (SB) LOCAs. In terms of consequences LBLOCAs are the most severe and they bound the consequences of the IBLOCAs and SBLOCAs. In this appendix, only the LBLOCAs characterized by a double-ended guillotine break (DEGB) in several pipes external to the cavity vessel are analyzed. LBLOCAs that occur inside the cavity vessel, referred to as internal LBLOCAs, result in different system responses, and they are analyzed in Appendix BC.

Different locations of external LBLOCAs result in different system responses. They may be different depending on the size of the broken pipe and its location relative to other key primary HR components such as the pressurizer and pumps. Therefore, a number of break locations are analyzed. A schematic flow diagram of the primary HR and residual heat removal (RHR) systems of the APT blanket system is shown in Fig. BB-1. The break locations herein analyzed are marked as A through E. The five break locations selected for the external LBLOCA simulations are believed to provide a bounding envelope for quantifying the system response to an external-LBLOCA. Table BB-1 provides the pipe size for each break location and the corresponding reference name.

Table BB-1 Break locations of external LBLOCAs discussed in Appendix BB.

Break Location in Fig. BB-1	Reference Name used in Appendix BB	Pipe size for external LBLOCA simulations (ID)
A	Pressurizer surge-line break	6.065" (6" schedule 40)
B	Hot leg break	18.814" (20" schedule 40)
C	Pump discharge line break	15.000" (16" schedule 40)
D	Cold leg break	18.814" (20" schedule 40)
E	RHR cold leg break	6.065" (6" schedule 40)

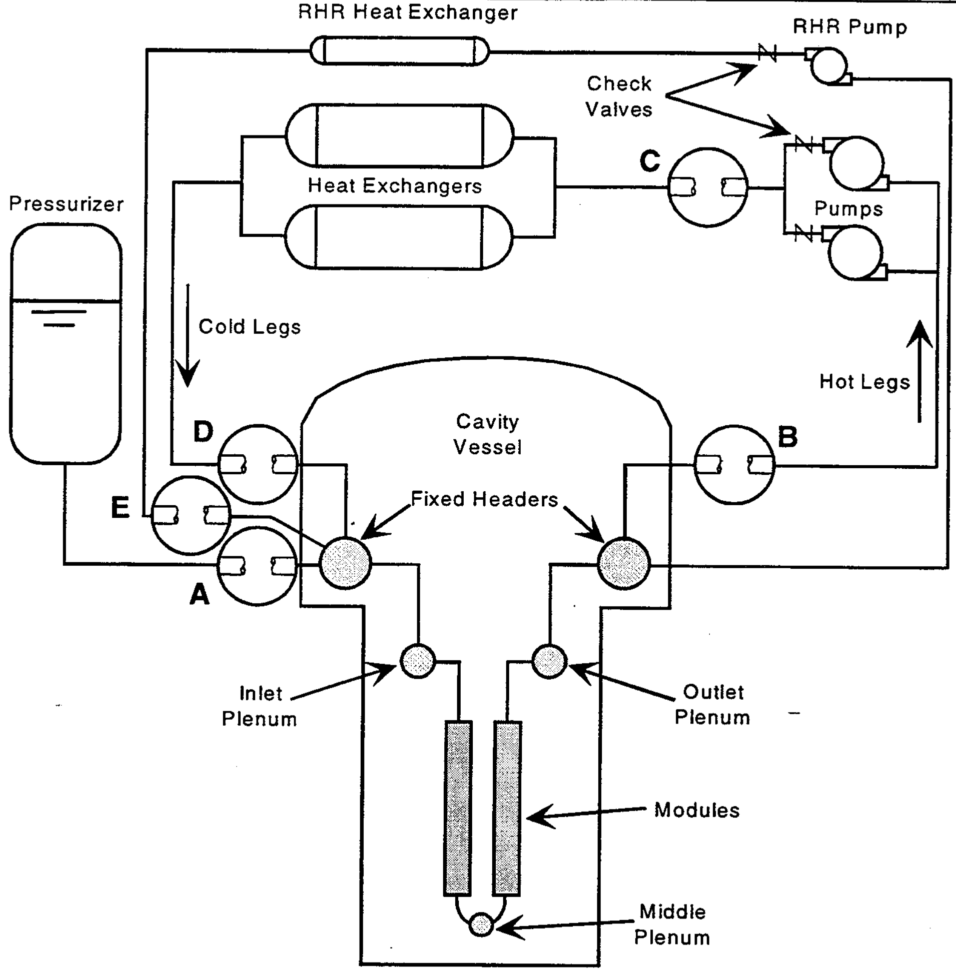


Figure BB-1 Schematic flow diagram for the APT blanket primary HR and RHR systems and the break locations for external LBLOCA analyses.

As discussed in Chapter 3 of this PSAR, during the hazard analysis phase, multiple causes are identified for an external LBLOCA. Table BB-2 provides a discussion of the various potential initiators. Given the design features and the applicable operating controls, all the initiators for a double-ended guillotine break in the piping external to the cavity are in the extremely unlikely frequency range. Independent of the initiator, all the external LBLOCA analyses can be mapped into the event tree discussed in Section 2 of this appendix. The objective of this appendix is to provide a summary of the analyses performed for the event sequences of the External-LBLOCA.

Table BB-2 Discussion of the Initiators for external LBLOCA.

Initiator	Discussion
Material defects in piping	All materials will be selected, procured and inspected consistent with the PC-3 requirements.
Assembly and welding defects	All the assemblies and welds will be performed and inspected according to PC-3 requirements.
Flow induced vibrations (FIV)	The loops will be designed to minimize the FIV phenomenon. Pumps will be mechanically isolated from the piping. FIV will be monitored during operations.
Water hammer	There are no quick closing isolation valves. All the valves will be locked open during operations.
Excessive internal pressure	There is continuous pressure monitoring and pressure relief valves.
Drop or impact of heavy equipment	There will be no lift or transport of heavy equipment over or near the HRS. Piping will be protected against collisions.
Seismic Event	Discussed separately in Appendix TBD.
Building collapse caused by external or natural events	Examples are large fires, flood, helicopter crash, etc. The potential for losing the detection instruments must be addressed.
Pressure relief valve stuck open	Results in loss of pressurizer cover gas and can be detected quickly. Results in loss-of-pressure but not in loss of water inventory unless a large steam (or gas) bubble exists in the system.

2 LBLOCA Event Sequences and Analyses

The event tree shown in Fig. BB-2 is applicable to all the external LBLOCAs, regardless of the break locations. The blanket primary HRS is a low pressure system. The initiator frequency for a LBLOCA in a low pressure system is estimated to be extremely unlikely. This judgment is believed to be applicable for all the initiators discussed in Table BB-2. One initiator, the potential for the pressure relief valve to be stuck open is more likely than the remaining initiators. However, because no loss of inventory occurs as a result, the consequences of this accident are bounded by the consequences of the classical LBLOCAs where coolant inventory is lost.

Upon loss of coolant inventory due to an external LBLOCA , the system pressure drops rapidly and consequently the liquid flowrate is reduced. As a result of the flowrate reduction, the heat removal capacity of the blanket coolant system decreases. Key thermal-hydraulic parameters of the blanket system before the initiation of the external LBLOCA are shown in Table BB-3.

Once initiated, an external LBLOCA can be detected by the following measurements:

- reduction in system pressure;
- decrease in system flowrate (however, during the early phases of the transient fluid acceleration and temporary increase of flow at certain locations can occur);
- increase in system temperature;
- decrease in pressurizer liquid level; and
- increase in radiation monitoring at the break location.

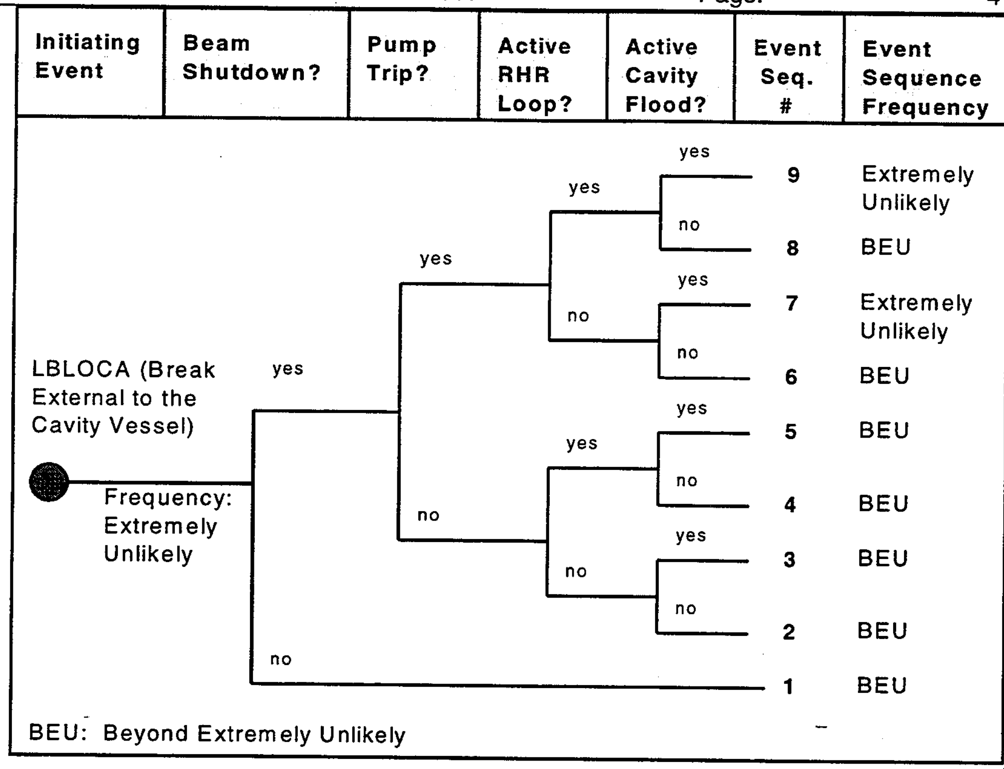


Figure BB-2 Event-tree for a LOCA initiated by a large DEGB external to the cavity vessel.

Upon detection of the upset conditions, the following mitigative actions are taken:

1. The beam is shut down. The primary beam shutdown system is based upon the above measurements in the HR system. The reliability of the primary and back-up beam shutdown systems is discussed in Appendix RA. Based on this discussion, the frequency of failure to shutdown the beam given a LBLOCA is in the Beyond Extremely Unlikely (BEU) range. In addition, there is a "passive" beam shutdown system that is automatically activated upon pressurizing the cavity vessel. If the external LOCA progresses to a point where a failure in the pressure boundary of the HR system occurs inside the cavity, the passive system shuts the beam down.

2. The pumps on the primary HR system are shut down to limit (or delay) the amount of inventory loss. The reliability of the pump shutdown system is discussed in Appendix RB.

3. Following the beam shutdown, the Residual Heat Removal (RHR) System pumps are started. There are two independent RHR loops each being capable of removing the total decay heat in the blanket. The reliability of the RHR system is discussed in Appendix RB. The RHR pumps are battery operated. If extended service is required, diesel generators are also available for continued use of the RHR pumps.

4. Upon loss of pressurizer inventory or in the unlikely event that neither one of the RHR system pumps can be activated, the cavity flood is the next step in the mitigation. The reliability of the cavity flood system is discussed in Appendix RB. Independent and diverse means are available to actuate the cavity flood valves.

It is important that the upset conditions that result in a LBLOCA do not result in losing the detection and/or mitigation capabilities. In general, an independent power source is provided for the critical detection instruments. Furthermore, the detection instruments are designed to fail safe such that failure of an instrument automatically results in beam shutdown. Finally, for the external events (such as a large facility fire) or natural phenomena hazards (e.g. seismic, flood), the beam is automatically shutdown without relying on the primary HRS signals for upset conditions.

In Fig. BB-2, sequences are numbered starting from fully unmitigated (Sequence 1) towards the mitigated sequences. Sequences numbered 7 and 9 in Fig. BB-2 are the design-basis event (DBE) sequences. The remaining sequences are the beyond-design basis event (BDBE) sequences. An analytic discussion of all the sequences shown in Fig. BB-2 are provided.

Table BB-3 Key thermal-hydraulic parameters under normal operation conditions for the APT blanket coolant system.

Parameter	Calculated SI Units	Calculated English Units
Total power deposited in blanket modules	56.5 MW	-
Total flow rate	1569 kg/sec	25252 gpm
Pressure in cold-leg fixed header	0.7325 MPa	106.24 psia
Pressure in hot-leg fixed header	0.4563 MPa	66.180 psia
Pressurizer (cell #1) pressure	0.7311 MPa	106.03 psia
Pump #1 suction pressure	0.2751 MPa	39.90 psia
Pump #1 discharge pressure	1.0356 MPa	150.20 psia
Pump #2 suction pressure	0.2958 MPa	42.91 psia
Pump #2 discharge pressure	1.0409 MPa	150.97 psia
Temperature in cold-leg fixed header	49.43 C	121.0 F
Temperature in hot-leg fixed header	58.03 C	136.5 F
Max. fluid temperature of the hottest module	71.95 C	161.5 F

2.1 External LBLOCA without Beam Shutdown (Event Sequence 1 in Fig. BB-2)

This event sequence represents the completely unmitigated external LBLOCA. In the HA, it was recognized that during an external LBLOCA in the target without a beam shutdown, a potential exists to release a significant fraction of the tungsten inventory and some of its spallation products (i.e., tungsten can be oxidized at high temperatures, see Appendix SA). On the other hand, within the blanket modules lead and mercury (i.e., one of the spallation side products) were considered as potential source terms. Due to the very low vapor pressures for molten lead and mercury, release mechanisms are limited as discussed in Appendix SB. Given the lack of credible release mechanisms, the blanket modules themselves will contribute a negligible amount to the overall off-site consequences resulting from this unmitigated event sequence. However, the loss in coolable geometry associated with the blanket modules can result in a potential detrimental impact in the cooling capability of neighboring target ladders. Uncontrolled and unwanted excessive movement (e.g., slumping over) of the massive blanket modules could occur during this scenario; thus, jeopardizing their neighboring target ladders.

Since the tritium bearing helium tubes are closely distributed throughout the blanket modules, slumping of the blanket modules would most likely rupture numerous helium tubes resulting in the release of gaseous tritium product. At any particular point in the operation of the APT facility, tritium inventory is kept low due to the proposed online batch extraction processing being considered for tritium gas recovery. In addition, during an external LBLOCA, the total coolant inventory is assumed to be spilled. Thus, the total volatile radionuclite inventory in the coolant also is included in the source term.

The discussion of this event sequence is broken into two categories. The first set of discussions contained in Sec. 2.1.1 is aimed at quantifying the unmitigated source term. The discussion in Section 2.1.1 assumes that, the beam remains operational without any time limitations following an external LBLOCA. The main objective of this section is to determine the safety classification of the beam shutdown system. A more realistic assessment of the same event sequence also is developed and included in Section 2.1.2. The discussion in Section 2.1.2 analyzes the event sequence as a Beyond Design Basis Event (BDBE) sequence and is aimed at quantifying the realistic consequences associated with this event sequence.

2.1.1 Unmitigated External LBLOCA Analysis

Following an external LBLOCA initiator, if no mitigation actions are taken and the beam remains operational for an extended period of time, overheating of various blanket components will occur. Overheating can result in either local melting and/or slumping of blanket modules. To conservatively estimate the radiological consequences associated solely with the blanket system, there are three potential contributors to a radiological release that must be accounted for:

- It is assumed that the entire coolant inventory is spilled and ultimately released, along with its gaseous radionuclide inventory, plus a limited fraction of other isotopes contained within the coolant of the blanket primary HR system. The activity in the primary coolant is limited in magnitude by the purification system during normal operation;
- It is also assumed that the entire tritium inventory contained within the Target/Blanket building is released to the environment The tritium gas in the helium system will be limited in magnitude due to online batch processing (the concentration of tritium is assumed to be at its maximum exposure limit prior to a batch process); and
- It is assumed that the entire lead inventory contained within the blanket modules melts and that a fraction of the lead spallation products are released (This source term is limited by the low vapor pressure of the spallation products in the lead). Conservative analyses based on the diffusion and vapor pressure properties of molten lead in the blanket indicates that only 2% of the mercury inventory will be released (See Appendix SB). The radiological consequences of this release have been calculated and the results are presented in Appendix CC.

In Table BB-4, the onsite and off-site consequences are obtained using the unit-dose calculations provided in Appendix CC. A unit-dose calculation corresponding to the following assumptions are used in computing the consequences:

- The release occurs rapidly (in less than 1 hr) such that meandering effects are not credited;
- The release to the environment occurs very early into the decay chain (< 10 seconds);
- The release occurs at ground level without initial momentum or buoyancy;
- Consequences are bounding for 95% of the weather conditions for the bounding year (1987), (see Appendix CC); and
- Deposition velocity was selected as zero which was the bounding case calculated in Appendix CC.

Consequently, the dose estimates given in Table BB-4 are very conservative and provide an upper bound.

Table BB-4 Blanket only consequences of an external LBLOCA without a beam shutdown.

Material	Quantity	Onsite Dose (rem)	Off-Site Dose (rem)
Mercury	2%	17	0.06
Coolant*	100%	12	0.028
Tritium*	94 g	23	0.07
Total*	NA	52	0.16

* This is the total release from only the primary blanket coolant systems (HR, RHR, modules, fixed headers, and pressurizer systems). For this scenario, the release from the window and target systems must also be added to compute the total consequences.

The 2% release fraction for the mercury inventory is a conservative bound, since the following aspects that would reduce this release fraction are ignored:

- Condensation of mercury vapor onto colder surfaces;
- Potential partial filtering provided by the HEPA filters;
- Only a fraction of the release would pass through the stack, which would reduce the onsite consequences with negligible impact on the off-site consequences (see Appendix CC); and
- During the heat up phase structural load limits would be exceeded such that a significant fraction of the blanket modules would slump over and not participate in the melting process.

Assuming a 100% release of the entire tritium inventory within the Target/Blanket building is also conservative because helium headers are separated for each module unit.

The totals provided in Table BB-4 do not exceed the evaluation guidelines. The total radiological consequences for the blanket represents only a small fraction (i.e., less than 1%) of those for the target during a similar unmitigated external LBLOCA (see Appendix TB). Based purely on the conservative radiological consequences computed above for the blanket, the beam shutdown would not in-and-of-itself be required to be designated a *safety class* function. However, the potential loss-of-coolable blanket module geometries could result in an impact on their neighboring target ladders. To ensure that no unwanted side-effects occur, the beam shutdown is designated a *safety class* function. A redundant, diverse and highly reliable set of beam shutdown systems are being designed. The reliability of the beam shutdown systems is discussed in Appendix RA.

2.1.2 Analysis of the Beyond Design-Basis External LBLOCA Event Sequence

Since the beam shutdown system is designed to perform a *safety class* function, and given the level of reliability associated with this design, event sequences without beam shutdown fall within the beyond extremely unlikely (BEU) frequency range.

[TBA...]

2.2 External LBLOCA with Beam Shutdown and without Pump Trip (Event Sequence 2 in Fig. BB-2)

For this set of break location scenarios, it is assumed that the trip signal to shutdown the beam is initiated based on a 5% reduction in pressurizer surge-line pressure. Signal detection occurs within hundredths of a second following the initiating event. The trip signal is activated approximately 0.01 seconds after the initiating event occurs. A conservative 0.2 seconds time delay to account for signal processing is assumed (i.e., best estimate values range within 0.1 to 0.2 seconds delays). The actual beam shutdown begins to occur at approximately 0.21 seconds after the initiating event occurs. Blanket deposited power drops rapidly. For example, power levels are approximately 1 to 3% of their pre-shutdown levels within 1 second.

Primary HR pump trips are based on the same logic as for a beam shutdown. For this set of break location scenarios it is assumed that the primary HR pumps fail to trip. Also, the primary RHR pumps and the cavity flood system are assumed to not operate. For each break location, this event sequence is in the beyond extremely unlikely frequency range. After a beam shutdown, no other available mitigation options are activated. The geometrical configuration of the external piping for the primary HR system, in relation to the fixed headers, has been designed such that any external large break would eventually break seal and would not continue to draw coolant inventory out of the blanket modules and their fixed headers.

The solution strategy chosen is based on the realization that simulation times on the order of days are unattainable using the integrated system model and that a simplified bounding analysis is preferred when such analyses provide acceptable results. A simplified conservative evaluation model (EM) based on a lumped overall energy balance is used. The transient behavior of individual blanket modules was predicted using as the initial conditions the results from the integrated system model 950 seconds into an external LBLOCA (see Ref. BB-2). At this point in time after a large break initiating event, the system behavior (i.e., blanket module and HR coolant loop temperatures) is essentially the same regardless of break location. Therefore, the following EM results are valid for the entire set of break locations considered.

The EM approach conservatively assumes that beyond 950 seconds the pressurizer inventory has been depleted and external loop flow to and from the fixed headers has ceased. Beyond this point, since all potential external break locations are above the fixed inlet headers, no additional loss of coolant inventory due to siphoning will occur. At 950 seconds we also no longer take credit for any water remaining in the loops beyond the fixed headers including the inventory within the fixed headers themselves. Water inventory within each module unit is assumed to be completely isolated from its neighboring modules.

In the first phase of the EM approach an adiabatic sensible heat-up calculation is performed where credit is taken for the thermal capacitance of: the metal and water residing within the blanket modules; and the water contained within the module plenums and inlet/outlet piping attached to the fixed headers. These calculations are performed until saturation conditions are reached within the heated sections of each module. Each module is materially and thermally isolated from its surrounding structures. During the second phase of the EM approach boil-off calculations are performed based on the latent heat of vaporization of water until the level of water remaining within the system reaches the top of the module units. No credit is taken for condensation/reflux due to cold surfaces above each blanket module. Limited preliminary FLOWTRAN-TF bin analyses have been performed to investigate the heat removal capability of the long narrow discrete channels under partially filled conditions.

The following is a brief discussion of the EM calculations and results:

- Composite deposited power decay curves were generated and integrated over time to determine the total amount of heat released as a function of time. Figure BB-3 summarizes the decay curves for the six composite lumped modules.
- Module 1 (lateral front and back modules), which has the largest ratio of deposited power to mass of available cooling water, was selected as the worst case (i.e., the module that will become uncovered quickest) for further analysis.
- From Ref. BB-2 system temperatures are approximately 50 C at 950 seconds after a large break and the fixed headers are near atmospheric pressure. Considering the hydrostatic pressure from the head of water between the center of the module and the fixed headers, saturation temperatures within the heated channels of the modules were estimated to be approximately 116 C.
- Starting at a system temperature of 50 C, adiabatic sensible heat-up calculations were performed predicting that the Module 1 will reach 116 C in approximately 4 hours at which point the onset of bulk boiling is initiated.
- Beyond 4 hours into the transient, decay power levels are sufficiently low to preclude the potential for a counter-current-flow limitation (CCFL). Saturated boiling occurs within the Module 1 flow channels where it is assumed that circulation is sufficient to bring the liquid inventory to a nearly uniform temperature (no credit is taken for potential condensation or reflux at the higher elevations within the piping network).
- Once boiling occurs (i.e., at 4 hours into transient) the liquid level gradually drops. No liquid inventory draining in from the HR, RHR, or pressurizer external piping is

accounted for. By approximately 22 hours after the initiating event the top of the blanket Module 1 is uncovered (the other modules will take substantially longer to uncover). During the boiling phase, we assume that the metal temperature follows the liquid saturation temperature. Therefore, as water is boiled away, the static pressure within the modules drops and the metal temperature slowly decreases. The thermal energy balance in the EM calculation accounts for the release of stored energy in the metal and remaining water inventory as the average temperature decreases.

- Beyond the EM calculation limit, boil-off continues to occur until a sufficient fraction of the heated module channels become uncovered. Preliminary FLOWTRAN-TF calculations indicate that acceptable metal temperatures are maintained for channels moderately filled with water. However, at some reduced liquid level the onset of a thermal excursion is expected to occur. Further calculations are required to quantify the point of thermal excursion.

The estimated coolant liquid level and maximum aluminum metal temperatures within the modules are shown in Figs. BB-4 and BB-5, respectively. For comparison purposes, the steady-state and 10k exposure temperature limit criteria for aluminum are also provided. As Fig. BB-5 indicates, aluminum temperatures remain below the 150 C limit throughout the early times of the event sequence and also below the 115 C steady-state limit except for a brief exposure near the time when boiling begins. At the point where the blanket modules begin to be uncovered the estimated boil-off rate corresponds to 0.35 gpm of liquid water. Without taking any corrective measures, it is anticipated that peak metal temperatures would begin to rise and exceed the design criteria for times beyond approximately 22 hours. Details on the analysis presented above is provided in Ref. BB-3.

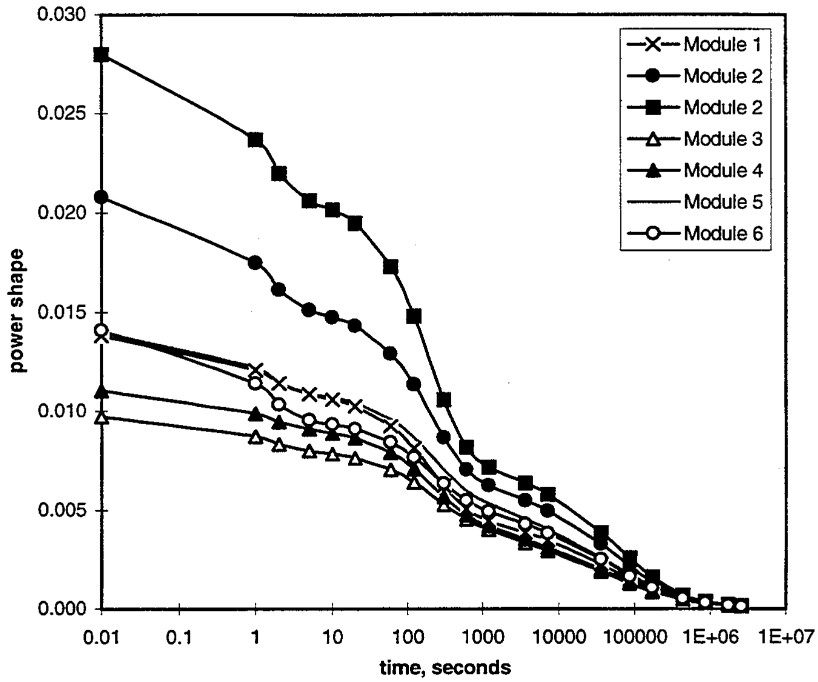


Figure BB-3 Deposited power profiles used in evaluation model analysis.

In the above conservative calculations, credit was taken only for the safety class beam shutdown system. The calculations indicate that margin exists at early times in the accident and, to prevent the loss of coolable geometry at later times, some sort of corrective measures must be taken within approximately the first day (i.e., an ultimate heat sink must be established). This time duration is sufficiently long that it is realistic to assume that additional administrative measures can be implemented, such as:

- restoring the availability of the RHR system or cavity flood system, or
- replenishing liquid coolant inventory that is boiled-off using, for example, purification lines (initially about 0.35 gpm would be required with demand decreasing as the residual deposited power decays).

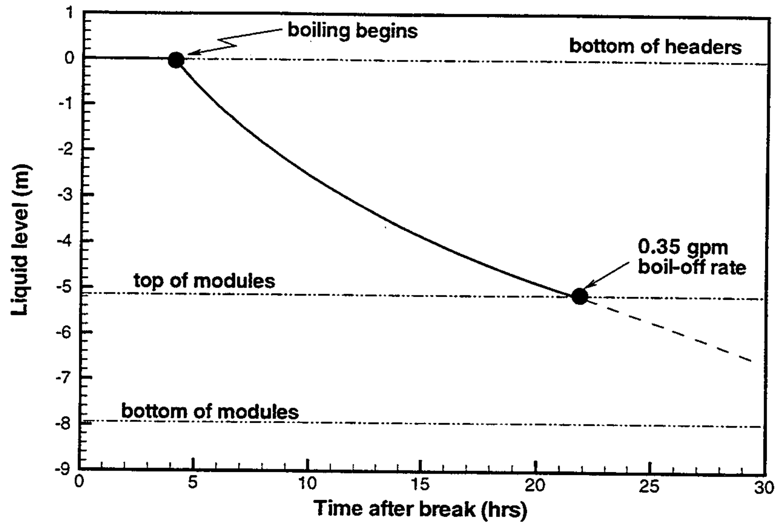


Figure BB-4 Estimated coolant liquid level as a function of time based on evaluation model.

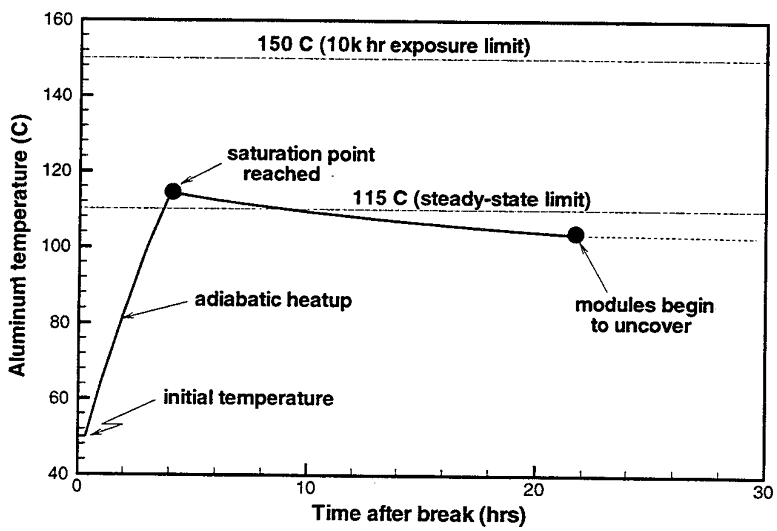


Figure BB-5 Estimated maximum aluminum temperature as a function of time based on evaluation model.

In conclusion, without corrective actions the consequences for this event sequence are similar to those for Sequence 1, where the maximum onsite and off-site consequences would be bounded by 52 rems and 0.16 rems, respectively (value taken from Table BB-4).

Based on considerations to be discussed under Sequence 9, the combined automatic activation of the RHR system and the cavity flood system becomes the preferred choice for mitigation. The RHR system is designed for operation in standard shutdown modes and can also fully mitigate most of the external LBLOCAs (excluding RHR discharge line breaks) as discussed in Sections 2.4 and 2.8. The cavity flood system can fully mitigate all of the external LBLOCAs as discussed in Sec. 2.3. For most event sequences, the RHR is preferred over the cavity flood because there is much less involved in returning to normal operation following such an accident. However, to ensure coverage over all possible external LBLOCAs, the cavity flood system is included as a backup system.

Based purely on the conservative exposure assessment above, the RHR and/or cavity flood systems would not in-and-of-themselves be required to be designated as *safety-significant* functions. However, the potential loss-of-coolable blanket module geometries could result in an impact to neighboring target ladders. Therefore, RHR and cavity flood are designated as *safety-significant* functions.

2.3 External LBLOCA with Beam Shutdown and Cavity Flood but without Pump Trip (Event Sequence 3 in Fig. BB-2)

This is a beyond DBA event sequence with a frequency estimated to be beyond extremely unlikely. The immediate response to any LBLOCA event is designed to be beam shutdown followed by trip of the primary HR pumps and activation of at least one of the blanket RHR systems. The primary function for the cavity flood system is to mitigate the consequences resulting from internal (as well as external) loss-of-coolant accidents (LOCAs) within the target and blanket primary HR systems. The primary signal that activates the cavity flood is the pressurizer liquid inventory level. Its cooling capability for receiving decay heat from the blanket modules provides a defense-in-depth strategy. Early in an external LBLOCA significant liquid inventory is lost and the system pressure decreases rapidly. The pressurizer level will also start to decrease as coolant inventory is lost. The cavity flood option will therefore be actuated.

As discussed in Sec. 2.3 of Appendix BA, upon actuation of the cavity flood system all modules are covered with subcooled water in less than 100 seconds and by 800 seconds the tops of the fixed headers are covered within the cavity vessel. The primary HR pumps/piping are designed to break suction prior to pumping the modules dry, and pressurizer flow replenishes the HR system inventory to some extent for approximately 950 seconds. Dryout conditions within modules cannot occur until the pressurizer inventory is exhausted. Regardless of the status for primary HR pump trip and/or RHR activation, the pressurizer inventory exists for times well in excess of 100 seconds. The result is to leave the blanket modules full of water well beyond 100 seconds, sitting in a cavity space flooded with subcooled water.

As demonstrated in Ref. BB-5, the plate-type blanket design is very robust from a thermal perspective. The main feature of the plate-type design is its continuous heat structure at the bin level with discrete one-dimensional flow channels (of simple well known shapes) dispersed throughout the heat structure. For the highest powered modules (i.e., front/back lateral and downstream row-1/decoupler modules) the horizontal conduction path lengths are kept to a minimum by allowing each plate component to be in direct contact with neighboring cavity vessel spaces. Results from Ref. BB-5 (further discussed in Ref. BB-6) indicate that the plate-type design modules can, by heat conduction alone, transfer all of their decay heat to neighboring flooded cavity spaces (typically, small rectangular gaps on the order of one to one and a half inches wide)..An evaluation model (EM) was developed based on several conservative assumptions (see Ref. BB-5) to demonstrate the robust capability of the cavity flood system. This EM consists of a three -dimensional finite element conduction model of a section of a plate-type component driven by conservative boundary conditions. A summary of this EM and its key results are discussed in Sec. 2.3 of Appendix BA. Also discussed in Appendix BA is an analysis that shows that the decay power loads do not cause CCFL to occur in the narrow channels of the flooded cavity (see Ref. 8).

Figure BB-6 shows the maximum metal temperatures predicted by this EM in a downstream Row-1 plate-type component subject to internal dryout 100 seconds after beam shutdown. The cavity is flooded and all of the decay heat is ultimately transferred to this heat sink. The maximum metal temperature exceeds the steady-state design criteria of 115°C for the initial approximately 80 hours of the event sequence. At no time does the maximum metal temperature exceed its 10k hour exposure design criteria of 150°C. These results bound event sequences in which dryout occurs in a module after 100 seconds have elapsed and the cavity flood has been actuated. Complete dryout of a module within 100 seconds of the initiation of a external LBLOCA is bounding. The primary HR pumps will break suction prior to pumping the modules dry, and pressurizer flow replenishes the HRS inventory to some extent for approximately 950 seconds.

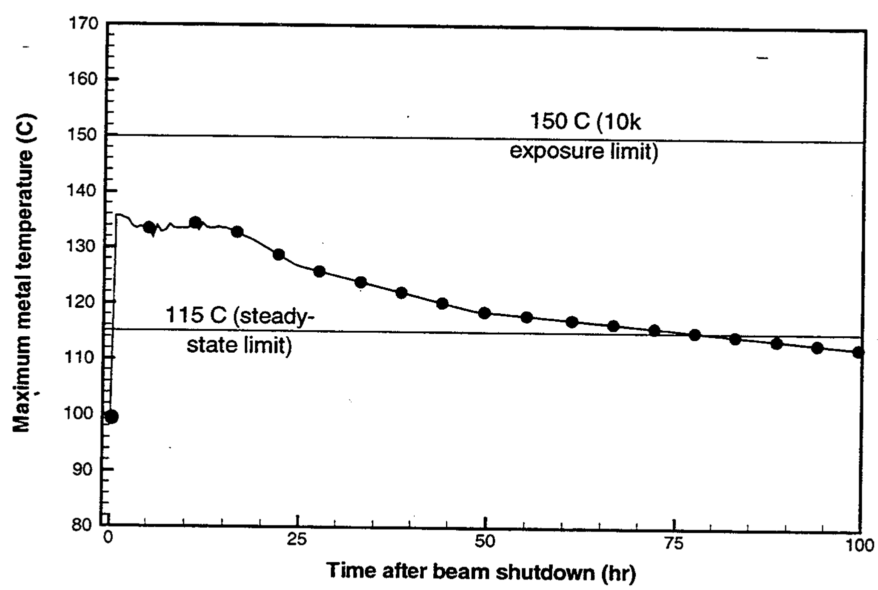


Figure BB-6 Downstream Row-1 plate-type maximum metal temperature response to channel dryout conditions initiated at 100 seconds after beam shutdown.

Since the cavity flood system has the capability of preventing blanket aluminum/lead temperatures from exceeding the 10k hour 150°C material temperature limit, and thereby ensuring the reuse capability of the blanket components, the cavity flood system is designated as a *safety-significant* function, and it is designed to safety class standards (mainly for worker safety and investment protection). The control associated with the activation of cavity flood upon a reduction in HR system pressure or pressurizer inventory is a *safety-significant* control.

Because of the expected extended duration for the necessary response, a manual cavity flood activation would be appropriate as a defense-in-depth measure with respect to external LBLOCA mitigation. The only consequence would result from the release of contaminated cooling water as shown in Table BB-4.

For external LBLOCAs where cavity flood mitigates the event, the ability of the cavity vessel to retain the water is credited. Also the beam window must be capable of withstanding the full hydrostatic pressure under cavity flood. Based on these considerations, integrity of the cavity vessel and beam window are designated to perform *safety-significant* functions

2.4 External LBLOCA with Beam Shutdown and Active RHR but without Pump Trip (Event Sequence 4 in Fig. BB-2)

For this sequence a number of calculations corresponding to different break locations illustrated in Fig. BB-1 are considered. These calculations are summarized in the following subsections. For the majority of locations analyzed, the calculations show that the external LBLOCA can be effectively mitigated by the RHR system without a cavity flood backup.

However (similar to the results discussed in Sec. 2.8), for break locations on the discharge side of the active RHR system, the active RHR system does not mitigate but instead aggravates the situation. For this sequence the primary HR pumps are tripped. Tripping of the HR pumps changes rate of flow decay and slightly decreases overall inventory loss. Given this, Sequences 4 and 8 end up in similar conditions at approximately 950 seconds due to pressurizer inventory reduction. beyond 950 seconds the blanket modules internally dryout and begin to heat up. As the heating up process continues axial conduction to neighboring thermal shields may limit their maximum temperatures. This particular scenario could be mitigated by isolating the affected RHR loop or turning off its pump. However, automatic operation of the Cavity Flood System when the pressurizer level decreases below the pressurizer setpoint will mitigate the consequences (see Sec. 2.3).

The methodology for analyzing the response of this external LBLOCA is discussed in Sec. 2.8. One-dimensional TRAC system model layouts for the external HR and RHR systems are provided in Ref. BB-8. References BB-9 and BB-10 describe the FLOWTRAN-TF model.

An external LBLOCA with a beam trip, an active RHR system, and no HR pump trip is a BDBA scenario with an anticipated frequency classification of BEU. Power to the beam is tripped 0.2 seconds after the pressurizer surge line pressure drops 5% below the normal operation value. The surge line pressure rapidly drops to the set point approximately 0.01 s after the occurrence of the break. The post accident transient is mitigated by activation of one of the two RHR systems (i.e., the remaining RHR loop becomes the worst-case single failure). The RHR pump is activated at the start of the transient, and it attains full speed within 15 seconds. The HR pumps are not tripped and continue to run at full speed for the duration of the simulations. LBLOCAs at the five locations shown in Fig. BB-1 are considered. The analyses of these accident scenarios are discussed in the following sub-sections (2.4-1 through 2.4-5).

2.4.1 Pressurizer Surge Line Break (Location A in Fig. BB-1)

[TBA...]

2.4.2 HR Hot Leg Break Close to the Outlet Header (Location B in Fig. BB-1)

[TBA...]

2.4.3 HR Hot Leg Break at the Pump Discharge (Location C in Fig. BB-1)

This scenario is simulated with TRAC and FLOWTRAN-TF. Details of the analysis are provided in Ref. BB-4. The break occurs in the section of 16 inch pipe between the pumps and heat exchangers through which all of the HR system flow passes under normal operation (break C in Fig. BB-1). The accident simulation lasts for 600 seconds, long enough for the severe transients to die out, and for temperatures, pressures, and flows to stabilize.

Figure BB-7 shows the transient pressures in the fixed inlet and outlet headers. There is an almost immediate system depressurization when the break occurs. The inlet header pressure drops 124 kPa (18 psia), and the outlet header drops to 69 kPa (10 psia). After the initial depressurization, these pressures decrease slowly over the next 120 seconds, reaching minimum pressures of 83 kPa (12 psia) and 55 kPa (8 psia) for the inlet and outlet headers, respectively. The pressures then start to increase, and by 240 seconds the header pressures are at 145 kPa (21 psia). After 240 seconds, the header pressures remain constant.

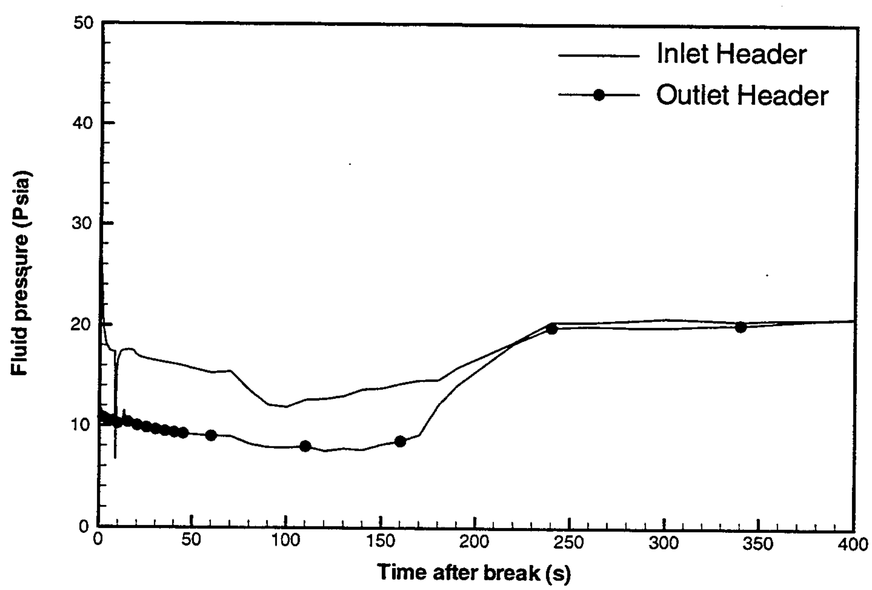


Figure BB-7 Transient fixed header pressures.

The mass flowrate in the HR hot leg, the pump side break flow, very quickly drops to 600 kg/s and remains at this level for 70 seconds. The flowrate thereafter drops to zero over the next 120 seconds. Between 50 and 110 seconds flashing occurs in the high elevation sections of the hot leg pipe. The pumps cavitate for the initial 120 seconds, and thereafter air is entrained in the flow. The mass flowrate drops to essentially zero at 190 seconds and remains there for the duration of the simulation. The air enters the HR system through the heat exchanger side of the break and is convected around the loop, through the blanket modules, to the HR hot leg pipe. Figure BB-8 shows both the pump side and heat exchanger side break flows. The flow in the heat exchangers inlet piping reverses immediately with the break occurrence, and the liquid in the first pass of each heat exchanger drains out of the break in the initial 20 seconds of the accident simulation. Forward flow continues in the HR pipe between the heat exchanger discharges and the inlet header as the second passes of the heat exchangers drain to the inlet header. At approximately 50 seconds, air entering through the heat exchanger side of the break is entrained in this flow, and the flowrate drops to zero over the next 50 seconds. Figure BB-9 shows the HR cold leg flow, downstream of the heat exchangers, for the initial 400 seconds of the accident scenario. There is no flow in the HR cold leg pipe until reverse flow from the inlet header (out of the break) is established at 220 seconds. This reverse flow persists for the duration of the accident scenario.

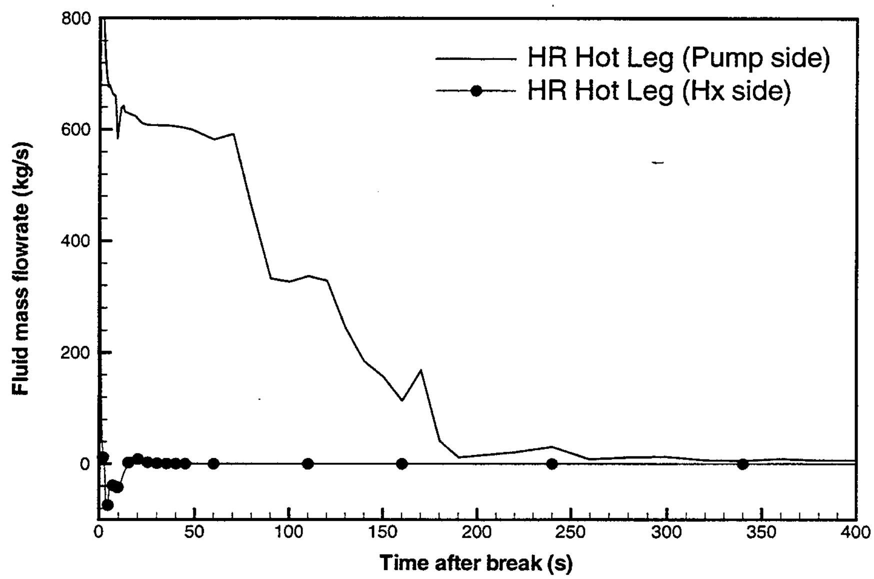


Figure BB-8 Mass flowrates on the pump and heat exchanger sides of the break.

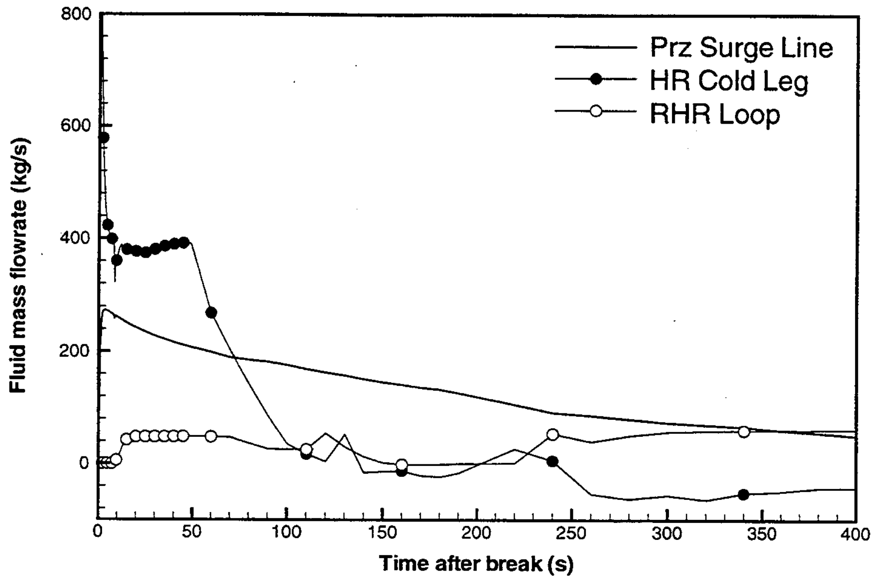


Figure BB-9 Pressurizer surge line, HR cold leg, and RHR system mass flowrates.

Figure BB-9 also shows the pressurizer mass flow into the inlet header and the RHR system flowrate. The pressurizer flow is established very quickly. It is initially 275 kg/s, and it drops slowly as the pressurizer gas space expands. At 600 seconds the pressurizer flow is 13 kg/s. The RHR pump starts at occurrence of the break, and it comes up to full speed in 15 seconds. The check valve opens at 10 seconds, and the mass flowrate quickly increases to 48 kg/s. Between 60 and 110 seconds, the RHR pump cavitates and the flowrate drops to 25 kg/s. The RHR system mass flowrate briefly shoots up to 55 kg/s when the cavitation stops, and then quickly drops to zero due to entrained air from the outlet header. The RHR flow is essentially zero between 150 and 220 seconds. Flow is reestablished at 220 seconds and it increases to 62 kg/s, 4% of the HR system normal operation flowrate, by 400 seconds. The flowrate remains constant thereafter. From 300 seconds onward in the simulation, the temperature drop across the RHR system heat exchanger is approximately 0.6 C.

Air entering the HR system through the heat exchanger side of the break is entrained into the inlet header. The inlet header void fraction increases from zero at 60 seconds to 0.5 at 120 seconds. Air is entrained in the flow through the modules, and reaches the outlet header at 110 seconds. The outlet header void fraction quickly rises to 0.45. Air from the outlet header severely degrades the RHR pump performance at this point. Commencing at 220 seconds, the point at which reverse flow is established in the HR cold leg and air is no longer introduced into the system, the void fractions in both headers drop. By 300 seconds the void fractions in the headers are approximately 0.1 for the inlet header and almost zero for the outlet header. Figure BB-10 shows the transient void fractions in the six TRAC model modules. The highest flowrate occurs through module 1 (row 1 and decoupler) and this module has the highest void fraction. There is air in module 1 between 90 and 220 seconds, and the void fraction peaks at 0.42. There is no significant void in modules 2 and 3, and the remaining three modules have considerably less than module 1.

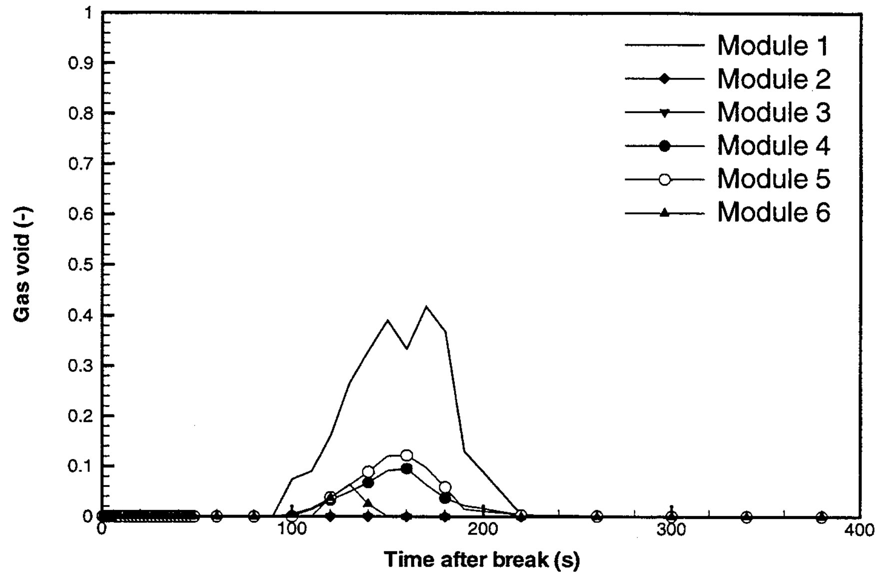


Figure BB-10 Void fractions in the six modules.

Results of the FLOWTRAN-TF model of a module 1 plate assembly are presented. Figure BB-11 shows the transient peak aluminum clad and lead temperatures, along with material temperature limits. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1 is 112.8 C as predicted by the FLOWTRAN-TF model. This occurs in the lead plate, and it is well below the lead melting point, 327.5 C. The peak aluminum temperature is 100 C, below the long term temperature limit of 115 C. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially the pre-incident values. Actually, maximum temperatures are reached 1 second after the start of the accident when the beam trips. However, the thermal inertia of the solid is such that this brief time delay is negligible. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the center of the beam location.

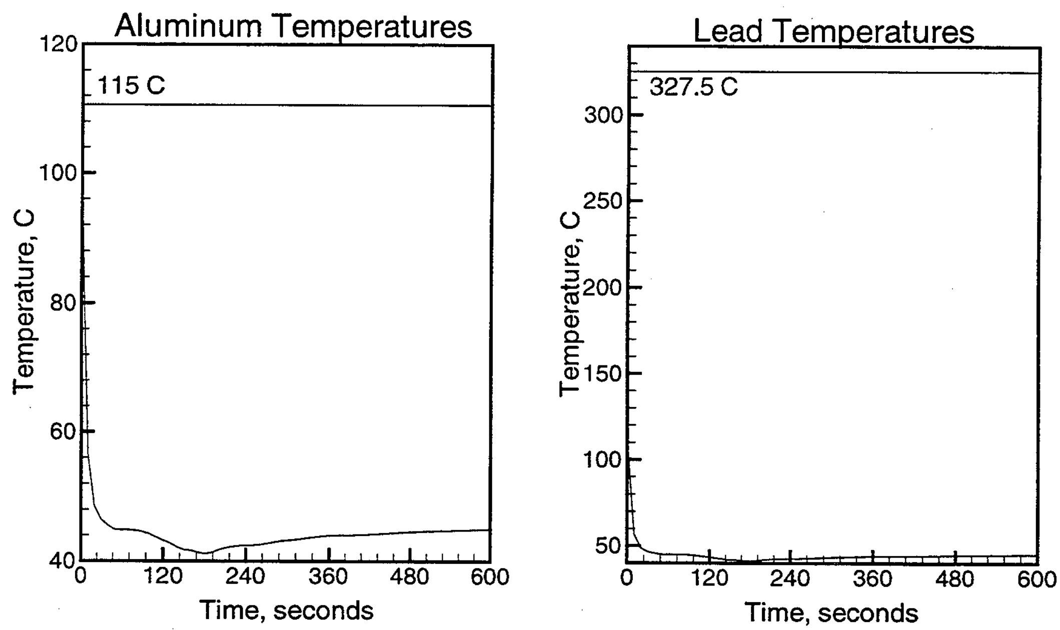
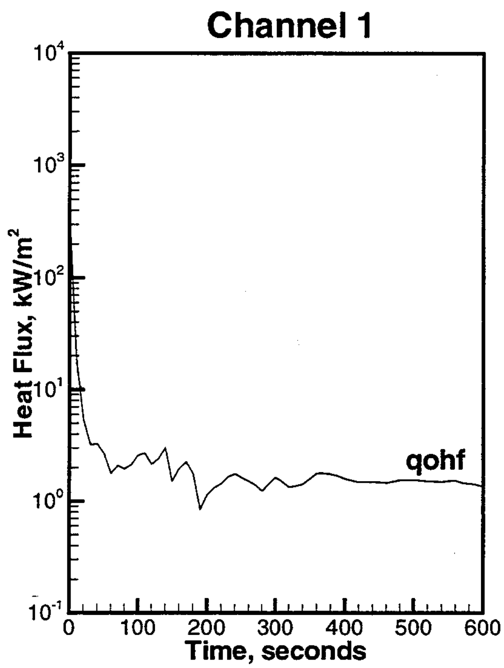
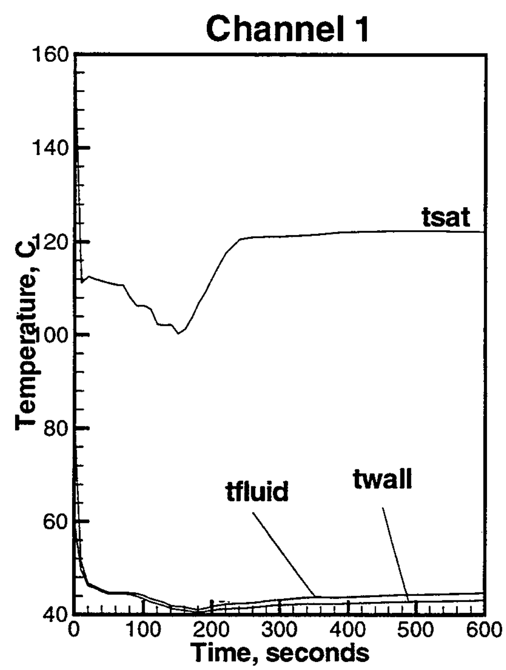
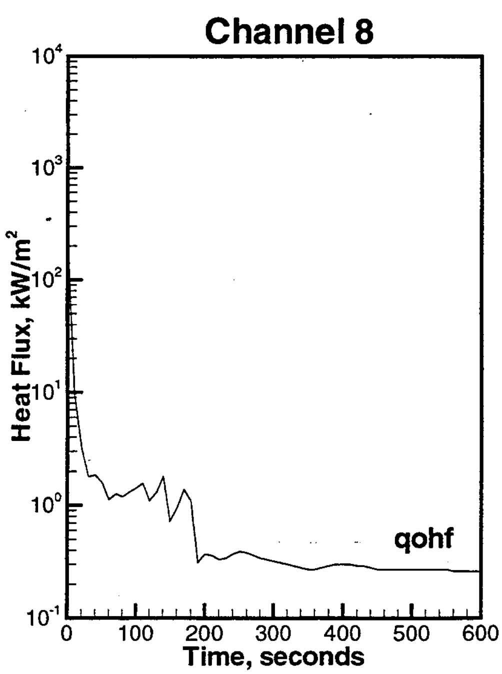


Figure BB-11 Maximum metal temperatures in module 1.

It is clear from the peak aluminum temperatures that channel surface temperatures are not close to local saturation conditions so local boiling will not occur. Fig. BB-12 shows peak transient axial operating surface heat fluxes and the wall, fluid, and saturation temperatures for channels 1 and 8. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, and channel 8 is the adjacent annular channel. The large margins between the operating temperatures and the material limits are readily apparent.


Channel 1
Heat Flux, kW/m2
Time, seconds
qohf


Channel 1
Temperature, C
Time, seconds
tsat
tfluid
twall


Channel 8
Heat Flux, kW/m2
Time, seconds
qohf

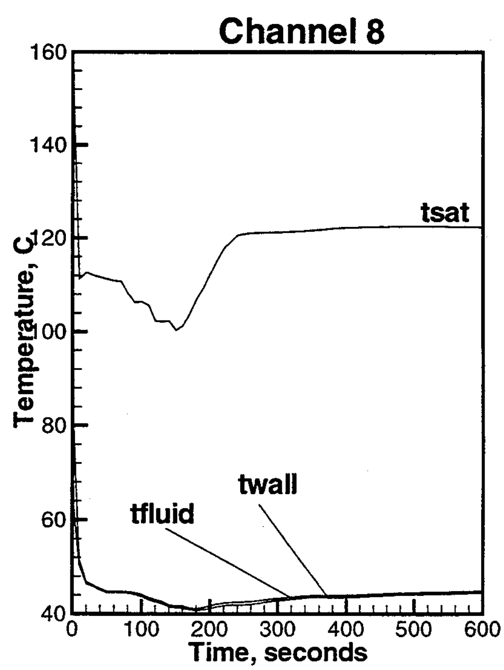

Channel 8
Temperature, C
Time, seconds
tsat
twall
tfluid

Figure BB-12 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

On a module-by-module basis, the steady-state material and thermal onset criteria for LOCA's are compared to the FLOWTRAN-TF detailed bin model results. The bin model results for the reference 1 plate-type module are tabulated in Table BB-4 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 do not presently exist). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BB-4. Note that these are generally more stringent than the chosen imposed design criteria.

Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BB-5 represent primarily best estimate values (however, some parameters were set to their estimated upper bounds, such as power density). Quantification of overall uncertainties and then their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined.

Table BB-5 FLOWTRAN-TF model results.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio
1	112.8	100.0	0.317	0.546
2	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD

Simulations performed using the TRAC system model and the FLOWTRAN-TF detailed bin model show that the APT blanket modules maintain a coolable geometry during this external LOCA scenario. Blanket conditions during this LOCA scenario fall within all specified T/H design criteria. No off-site impact to people or the environment would occur as a result of a pump discharge LOCA with an operational RHR system and without HR pump trips. The only consequence would result from the release of contaminated cooling water as shown in Table BB-4.

2.4.4 HR Cold Leg Break Close to the Inlet Header (Location D in Fig. BB-1)

Similar to the behavior observed in an external break located on the pump discharge line (location C) and discussed in Sec. 2.4.3, it is anticipated that following a cold leg break a significant quantity of air will be drawn into the primary HR system. Degradation of the RHR pump will again result in the flushing out of most of the air.

[TBA...]

2.4.5 RHR Cold Leg Break Close to the Inlet Header (Location E in Fig. BB-1)

[TBA...]

2.5 External LBLOCA with Beam Shutdown, Active RHR, and Cavity Flood, but without Pump Trip (Event Sequence 5 in Fig. BB-2)

For many break locations the RHR system provides sufficient decay heat removal for accident mitigation, but there are break locations that result in air entrainment, inventory loss associated with RHR pump operation, and there may be failures of the RHR circulation. For these external LBLOCAs, which are low frequency events in the beyond extremely unlikely category, the cavity flood will be initiated if the pressurizer level falls below a low level setpoint. The T/H response for Sequence 5 is very similar to the response for Sequence 9 discussed in Sec. 2.9.

The conductive capability of the plate-type blanket modules to dump all of their decay heat to their neighboring cavity spaces when flooded has been demonstrated in Ref. BB-5 and summarized in Sec. 2.3 of this appendix. This conductive feature adds to the overall heat removal capability already present. As such, this event sequence is bounded by Sequences 3 and 4 and the consequences are limited to the activity in the coolant as shown in Table BB-4.

2.6 External LBLOCA with Beam Shutdown and Pump Trip (Event Sequence 6 in Fig. BB-2)

The event sequence analyzed here corresponds to external LBLOCAs where a beam shutdown and a primary HR pump trip is assumed. No credit is taken for the mitigation features of the RHR system(s) and/or cavity flood system. The frequency of every break location scenario within this event sequence is in the beyond extremely unlikely range.

The accident analysis for this set of break location scenarios is similar to the analysis provided in Sec. 2.2 for the external LBLOCA with only a beam shutdown. This set includes the RHR break location E shown in Fig. BB-1 where it is assumed that neither RHR system becomes active.

The evaluation model used in Sec. 2.2 computes bounding results that are independent of whether or not the primary HR pumps are tripped. At 950 seconds into the transient it is assumed that the pressurizer exhausts itself and coolant flow to/from the HR loop is completely lost and isolation of each module occurs. Tripping the primary HR pumps slightly reduces the point where breaking the coolant seals results in terminating coolant loop flow. As was the case in Sec. 2.2, beyond this point, since all potential external break locations are above the fixed inlet headers, no additional loss of coolant inventory due to siphoning will occur.

The consequences of this event sequence are bounded by the consequences given in Sec. 2.2.

2.7 External LBLOCA with Beam Shutdown and Pump Trip, and Cavity Flood (Event Sequence 7 in Fig. BB-2)

This is a DBA event sequence within the extremely unlikely frequency range. It represents the preferred alternative to mitigate the external LBLOCA if an active RHR system is unavailable or ineffective. Shutting down the primary HR pumps will initially reduce circulation in the system but will leave the blanket modules full of water and avoid any air entrainment into the modules. This sequence is bounded by the analysis presented in Sec. 2.3 where no credit was taken for blanket cooling provided by forced circulation beyond 100 seconds. The consequences are limited to release of the coolant activity given in Table BB-4.

2.8 External LBLOCA with Beam Shutdown and Pump Trip, and Active RHR (Event Sequence 8 in Fig. BB-2)

For this sequence a number of calculations corresponding to different break locations illustrated in Fig. BB-1 were performed. These calculations are summarized in the following subsections. For the majority of locations analyzed, the calculations show that the external LBLOCA can be effectively mitigated by the RHR system without a cavity flood backup.

However, for break locations on the discharge side of the active RHR system, the active RHR system does not mitigate but instead aggravates the situation. Preliminary calculations indicate that the active RHR pump removes a significant fraction of the coolant inventory from the module units. The time to uncover the blanket modules by RHR pumping is approximately 950 seconds due to pressurizer inventory reduction. For this scenario, beyond 950 seconds the blanket modules internally dryout and begin to heat up. As the heating up process continues axial conduction to neighboring thermal shields may limit their maximum temperatures. Conduction/radiation modeling is underway to assess this particular accident scenario and the results of this effort will be provided in the next PSAR revision. This particular scenario could be mitigated by isolating the affected RHR loop or turning off its pump. However, automatic operation of the Cavity Flood System when the pressurizer level decreases below the pressurizer setpoint will mitigate the consequences (see Sec. 2.3).

The same blanket methodology is used for analyzing each of these external LBLOCAs The methodology is based on a two model approach: a 1-D TRAC model to integrate the entire blanket system; and a detailed FLOWTRAN-TF model to assess local T/H performance of "hot" plate-type blanket components. The 1-D TRAC system model simulates T/H behavior for the overall APT blanket system under normal operation and then under accident conditions. The TRAC results are used as boundary conditions to the FLOWTRAN-TF model for detailed calculations of the T/H behavior within selected plate-type blanket components and their associated discrete flow channels. The current blanket system model consists of six lumped blanket modules based on the existing cruciform-type component design (note that, the necessary design specifications required to develop a plate-type set of composite modules are not currently available but will be used in future revisions to these calculations). Detailed descriptions of the blanket module lumping strategy and analysis methodology are provided in Ref. BB-6. One-dimensional TRAC system model layouts for the external HR and RHR systems are provided in Ref. BB-8, while Refs. BB-9 and BB-10 describe the FLOWTRAN-TF model.

External LBLOCAs under accident scenarios with beam and pump shutdown, and an active RHR system, were simulated by running TRAC in the transient mode with the steady-state normal operation results as initial conditions. Normal operation conditions for the key blanket system parameters are shown in Table BB-3.

FLOWTRAN-TF results are compared with T/H design criteria that are discussed in Appendix DB. For LOCAs the T/H onset criteria are based on meeting very strict phenomenological limits with a reasonable degree of confidence, as follows:

- for local heated surfaces exposed to single component flow within the module components, the onset-of-significant-voids [OSV]); and
- for the remaining unheated piping sections of the blanket system, the onset-of-bulk-boiling [OBB]).

Since air entrainment can create significant voids in the flow channels, the OSV criteria only applies under single component flow conditions. Additional material design criteria are also imposed on the maximum lead and aluminum (Series 6061 - Type T6) metal temperatures acceptable for the module components. The structural criteria are presented in Appendix DF. The limiting steady state values are 327.5 C and 115 C for lead and aluminum, respectively. These material design criteria ensure that a coolable geometry can be maintained throughout the expected lifetime of each module unit.

In addition to the steady state limits there are short term limits that can be used for transients. For the aluminum it is acceptable to go up to 150°C for periods shorter than 10,000 hr (i.e., protects the modules for potential reuse). In addition, the ASME code has higher limits for accident conditions where the equipment must not fail but will not be reused. These limits are being evaluated and will be included in Appendix DB in the next revision to the PSAR.

An external LBLOCA with beam and HR pump trip and an active RHR system is a BDBA scenario with a frequency classification BEU. Power to the beam and the HR pumps is tripped 0.2 seconds after the pressurizer surge line pressure drops 5% below the normal operation value. The surge line pressure drops to the set point approximately 0.01 seconds after the occurrence of the break. The post accident transient is mitigated by activation of one of the two RHR systems. The RHR pump is activated at the start of the transient, and it attains full speed within 15 seconds. LBLOCAs at the five locations shown in Fig. BB-1 are considered. The analyses of these accident scenarios are discussed in the following sub-sections (2.8-1 through 2.8-5).

2.8.1 Pressurizer Surge Line Break (Location A in Fig. BB-1)

The accident scenario for the break location A, shown in Fig. BB-1, simulated that the pressurizer component is completely disconnected from the primary HR system by breaking the external surge line near the fixed header. The model for the external pressurizer surge line break was run for 600 seconds after initiation of the accident. The simulation results show that a single RHR system can mitigate this DBA without any damage to the blanket module system and structure. The results also show that the temperatures of the coolant water surrounding the blanket modules do not reach saturation thereby leading to phase change inside the blanket system. The void fraction in the surge line of the pressurizer is zero during the entire transient satisfying the design requirement for the pressurizer component. Results from the TRAC system model calculations are graphically presented in Appendix B of Ref. BB-12.

It is noted that the cold-leg fixed header pressure decreases to atmospheric pressure in 7.0 seconds, and the hot-leg fixed header pressure dropped to less than atmospheric pressure within 0.2 seconds. After the pump coast-down, at about 35 seconds, the hot-leg fixed header pressure rose to near atmosphere pressure. Pressures of both fixed headers are stabilized at about 60 seconds after the accident as shown in Fig. BB-13. There is a steep decline in the temperatures and pressures in the flow channels of all six blanket modules in the first 100 seconds. During the first 26 seconds of the rapid depressurization in the primary HR system, pump cavitation occurs at the two HR pump suctions. All of the blanket modules start to have non-zero but very small void fractions (max. 8.5% void) at about 30 seconds transient time (i.e., about 4 seconds after the pumps start to cavitate). The void residence time within the blanket modules is approximately 60 seconds. After this period, liquid flowrates within the six blanket modules are stabilized for the remainder of the simulation. Under this accident scenario coolant flowrates through the HR loop, the RHR loop, and the broken pressurizer surge line reach steady values at about 100 seconds as shown in Fig. BB-14.

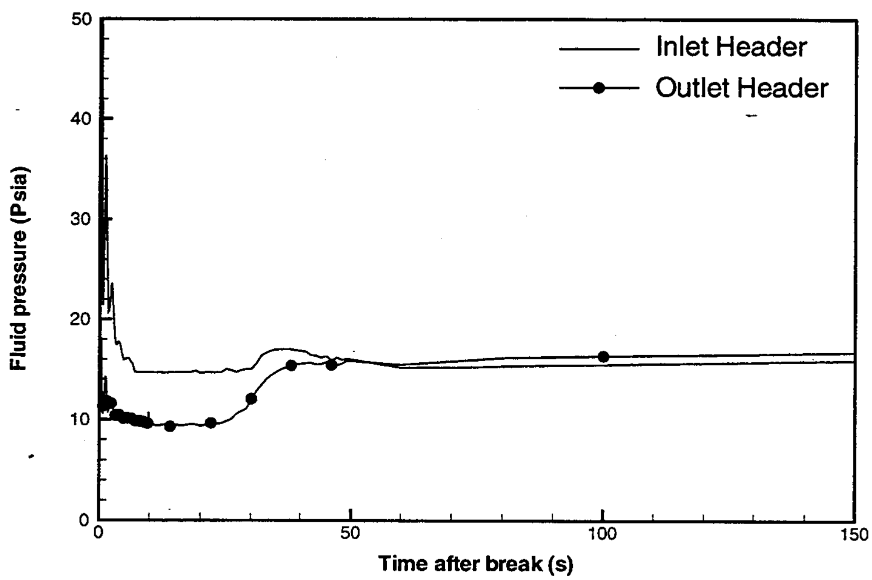


Figure BB-13 Transient fluid pressures at the inlet and outlet fixed headers

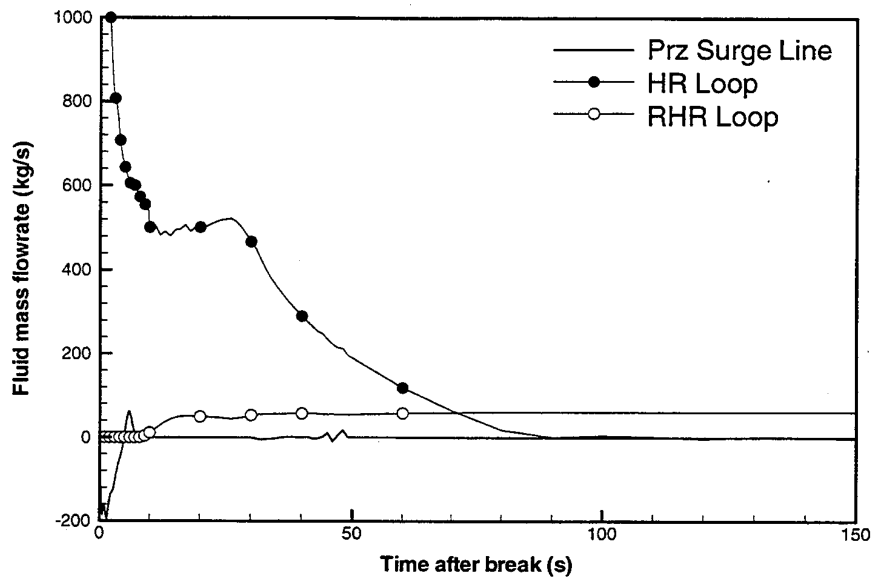


Figure BB-14 Transient fluid mass flowrates in the pressurizer surge line, the primary HR loop, and the RHR loop.

Results of the FLOWTRAN-TF model of a module 1 plate assembly were obtained using the transient boundary conditions provided by the TRAC system model for this scenario. Figure BB-15 shows the transient peak aluminum clad and lead temperatures, along with material temperature limits. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1, is 112.8 C as predicted by the FLOWTRAN-TF model. This occurs in the lead plate, and it is well below the lead melting point, 327.5 C. The peak aluminum temperature is 100 C, below the long term temperature limit of 115 C. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially the pre-incident values. Actually, maximum temperatures are reached 1 second after the start of the accident when the beam trips. However, the thermal inertia of the solid is such that this brief time delay is negligible. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the beam.

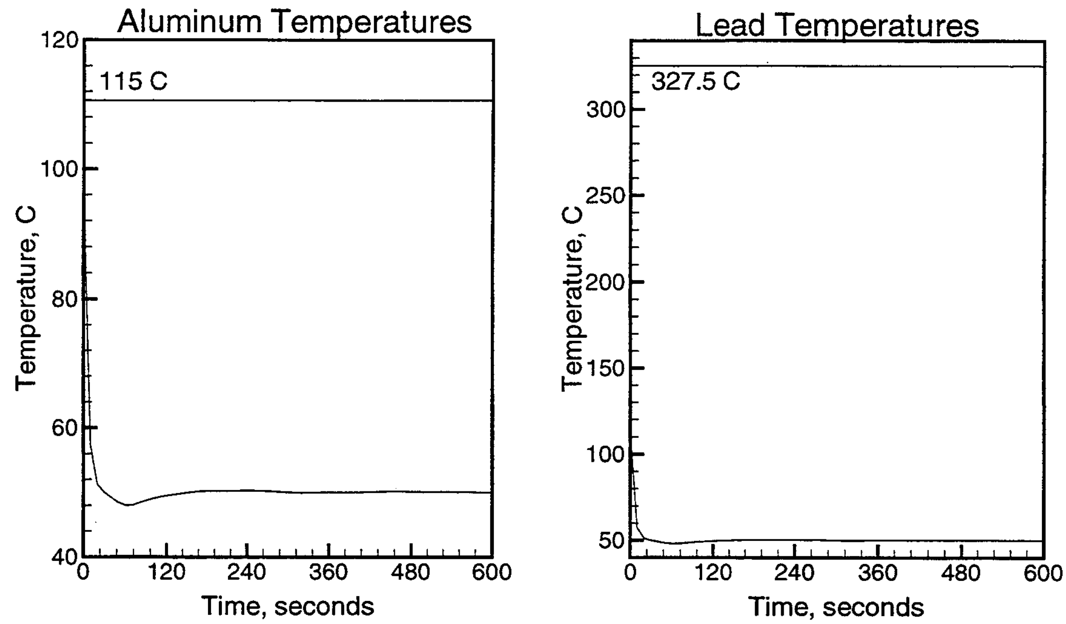
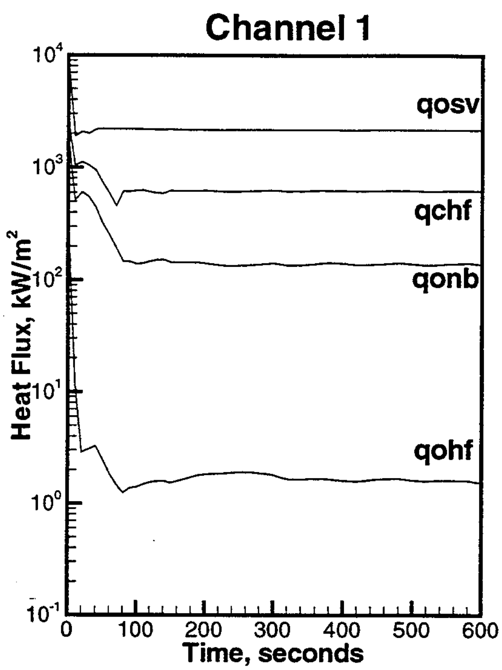
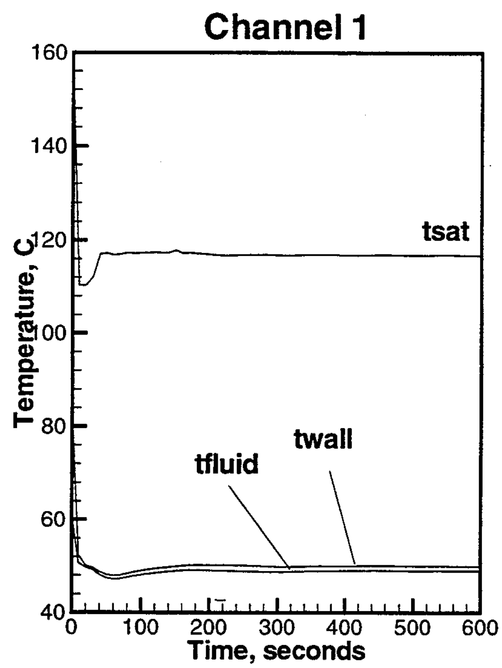
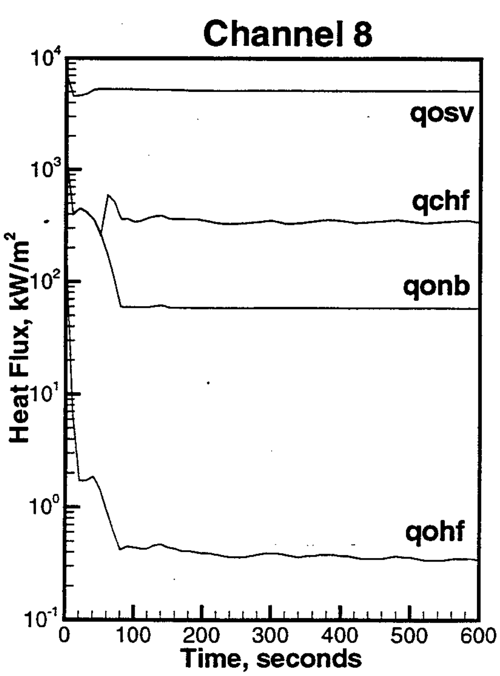


Figure BB-15 Maximum metal temperatures in module 1.

It is clear from the peak aluminum temperatures that the channel surface temperatures are not close to local saturation conditions. To further illustrate the safety margins, operating surface heat fluxes (q_{ohf}) were compared to the heat fluxes predicted for onset of nucleate boiling (q_{onb}), onset of significant void formation (q_{osv}) and the critical heat flux (q_{chf}). Fig. BB-16 shows transient axial peak operating surface heat fluxes and local values for the three boiling heat flux limits for channels 1 and 8. Also shown are plots of the wall, fluid, and saturation temperatures. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, and channel 8 is the adjacent annular channel. The large margins between the operating heat flux and the boiling limits are readily apparent. Notice that the CHF limits are lower than the OSV limits. These plots misleadingly imply that CHF would be encountered before OSV if the inlet subcoolings and flowrates in the channels were reduced, while in reality the limits would cross as they were approached and OSV would be reached prior to CHF.


Channel 1
qosv
qchf
qonb
qohf
Heat Flux, kW/m²
Time, seconds
10⁴
10³
10²
10¹
10⁰
10⁻¹
0 100 200 300 400 500 600


Channel 1
tsat
twall
tfluid
Temperature, C
Time, seconds
160
140
120
100
80
60
40
0 100 200 300 400 500 600


Channel 8
qosv
qchf
qonb
qohf
Heat Flux, kW/m²
Time, seconds
10⁴
10³
10²
10¹
10⁰
10⁻¹
0 100 200 300 400 500 600

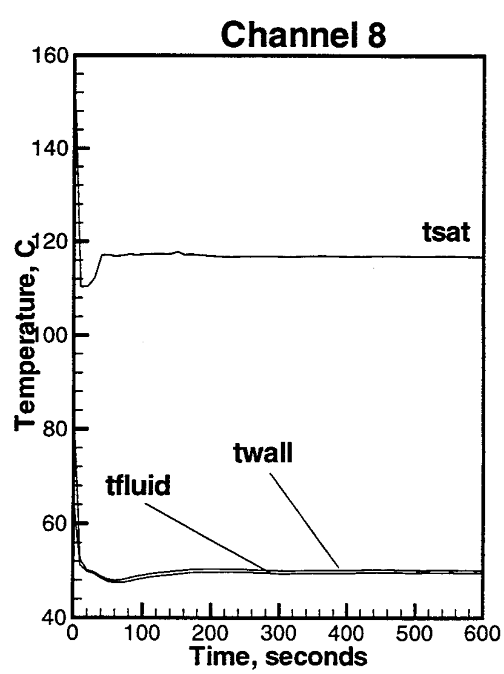

Channel 8
tsat
twall
tfluid
Temperature, C
Time, seconds
160
140
120
100
80
60
40
0 100 200 300 400 500 600

Figure BB-16 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

On a module-by-module basis, the steady-state material and thermal onset criteria for LOCAs are compared to the FLOWTRAN-TF detailed bin model results. The bin model results for the reference 1 plate-type module are tabulated in Table BB-6 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 do not presently exist). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BB-6. Note that these are generally more stringent than the imposed design criteria chosen.

Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BB-6 represent primarily best estimate values (however, some parameters were set to their estimated upper bounds, such as power density). Quantification of overall uncertainties and then their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined.

Table BB-6 FLOWTRAN-TF model results.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio	Max ONB Ratio	Max OSV Ratio	Max CHF Ratio
1	112.8	100.0	0.304	0.507	0.296	0.074	0.308
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Simulations performed using the TRAC system model and the FLOWTRAN-TF detailed bin model show that the APT blanket modules maintain a coolable geometry during this external LOCA scenario. Blanket conditions during this LOCA scenario fall within all specified T/H design criteria. No off-site impact to people or the environment would occur as a result of a pump discharge LOCA with an operational RHR system and without HR pump trips. The only on-site consequence would result from the release of contaminated cooling water.

2.8.2 HR Hot-Leg Break Close to the Outlet Header (Location B in Fig. BB-1)

[TBA...]

2.8.3 Pump Discharge Line Break (Location C in Fig. BB-1)

This scenario is simulated with TRAC and FLOWTRAN-TF. Details of the analysis are provided in Ref. BB-13. The break occurs in the section of 16 inch pipe between the pumps and heat exchangers through which all of the HR system flow passes under normal operation (break C in Fig. BB-1). The accident simulation lasts for 600 seconds, long enough for the severe transients to die out, and for temperatures, pressures, and flows to stabilize.

Figure BB-17 shows the transient pressures in the fixed inlet and outlet headers for the initial 300 seconds of the simulation. There is an almost immediate system depressurization when the break occurs. The inlet header drops to approximately 131 kPa (19 psia) and the outlet header drops to 69 kPa (10 psia). The pressurizer flow maintains the inlet header pressure at approximately the same level for the duration of the simulation. The outlet header pressure is initially depressed below that of the inlet header by the HR pump flows. There is flashing in the HR hot leg piping during the initial 15 seconds, and the pumps cavitate for 40 seconds during which the hot leg flowrate is essentially constant at 600 kg/s. The pumps continue to spin down for another 40 seconds after the cavitation ceases, and during this period the hot leg flowrate decreases with the pump speeds. At approximately 80 seconds the flow in the HR hot leg drops to zero. Between 40 and 120 seconds, the outlet header pressure increases from 69 to 138 kPa (20 psia).

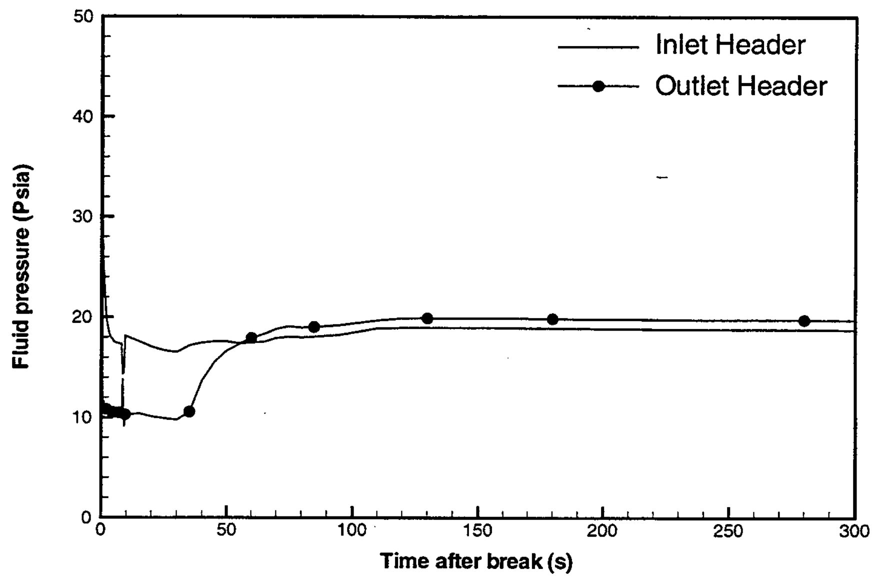


Figure BB-17 Transient fixed header pressures.

Figure BB-18 shows the transient mass flowrates on both sides of the break. As previously noted, the pump side break flow drops to zero by 80 seconds. The flow in the heat exchangers inlet piping reverses immediately with the break occurrence, and the liquid in the first pass of each heat exchanger drains out of the break in the initial 20 seconds of the accident simulation. Flow out of the heat exchanger side of the break is negative in the figures. From 20 to 130 seconds there is no break flow on this side, and thereafter coolant flows out of the heat exchanger side of the break for the duration of the simulation.

Figure BB-19 shows the HR cold leg mass flowrate downstream of the heat exchangers for the initial 300 seconds of the LOCA simulation. Forward flow continues, after the break occurrence, in the HR cold leg as the second passes of the heat exchangers drain to the inlet header. At approximately 50 seconds, the flow in the HR cold leg reverses. For the next 80 s the drained primary sides of the heat exchangers refill, and thereafter there is flow out of the heat exchanger side of the break. Initially the reverse mass flowrate is 200 kg/s, and it slowly drops to 30 kg/s at 600 seconds, the end of the simulation. This reverse flow out of the heat exchanger side of the break matches the pressurizer flow into the inlet header, so the HR system liquid inventory remains constant after the initial 130 seconds. Figure BB-19 shows the pressurizer flow into the inlet header and the RHR system flow, as well as the HR cold leg flowrate.

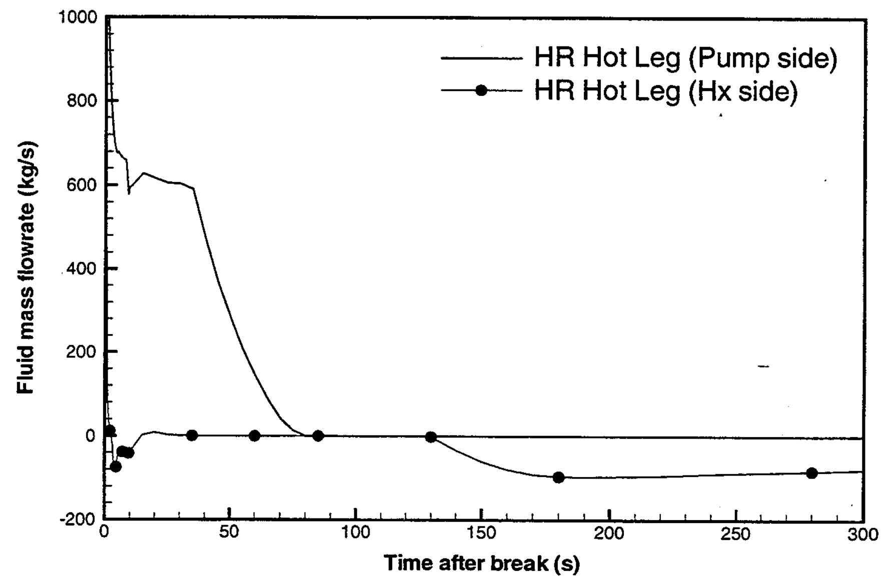


Figure BB-18 Mass flowrates on the pump and heat exchanger sides of the break.

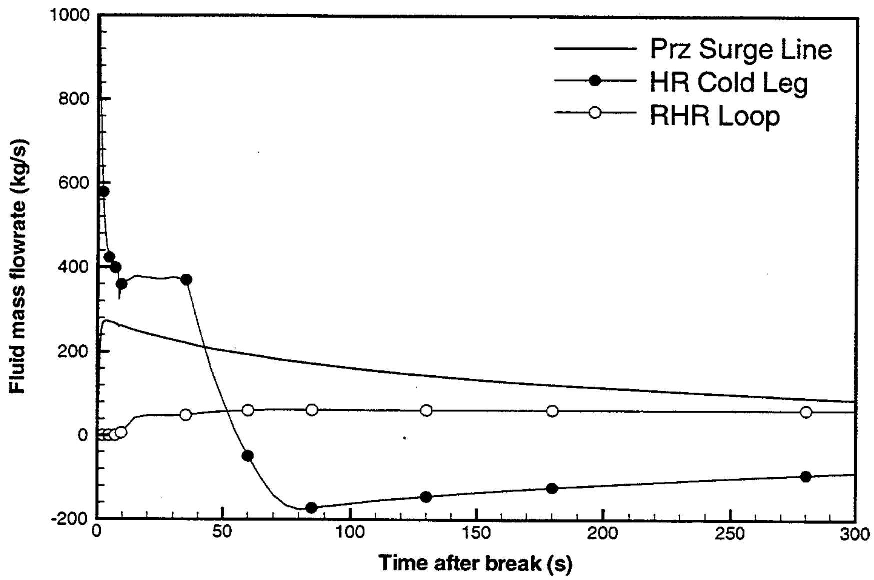


Figure BB-19 Pressurizer surge line, HR cold leg, and RHR system mass flowrates.

In the simulation the RHR pump starts at the occurrence of the break, and it comes up to full speed in 15 seconds. The RHR system check valve opens at 10 seconds, and over the next 50 seconds the flowrate increases to 62 kg/s, 4% of the HR system normal operation flowrate. The RHR system flowrate remains constant thereafter. After the initial 40 seconds of the simulation, the entrance and exit RHR heat exchanger temperatures drop monotonically, and the temperature drop across the heat exchanger at the end of the simulation is 0.6 C.

In this accident scenario, the void fractions of the flows through the six modules are zero for the entire simulation. No air is entrained in the module flows, and no boiling or flashing occurs.

Results of the FLOWTRAN-TF model of a module 1 plate assembly are presented. Figure BB-20 shows the transient peak aluminum clad and lead temperatures, along with material temperature limits. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1, is 112.8 C as predicted by the FLOWTRAN-TF model. This occurs in the lead plate, and it is well below the lead melting point, 327.5 C. The peak aluminum temperature is 100 C, below the long term temperature limit of 115 C. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially the pre-incident values. Actually, maximum temperatures are reached 1 second after the start of the accident when the beam trips. However, the thermal inertia of the solid is such that this brief time delay is negligible. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the beam.

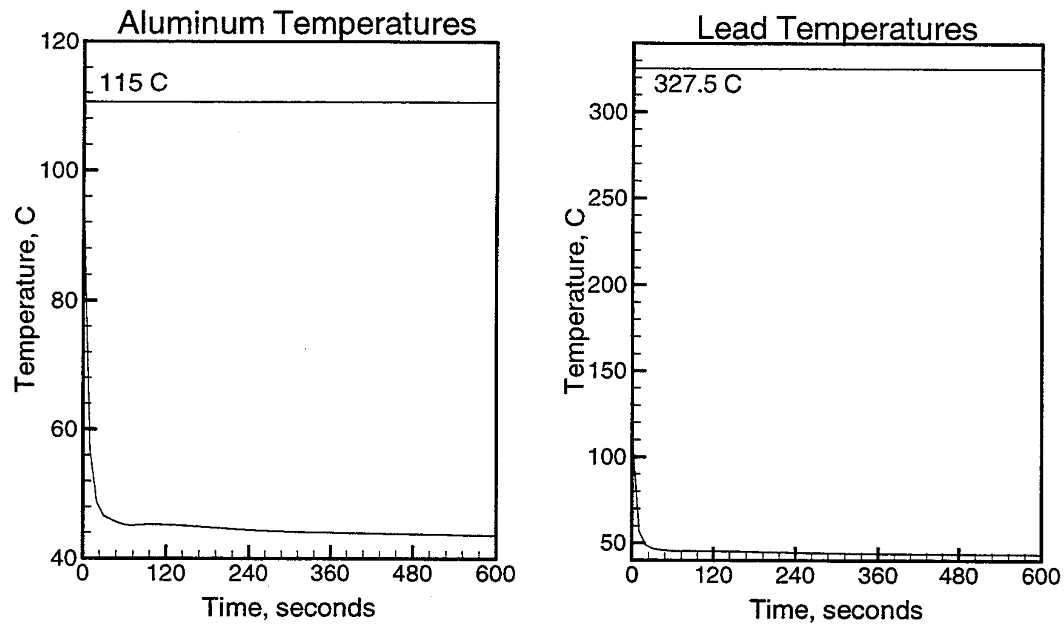


Figure BB-20 Maximum metal temperatures in module 1.

It is clear from the peak aluminum temperatures that the channel surface temperatures are not close to local saturation conditions. To further illustrate the safety margins, operating surface heat fluxes (q_{ohf}) were compared to the heat fluxes predicted for onset of nucleate boiling (q_{onb}), onset of significant void formation (q_{osv}) and the critical heat flux (q_{chf}). Fig. BB-21 shows transient axial peak operating surface heat fluxes and local values for the three boiling heat flux limits for channels 1 and 8. Also shown are plots of the wall fluid and saturation temperatures. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, and channel 8 is the adjacent annular channel. The large margins between the operating heat flux and the boiling limits are readily apparent. Notice that the CHF limits are lower than the OSV limits. These plots misleadingly imply that CHF would be encountered before OSV if the inlet subcoolings and flowrates in the channels were reduced, while in reality the limits would cross as they were approached and OSV would be reached prior to CHF.

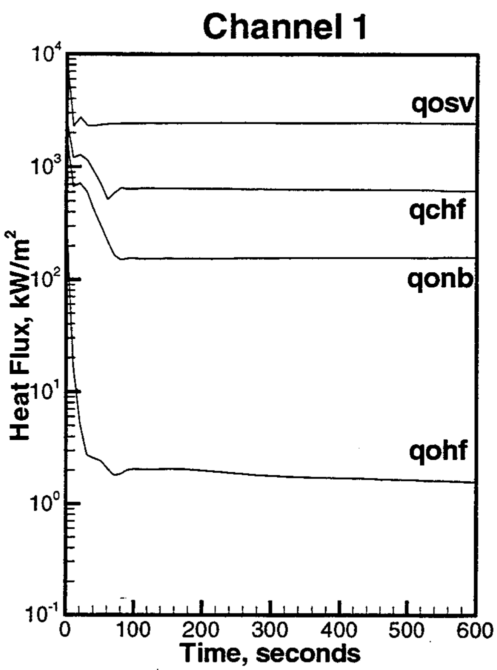
On a module-by-module basis, the steady-state material and thermal onset criteria for LOCAs are compared to the FLOWTRAN-TF detailed bin model results. The bin model results for the reference 1 plate-type module are tabulated in Table BB-7 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 do not presently exist). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BB-7. Note that these are generally more stringent than the imposed design criteria chosen.

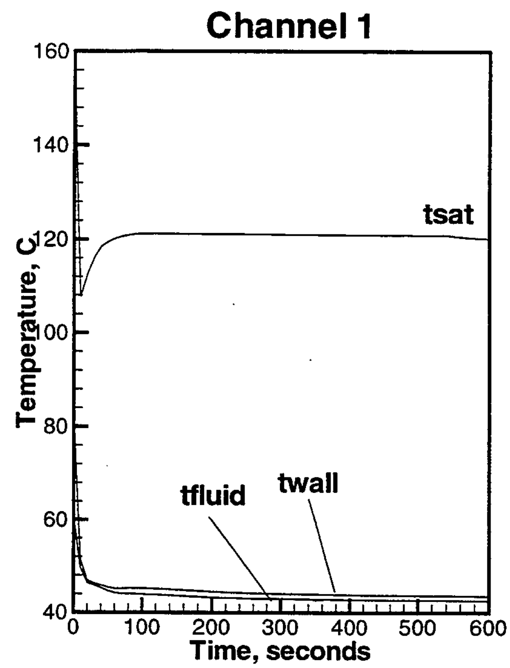
Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BB-7 represent primarily best estimate values (however, some parameters were set to their estimated upper bounds, such as power density). Quantification of overall uncertainties and then their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined.

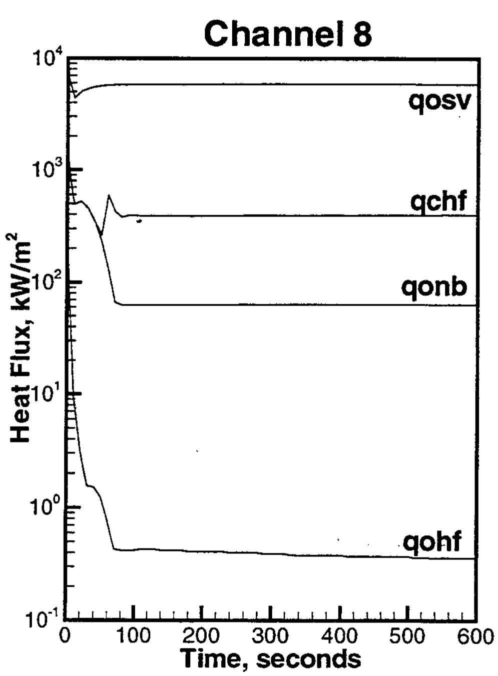
Table BB-7 FLOWTRAN-TF model results.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio	Max ONB Ratio	Max OSV Ratio	Max CHF Ratio
1	112.8	100.0	0.317	0.547	0.296	0.083	0.304
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Simulations performed using the TRAC system model and the FLOWTRAN-TF detailed bin model show that the APT blanket modules maintain a coolable geometry during this external LOCA scenario. Blanket conditions during this LOCA scenario fall within all specified T/H design criteria. No off-site impact to people or the environment would occur as a result of a pump discharge LOCA with an operational RHR system and without HR pump trips. The only on-site consequence would result from the release of contaminated cooling water.


Channel 1
qosv
qchf
qonb
qohf
Heat Flux, kW/m2
Time, seconds
0
100
200
300
400
500
600


Channel 1
tsat
tfluid
twall
Temperature, C
Time, seconds
160
140
120
100
80
60
40


Channel 8
qosv
qchf
qonb
qohf
Heat Flux, kW/m2
Time, seconds

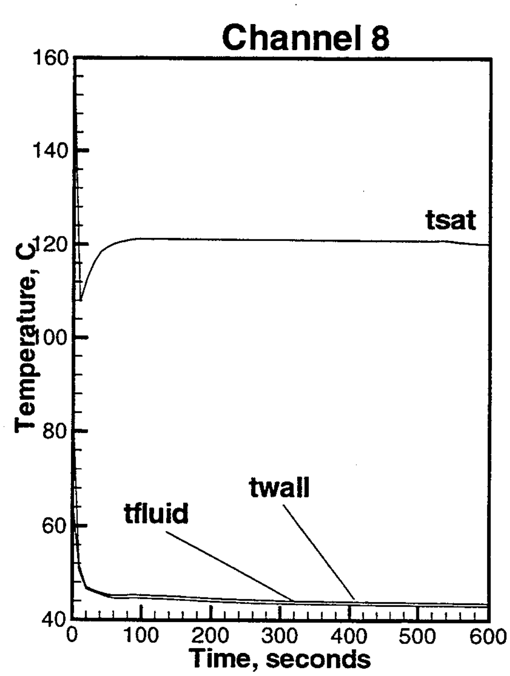

Channel 8
tsat
twall
tfluid
Temperature, C
Time, seconds

Figure BB-21 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

2.8.4 HR Cold-Leg Break (Location D in Fig. BB-1)

A cold-leg LBLOCA external to the cavity vessel is simulated as one of the DBAs. The break location was selected to be close to the cold-leg fixed header to which the pressurizer surge line is connected. This is break location D in Fig. BB-1. This model was run for 600 seconds after the initiation of the accident. The simulation results show that the pressurizer and a single RHR system can mitigate this DBA without any damage to the blanket module system and structure. The temperature of the coolant water surrounding the blanket modules does not reach saturation during the accident. The void fraction in the surge line of the pressurizer is zero during the entire transient satisfying a design requirement for the pressurizer component.

Results from the TRAC system model calculations are graphically presented in Appendix B of Ref. BB-2. Pressures in the hot and cold legs drop quickly following initiation of the LOCA accident as shown in Fig. BB-22. The results show that the cold-leg fixed header pressure decreases to atmospheric pressure in 3.5 seconds and the hot-leg pressure drops to less than atmospheric pressure within 1 second. After the 60 seconds pump coast-down, the hot-leg fixed header pressure rises to near atmospheric pressure. Pressures of both fixed headers are stabilized at about 55 seconds after the accident. The simulation results show rapid temperature and pressure drops for the flow channels of the six blanket modules during the initial 100 s after initiation of the LOCA. During the first 20 seconds of the rapid depressurization of the HR system, pump cavitation occurs at the pump suction and then coolant flow decreased without flow reversal across the pump.. At the same time, the RHR check valve opens and RHR coolant water at 40 C is introduced into the blanket modules. As a result, the fluid temperatures of the six blanket modules drop quickly. After recovery from the HR cavitation, the RHR pump suction side cavitated around 40 seconds after the accident, but coolant flow decreased without flow reversal across the RHR pump. This caused the module fluid temperatures to rise for about 10 seconds by which time blanket system pressure was recovered. Eventually, small liquid flowrates controlled by the gravitational hydraulic head were established to the six blanket modules. Figure BB-23 shows that the pressurizer provides coolant water through the inlet fixed header to the blanket coolant system adequately without air entrainment during the accident.

Results of the FLOWTRAN-TF model of a module 1 plate assembly are presented. Figure BB-24 shows the transient peak aluminum clad and lead temperatures, along with material temperature limits. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1, is 112.8 C as predicted by the FLOWTRAN-TF model. This occurs in the lead plate, and it is well below the lead melting point, 327.5 C. The peak aluminum temperature is 100 C, below the long term temperature limit of 115 C. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially the pre-incident values. Actually, maximum temperatures are reached 1 second after the start of the accident when the beam trips. However, the thermal inertia of the solid is such that this brief time delay is negligible. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the beam.

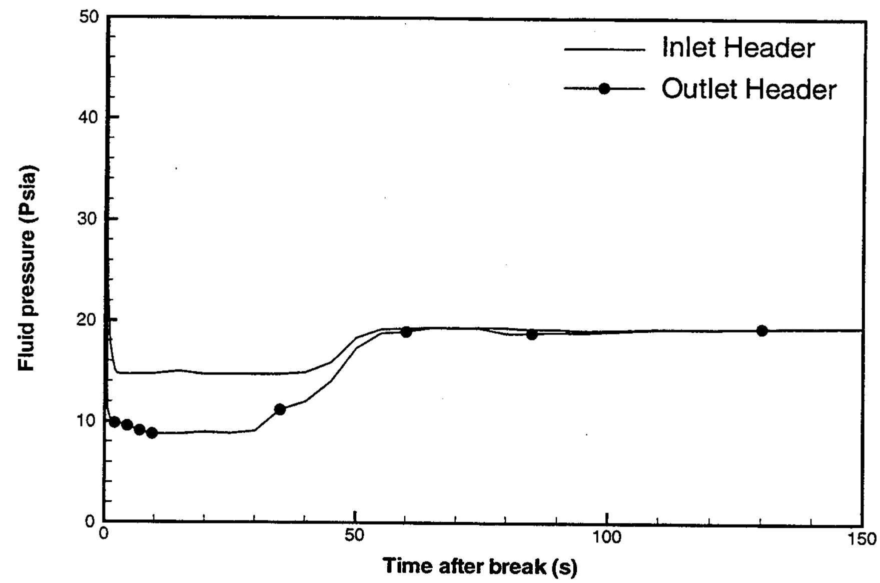


Figure BB-22 Transient fluid pressures at the inlet and outlet fixed headers.

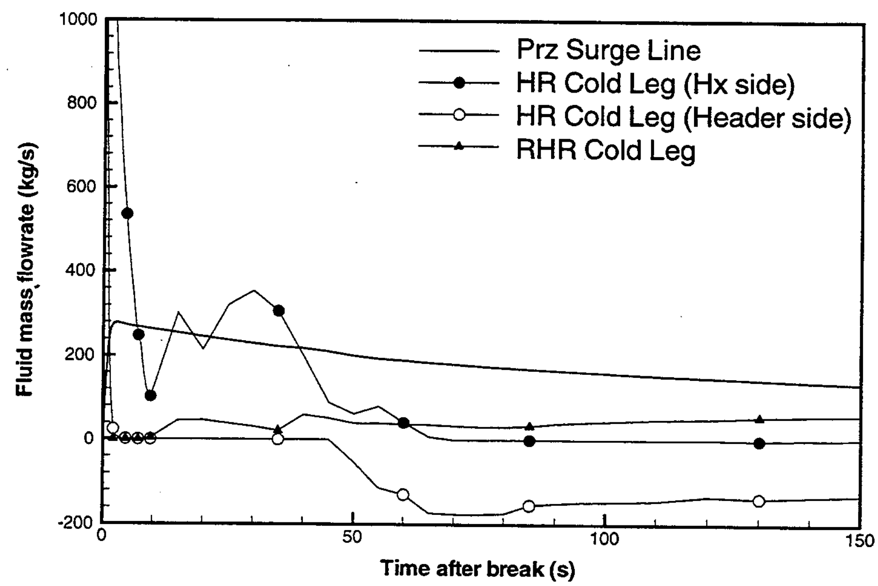


Figure BB-23 Transient fluid mass flowrates in the pressurizer surge line, the primary HR loop, and the RHR loop.

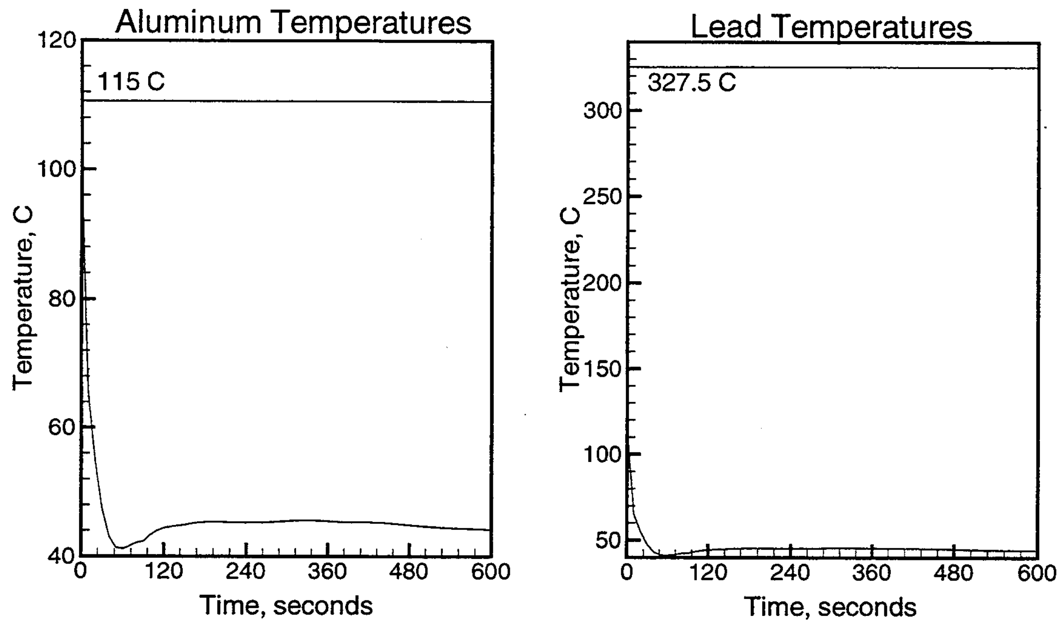


Figure BB-24 Maximum metal temperatures in module 1.

It is clear from the peak aluminum temperatures that the channel surface temperatures are not close to local saturation conditions. To further illustrate the safety margins, operating surface heat fluxes (q_{ohf}) were compared to the heat fluxes predicted for onset of nucleate boiling (q_{onb}), onset of significant void formation (q_{osv}) and the critical heat flux (q_{chf}). Fig. BB-25 shows transient axial peak operating surface heat fluxes and local values for the three boiling heat flux limits for channels 1 and 8. Also shown are plots of the wall fluid and saturation temperatures. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, and channel 8 is the adjacent annular channel. The large margins between the operating heat flux and the boiling limits are readily apparent. Notice that the CHF limits are lower than the OSV limits. These plots misleadingly imply that CHF would be encountered before OSV if the inlet subcoolings and flowrates in the channels were reduced, while in reality the limits would cross as they were approached and OSV would be reached prior to CHF.

On a module-by-module basis, the steady-state material and thermal onset criteria for LOCAs are compared to the FLOWTRAN-TF detailed bin model results. The bin model results for the reference 1 plate-type module are tabulated in Table BB-8 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 do not presently exist). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BB-8. Note that these are generally more stringent than the imposed design criteria chosen.

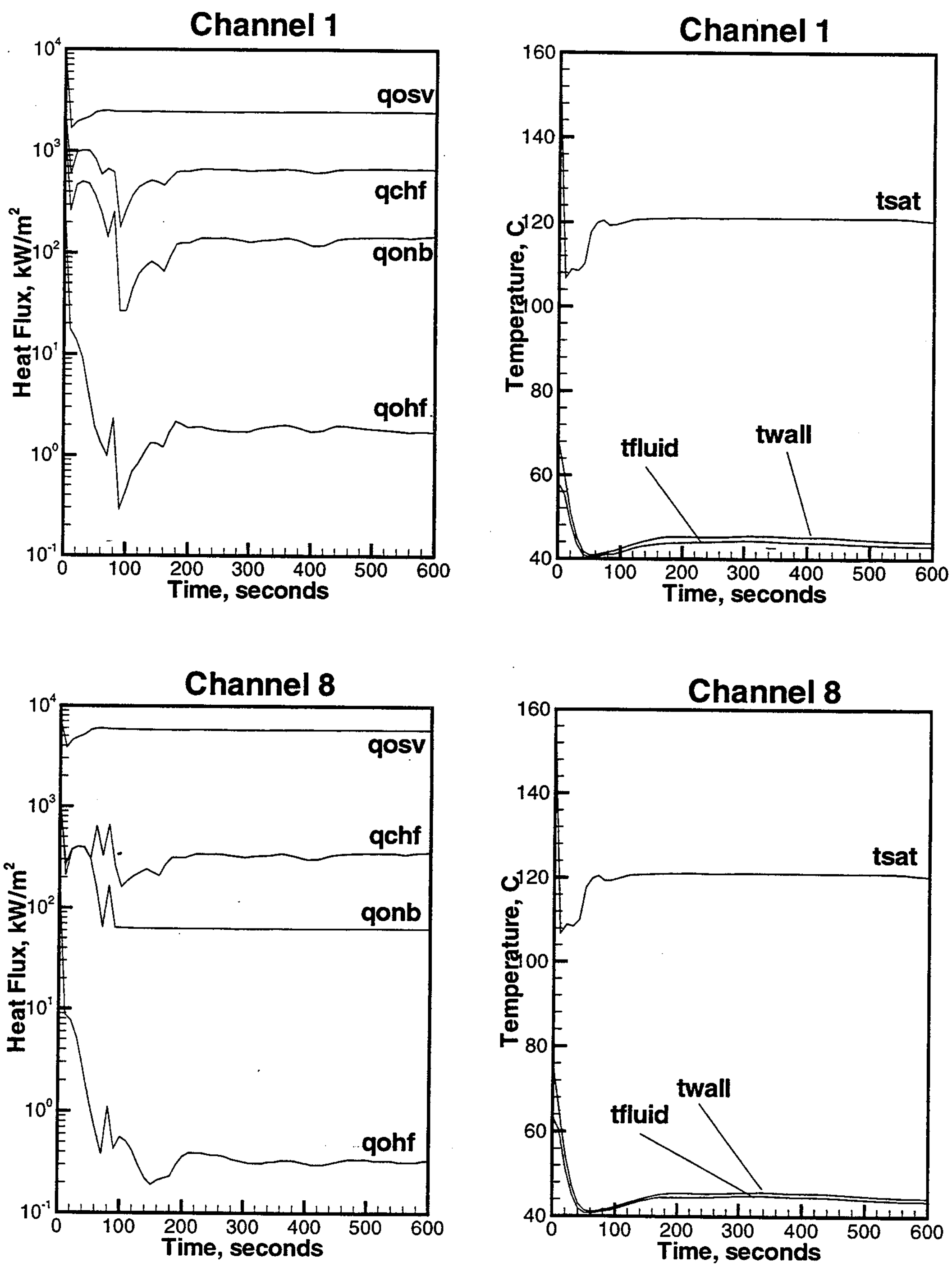

Channel 1
qosv
qchf
qonb
qohf
Heat Flux, kW/m^2
Time, seconds
Channel 1
tsat
tfluid
twall
Temperature, C
Time, seconds
Channel 8
qosv
qchf
qonb
qohf
Heat Flux, kW/m^2
Time, seconds
Channel 8
tsat
twall
tfluid
Temperature, C
Time, seconds

Figure BB-25 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BB-8 represent primarily best estimate values (however, some parameters were set to their estimated upper bounds, such as power density). Quantification of overall uncertainties and then their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined.

Table BB-8 FLOWTRAN-TF model results.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio	Max ONB Ratio	Max OSV Ratio	Max CHF Ratio
1	112.8	100.0	0.348	0.597	0.315	0.099	0.309
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Simulations performed using the TRAC system model and the FLOWTRAN-TF detailed bin model show that the APT blanket modules maintain a coolable geometry during this external LOCA scenario. Blanket conditions during this LOCA scenario fall within all specified T/H design criteria. No off-site impact to people or the environment would occur as a result of a pump discharge LOCA with an operational RHR system and without HR pump trips. The only on-site consequence would result from the release of contaminated cooling water.

2.8.5 RHR Cold-Leg Break (Location E in Fig. BB-1)

This accident scenario is initiated by a DEGB in one of the RHR systems cold-leg, that is external to the cavity and close to the fixed inlet header (location E in Fig. BB-1). The RHR system has 6 inch schedule 40 steel pipe (see Table BB-1). Power to the beam and the HR pumps is tripped 0.2 seconds after the pressurizer surge line pressure drops 5% below the normal operation value. The surge line pressure drops to the set point approximately 0.01 seconds after the occurrence of the break. The RHR pump, in the system with the break, is activated at the start of the transient, and it attains full speed within 15 seconds. The unusual aspect of this accident scenario is that the active RHR system does not mitigate but instead aggravates the situation. The TRAC model used in this simulation has only one RHR system and the break is assumed to occur in it. A 600 second simulation was run with the TRAC system model, as was the case with the rest of the TRAC external LOCA simulations (described in sections 2.4 and 2.8). The blanket module temperature responses in this 600 second simulation are benign, but the long term prospects, without intervention, are not.

Detailed results of this TRAC simulation are presented both graphically and in tabular form in Ref. BB-11. They show that the pressurizer can mitigate this accident without any damage to the blanket module system and structure for a time period in excess of 600 seconds (times in excess of 950 seconds). The temperature of the coolant water flowing through the blanket modules does not reach saturation, consequently there is no boiling.

There is a rapid depressurization of both fixed headers within a few seconds of initiation of the LOCA, as shown in Fig. BB-26. Pressure in the inlet header decreases from 724 kPa (105 psia) to 310 kPa (45 psia) and pressure in the outlet header decreases from 448 kPa (65 psia) to 103 kPa (15 psia). The inlet header pressure thereafter drops slowly for the duration of the simulation, and is 138 kPa (20 psia) at 600 seconds. The outlet header pressure partially recovers from the initial depressurization, and is approximately 1 psia above the inlet header pressure at 70 seconds. Thereafter the two header pressures slowly drop in concert. The inlet header has a higher elevation than the outlet header, and the hydrostatic pressure difference accounts for the -1.0 psi pressure drop between them. The irreversible pressure drop is very small with full RHR flow, 62 kg/s.

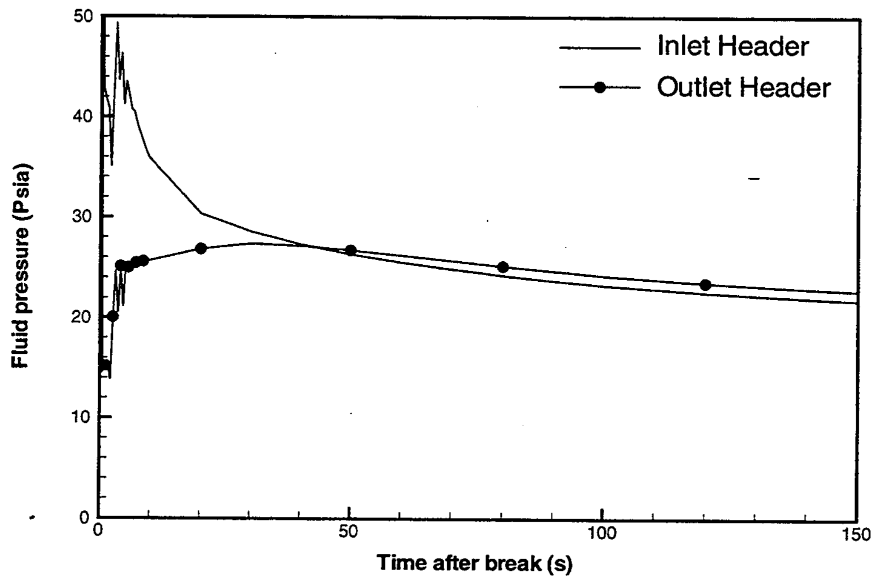


Figure BB-26 Transient fluid pressures at the inlet and outlet fixed headers for external LBLOCA due to the RHR cold-leg break.

Figure BB-27 shows transient mass flowrates through the pressurizer surge line, the primary HR loop, and the RHR cold-leg (heat exchanger side). The pressurizer flow is initiated very quickly and increases to 240 kg/s. It thereafter drops very slowly for the duration of the accident. The RHR check valve opens at 5 seconds and full RHR flow is established in the next 15 seconds. The RHR flow is discharged through the heat exchanger side of the break. From 70 seconds onward, the flow through the modules is the full RHR flow.

Results of the FLOWTRAN-TF model of a module 1 plate assembly are presented. Figure BB-28 shows the transient peak aluminum clad and lead temperatures, along with material temperature limits. There is considerable margin between the peak metal temperatures and the material limits. The peak blanket metal temperature in module 1, is 112.8 C as predicted by the FLOWTRAN-TF model. This occurs in the lead plate, and it is well below the lead melting point, 327.5 C. The peak aluminum temperature is 100 C, below the long term temperature limit of 115 C. Since the power decay is steeper than the flow decay the reported maximum metal temperatures are essentially the pre-incident values. Actually, maximum temperatures are reached 1 second after the start of the accident when the beam trips. However, the thermal inertia of the solid is such that this brief time delay is negligible. The maximum aluminum temperature occurs on the end of the plate adjacent to the decoupler and closest to the beam.

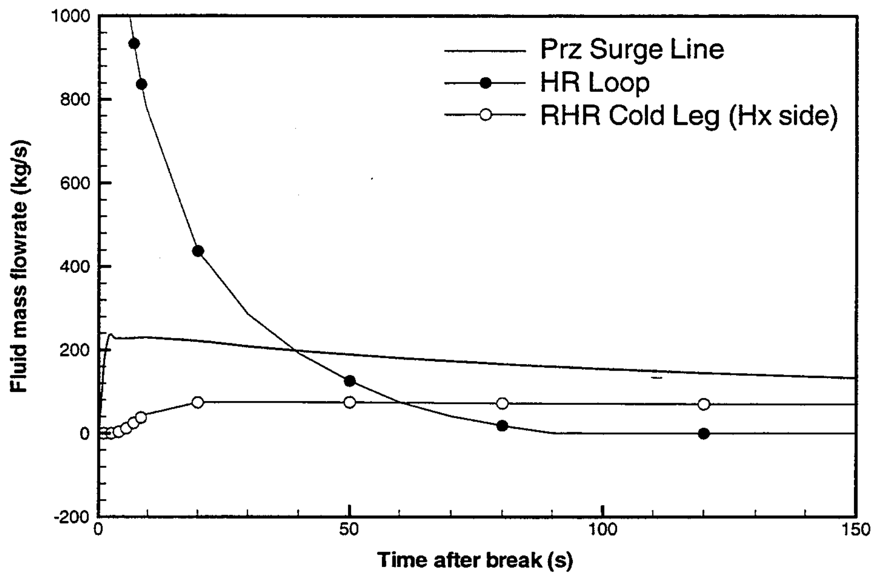


Figure BB-27 Transient fluid mass flowrates at the pressurizer surge line, the primary HR loop, and the RHR Cold-leg (Hx side).

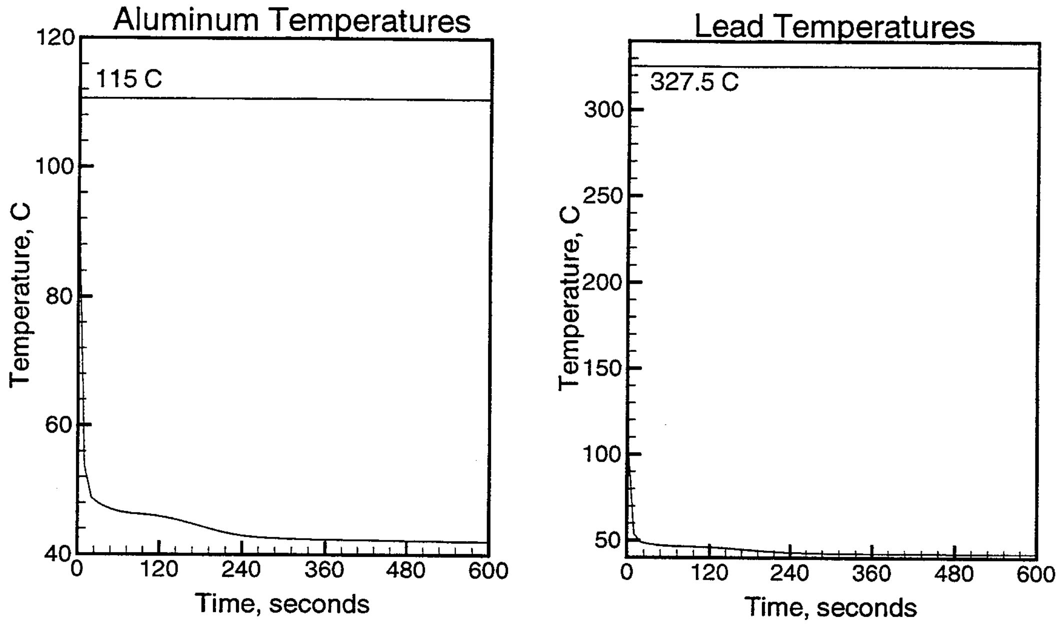


Fig. BB-28 Maximum metal temperatures in module 1.

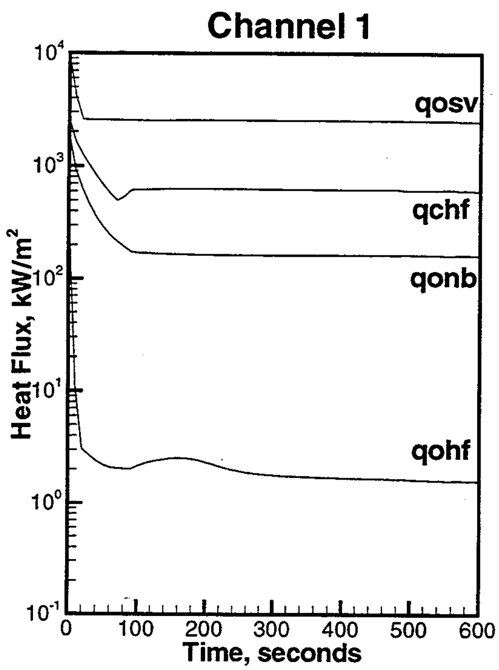
It is clear from the peak aluminum temperatures that the channel surface temperatures are not close to local saturation conditions and local boiling will not occur. To further illustrate the safety margins, operating surface heat fluxes (q_{ohf}) were compared to the heat fluxes predicted for onset of nucleate boiling (q_{onb}), onset of significant void formation (q_{osv}) and the critical heat flux (q_{chf}). Fig. BB-29 shows transient axial peak operating surface heat fluxes and local values for the three boiling heat flux limits for channels 1 and 8. Also shown are plots of the wall fluid and saturation temperatures. These plots show property values near the axial location in the channels where the peak powers occur. Channel 1 is the small rectangular channel at the decoupler end of the plate and consequently the channel with the largest surface heat flux, and channel 8 is the adjacent annular channel. The large margins between the operating heat flux and the boiling limits are readily apparent. Notice that the CHF limits are lower than the OSV limits. These plots misleadingly imply that CHF would be encountered before OSV if the inlet subcoolings and flowrates in the channels were reduced, while in reality the limits would cross as they were approached and OSV would be reached prior to CHF.

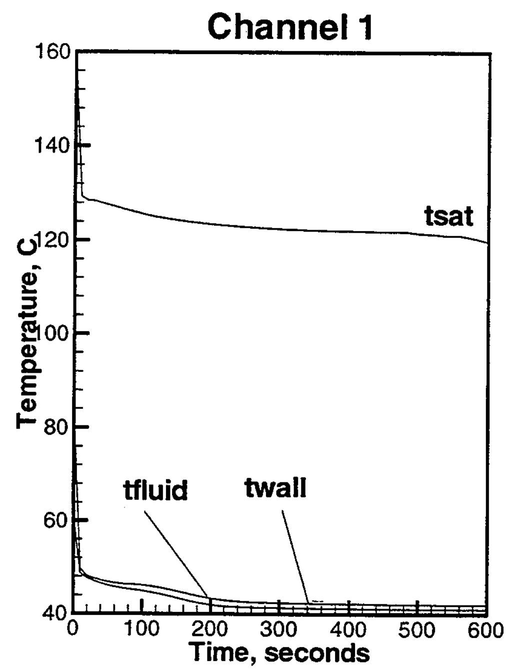
On a module-by-module basis, the steady-state material and thermal onset criteria for LOCAs are compared to the FLOWTRAN-TF detailed bin model results. The bin model results for the reference 1 plate-type module are tabulated in Table BB-9 (note that only module 1 results are currently available since the design specifications for modules 2 through 6 do not presently exist). However, module 1 should be close to the limiting module. Additional thermal onset criteria, which are typically considered, are also provided in Table BB-9. Note that these are generally more stringent than the imposed design criteria chosen.

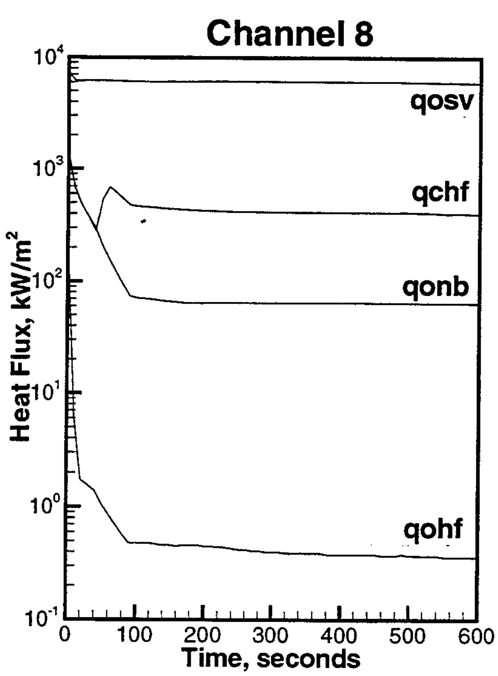
Confidence bounds are required to establish the acceptable level of probability of exceeding these criteria. The results presented in Table BB-9 represent primarily best estimate values (however, some parameters were set to their estimated upper bounds, such as power density). Quantification of overall uncertainties and then their corresponding confidence levels (i.e., operating and modeling uncertainties) have not yet been performed. Future efforts to perform a response surface analysis are planned. At that time quantification of safety margins will be determined.

Table BB-9 FLOWTRAN-TF model results under RHR cold-leg LBLOCA conditions.

Module #	Max Pb Temp (C)	Max Al Temp (C)	Max Subcooling Ratio	Max Superheat Ratio	Max ONB Ratio	Max OSV Ratio	Max CHF Ratio
1	112.8	100.0	0.252	0.437	0.278	0.062	0.279
2	TBD	TBD	TBD	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD	TBD	TBD	TBD
4	TBD	TBD	TBD	TBD	TBD	TBD	TBD
5	TBD	TBD	TBD	TBD	TBD	TBD	TBD
6	TBD	TBD	TBD	TBD	TBD	TBD	TBD


Channel 1
Heat Flux, kW/m2
qosv
qchf
qonb
qohf
Time, seconds


Channel 1
Temperature, C
tsat
tfluid
twall
Time, seconds


Channel 8
Heat Flux, kW/m2
qosv
qchf
qonb
qohf
Time, seconds

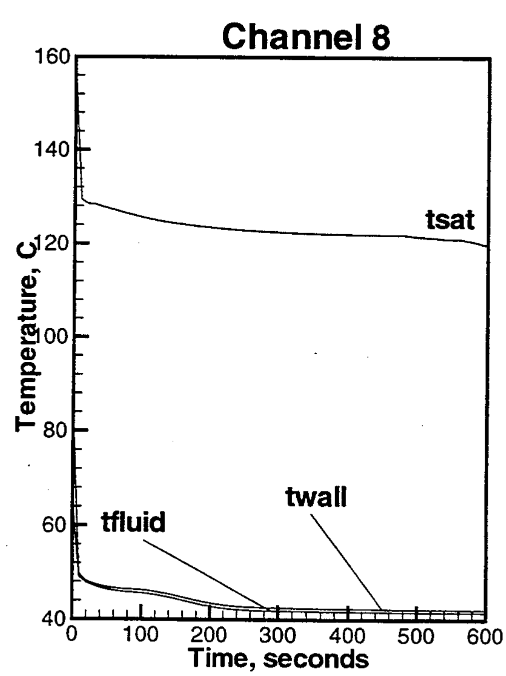

Channel 8
Temperature, C
tsat
tfluid
twall
Time, seconds

Fig. BB-29 Maximum surface heat fluxes and wall, fluid, and saturation temperatures for module 1, channels 1 and 8.

As long as the pressurizer flow is sufficient to replace the coolant lost through both sides of the break, the RHR pump circulates sufficient fluid through the blanket modules to maintain a coolable geometry. When the pressurizer flow ceases at approximately 950 seconds, Ref. BB-8, the RHR pump will draw air into the pipe connecting the inlet header to the blanket module inlet plenums (see Fig. BB-1). The RHR flowrate is insufficient to entrain air in the downward flow (see Sec. 2.4.3), so the air and water will stratify in this pipe. The free surface will be drawn down until either: (1) the pump cavitates; (2) the dead head conditions of the pump are reached; or (3) the free surface reaches the middle plenum and air is drawn through to the pump and suction is broken. The latter scenario would leave a module essentially dry at approximately 20 minutes after the break, and current calculations shows that this scenario is likely. The distance that the free surface could be drawn down below the inlet header, when the RHR pump begins to cavitate, was calculated to be approximately 9 m, and this is the approximate elevation difference between the fixed inlet header and the middle plenum for module 1 in the TRAC system model. The pump suction is at approximately the same elevation as the inlet header. Pump delta-P must be greater at dead head conditions than under flowing conditions (i.e., normal RHR pump is 4% flow and ~8.5 m total dynamic head). Therefore, under dead head conditions the modules are still uncovered. Additional analyses to determine the HR system behavior after the pressurizer flow ceases will be completed, and results will be provided in the next revision of this document.

This accident can be mitigated by initiating cavity flood automatically when the pressurizer level gets low. This accident could also be mitigated by tripping the RHR pump in the broken loop and activating the pump in the intact loop, but this strategy requires diagnosis of the situation. APT is trying to avoid depending on early operator action to successfully mitigate accidents unless it is very clear actions like flood the cavity. A similar case has been evaluated for the target and it appears that a small bypass line in each RHR loop will automatically break suction if there is a break in that RHR loop.

2.9 External LBLOCA with Beam Shutdown and Pump Trip, Active RHR and Cavity Flood (Event Sequence 9 in Fig. BB-2)

Sequence 9 represents the preferred mitigation strategy for addressing a blanket external LBLOCA. Both the RHR and cavity flood systems are automatically activated during this event. Typically, RHR starts up first based on a rapid decrease in system pressure, then followed by opening of cavity flood valves based on a decrease in pressurizer inventory. For the worst-case single failure, the remaining RHR system is assumed to be inoperative. The actuation of cavity flood does not interfere with the cooling capability of the operating RHR system and in most cases only assists in the removal of decay heat by further blanket temperature reductions.

For most break locations the discussion provided in Sec. 2.8 applies to this event sequence and bounds the consequences. However, as discussed in Sec. 2.8, there exists one unique scenario requiring additional consideration. The unusual aspect about this scenario is that the active RHR system does not mitigate but instead aggravates the situation. This scenario occurs for breaks located on the discharge side of the active RHR loop (such as, location E in Fig. BB-1). Preliminary calculations indicate that the active RHR pump removes a significant fraction of the coolant inventory from the module units. The time to uncover the blanket modules by RHR pumping is beyond 950 seconds due to pressurizer inventory reduction. This particular sequence could be mitigated by isolating the affected RHR loop or turning off its pump. However, automatic operation of the Cavity Flood System when the pressurizer level decreases below the pressurizer setpoint will mitigate the consequences.

Currently, it is assumed that the cavity flood is activated automatically (with a manual backup capability) upon loss of a predetermined amount of pressurizer inventory which occurs during this event. For most break locations, initiating the cavity flood during an external LBLOCA provides a backup to the RHR system cooling capability and significantly enhances safety with a defense-in-depth measure. Control logic could be developed to differentiate between break locations where cavity flood is needed and those where it is not. The benefit would be to avoid unnecessary cavity flood activation. The risk would be to complicate the control logic such that a situation arises where the cavity flood may not be activated on time when it is needed.

Obviously, having the cavity flooded impacts the time require to recover from the accident and to restart plant operations. An external LBLOCA in the blanket primary HR system is believed to be an extremely unlikely event. Thus, it has a small impact on availability analyses. Furthermore, the recovery time is more likely to be dominated by the post accident analyses and recovery actions necessary after an external LBLOCA. The time to drain the cavity flood water out of the cavity may not be the critical item in the recovery time.

Based on the results discussed above, cavity flood is designated to perform a *safety-significant* function and is being design to *safety-class* standards (mainly for worker safety and mission/investment protection). As discussed below in Section 3 of this appendix further analytical and experimental verification are needed to verify that confidence levels do provide expected safety margins.

For external LBLOCAs where cavity flood mitigates the event, the ability of the cavity vessel to retain the water is credited. Also the beam window must be capable of withstanding the full hydrostatic pressure under cavity flood. Based on these considerations, integrity of the cavity vessel and beam window are designated to perform *safety-significant* functions

3 Summary and Conclusions

In this appendix, results are presented for the accident analyses of LBLOCAs, external to the cavity, at the following locations:

- Pressurizer surge line near the fixed inlet header;
- HR hot leg near the fixed outlet header;
- HR hot leg after the pump discharges;
- HR cold leg near the fixed inlet header; and
- RHR cold leg near the fixed inlet header.

Table BB-10 provides a summary of the predicted onsite and off-site consequences for every event sequence analyzed. For design basis accidents these results show that the radioactive material releases to the environment are due to the activity in the coolant discharged through the breaks. A bounding release of 12 rems onsite and 0.028 rems off-site (i.e., the entire coolant inventory is assumed) is associated with the maintaining of a coolable blanket geometry throughout each event sequence.

For the BDBA event sequences, those event sequences without a beam shutdown, or without either an active intact RHR or cavity flood system with no corrective action for several days, could result in the loss of a coolable blanket geometry. For the case where there is a failure to shutdown the beam the blanket would be severely damaged. The bounding onsite and off-site consequences corresponding to the total release is shown in Table BB-4. This total release represents 2% of the mercury inventory, the entire tritium inventory (i.e., gaseous tritium in the helium system and the tritiated water in the activated primary coolant, assumed to be in the oxide form), and the activity in the coolant including 100% of the noble gases, and a fraction of the other isotopes (see Appendix CC).

3.1 Credited SSCs

For the external LBLOCA analyses, the following SSCs are credited:

- Primary, back-up and "passive" beam shutdown systems are determined to serve a safety class function.
- RHR operation is determined to be a safety significant function.
- Automatic cavity flood upon loss of pressurizer inventory is determined to be a safety significant function.
- Manual cavity flood based on extended inability to restore forced circulation to the blanket modules is determined to be a defense-in-depth function.
- The cavity vessel and the beam window are determined to serve safety significant functions.

Table BB-10 Summary of consequences for each event sequence analyzed.

Large Break Location	Event Sequence (id)	Event Sequence Category	Onsite Dose (rem)	Off-Site Dose (rem)
(A) Pressurizer surge-line	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	BDBA	12	0.028
	4	BDBA	TBD	TBD
	5	BDBA	12	0.028
	6	BDBA	52	0.16
	7	DBA	12	0.028
	8	BDBA	12	0.028
	9	DBA	12	0.028
(B) HR Hot leg	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	BDBA	12	0.028
	4	BDBA	TBD	TBD
	5	BDBA	12	0.028
	6	BDBA	52	0.16
	7	DBA	12	0.028
	8	BDBA	TBD	TBD
	9	DBA	12	0.028
(C) Pump discharge line	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	BDBA	12	0.028
	4	BDBA	12	0.028
	5	BDBA	12	0.028
	6	BDBA	52	0.16
	7	DBA	12	0.028
	8	BDBA	12	0.028
	9	DBA	12	0.028
(D) HR cold leg	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	BDBA	12	0.028
	4	BDBA	TBD	TBD
	5	BDBA	12	0.028
	6	BDBA	52	0.16
	7	DBA	12	0.028
	8	BDBA	12	0.028
	9	DBA	12	0.028
(E) RHR cold leg	1	BDBA	52	0.16
	2	BDBA	52	0.16
	3	BDBA	12	0.028
	4	BDBA	TBD	TBD
	5	BDBA	12	0.028
	6	BDBA	52	0.16
	7	DBA	12	0.028
	8	BDBA	TBD	TBD
	9	DBA	12	0.028

3.2 Summary of Control Logic and TSRs

The quantitative set of control logic for blanket external LBLOCA mitigation and the associated parameters are summarized in Table BB-11. This table is provided as an input for the development of the TSRs. Table BB-11 shows the signals based on the primary loop and cavity vessel measurements. For an external LBLOCA, the cavity flood is activated based on the pressurizer level measurements.

Table BB-11 Shutdown and Start-Up Set-Points for the Blanket External LBLOCA Mitigation.

SIGNAL	Beam Shutdown	Pump Shutdown	RHRS Start	Cavity Flood
PRIMARY LOOP				
Flow Rate				
- Pump Exit	75%	75%	75%	NA
- Pump Inlet	75%	75%	75%	NA
Pressure				
- Pump Inlet*	90%	75%	75%	NA
- Pressurizer*	90%	75%	75%	NA
Pressurizer Level	90%	75%	75%	25%
Temperature				
- HX Inlet	80°C	85°C	85°C	
- HX Exit	55°C	60°C	60°C	
CAVITY VESSEL				
- Pressure	25 torr	NA	NA	TBD

* These are the signals used in the present analyses.

In addition, the beam will be shutdown based on high radiation measurements which is implemented as an administrative control.

3.3 Discussion of Conservative Analysis Assumptions and Future Plans for Analyses and Experiments

In the external LBLOCA analyses, all the consequence calculations are performed conservatively. In the quantification of the control points, in general, best-estimate analyses (TRAC and FLOWTRAN-TF) are used.

The following are some of the planned future analyses to supplement the results presented in this appendix:

- Assessment of the TRAC/FLOWTRAN-TF lumping strategies by additional component analyses driven by the boundary and initial conditions obtained from systems analyses.
- Verification of TRAC/FLOWTRAN-TF constitutive packages for low flow conditions using representative separate effects data.
- Assumptions made in boil-off calculations need to be re-examined.

- Impact of conduction and radiation during long term cooling conditions must be further addressed.
- Verification of TRAC to FLOWTRAN-TF interfacing.
- Sensitivity analyses to support quantification of safety margins and uncertainties.

4 References

BB-1 DOE Standard, "Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports,", DOE-STD-3009-94, (July, 1994).

BB-2 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Coolant Accident (LOCA) Analysis Based on Initial Conceptual Design - Case 1: External HR Break Near Inlet Header," Westinghouse Savannah River Company, WSRC-TR-98-0059 (July 1998).

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BB-4 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Coolant Accident (LOCA) Analysis Based on Initial Conceptual Design - Case 3: External HR Break at Pump Outlet without Pump Trip," Westinghouse Savannah River Company, WSRC-TR-98-0061 (July 1998).

BB-5 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Internally Dry Flooded Cavity Accident (IDFCA) Based on Initial Plate-Type Design - Demonstration of Bin Heat Conduction Capability," Westinghouse Savannah River Company, WSRC-TR-98-0064 (July 1998).

BB-6 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Safety Analysis Methodology," Westinghouse Savannah River Company, WSRC-TR-98-0052 (May 1998).

BA-7 S. Y. Lee and L. L. Hamm, "APT Blanket Safety Analysis: Counter Current Flow Limitation for Cavity Spaces," Westinghouse Savannah River Company, WSRC-TR-98-0086 (July 1998).

BB-8 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Model Based On Initial Conceptual Design - Integrated 1D TRAC System Model," Westinghouse Savannah River Company, WSRC-TR-98-0053 (July 1998).

BB-9 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket Detailed Bin Model Based on Initial Plate-Type Design - 3-D FLOWTRAN-TF Model," Westinghouse Savannah River Company, WSRC-TR-98-0055 (July 1998).

BB-10 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "FLOWTRAN-TF Code Modifications made for APT Blanket Safety Analyses," Westinghouse Savannah River Company, WSRC-TR-98-0056 (July 1998).

BB-11 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Coolant Accident (LOCA) Analysis Based on Initial Conceptual Design - Case 5: External RHR Break Near Inlet Header," Westinghouse Savannah River Company, WSRC-TR-98-0063 (July 1998).

BB-12 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Coolant Accident (LOCA) Analysis Based on Initial Conceptual Design - Case 4: External Pressurizer Surge Line Breaker Near Inlet Header," Westinghouse Savannah River Company, WSRC-TR-98-0062 (July 1998).

BB-13 L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-of-Coolant Accident (LOCA) Analysis Based on Initial Conceptual Design - Case 2: External HR Break at Pump Outlet with Pump Trip," Westinghouse Savannah River Company, WSRC-TR-98-0060 (July 1998).

5 Referenced Appendices

DB: Thermal-Hydraulic Design Criteria for the Blanket Heat Removal System

SB: Source Term Quantification for the Blanket System

SA: Source Term Quantification for the Target System

XD: The Consequence Analyses Methodology and Results

RA: Beam Shutdown Systems Reliability Assessment

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Appendix BC

Analyses of the Large-Break Loss-of-Coolant Accidents (LBLOCA) Internal to the Cavity Vessel in the Blanket Primary Heat Removal System

1.0 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal systems (HRS) identified the loss-of-coolant accident (LOCA) as a design basis accident (DBA).

The LOCAs are typically categorized as large-break (LB), intermediate-break (IB) or small-break (SB) LOCAs. In terms of consequences LBLOCAs are the most severe and they bound the consequences of IBLOCAs and the SBLOCAs. IBLOCA and SBLOCA are analyzed separately to quantify the system response and the necessary corrective actions. In this appendix, only the LBLOCAs, characterized by a double-ended guillotine break in various pipes internal to the cavity vessel, are analyzed. These accidents are identified as internal-LBLOCA. LBLOCAs that occur outside the cavity vessel, referred to as External-LBLOCA, result in different system responses and they are analyzed in Appendix BB.

Analyses of internal-LBLOCAs have not been completed. Results will be presented in the next revision of the PSAR. In an internal-LBLOCA, the system's thermal-hydraulic behavior varies depending upon the size of the piping at the break location and the relative position of the break location to other components (e.g. pressurizer). Therefore, a number of break locations will be analyzed. The break locations considered will be chosen to provide a bounding envelope for quantifying the system response to any internal-LBLOCA.

As discussed in Chapter 3 of this PSAR, during the hazard analysis phase, multiple causes for an internal LBLOCA were identified. Table BC-1 provides discussions of the various potential initiators. Given the design features and the applicable operating controls, all the initiators for a double-ended guillotine break in the piping internal to the cavity are in the extremely unlikely frequency range. Independent of the initiator, all the internal LBLOCA analyses can be mapped into the event tree discussed in Section 2 of this appendix. The objective of this appendix is to provide a summary of the analyses performed for the event sequences of the internal-LBLOCA.

Table BC-1 Discussion of the initiators for internal LBLOCA.

Initiator	Discussion
Material defects in piping	All materials will be selected, procured and inspected consistent with the PC-3 requirements.
Assembly and welding defects	All the assemblies and welds will be performed and inspected according to PC-3 requirements.
Flow induced vibrations (FIV)	The loops will be designed to minimize the FIV phenomenon. Pumps will be mechanically isolated from the piping.
Water hammer	No quick closing isolation valves. All the valves will be locked open during operations.
Excessive internal pressure	There is continuous pressure monitoring and pressure relief valves.
Drop or impact of heavy equipment	The cavity is sealed during operations.
Seismic Event	Discussed separately in Appendix TBD.
Building collapse caused by external or natural events	Examples are large fires, flood, helicopter crash, etc. The potential for losing the detection instruments must be addressed.
Other accidents resulting in blanket damage as a result of lack of cooling	Discussed separately with other accidents. Happens if such accidents are not mitigated.

2.0 Internal-LBLOCA Event Sequences and Analyses

The event tree shown in Fig. BC-1 is applicable to all the internal-LBLOCAs, independent of the break location. The blanket primary HRS is a low pressure system. The initiator frequency for a LBLOCA in a low pressure system is estimated to be extremely unlikely. This judgment is believed to be applicable for all the initiators discussed in Table BC-1. Once initiated, an internal LBLOCA can be detected by the following measurements:

- reduction in system flow (however, during the early phases of the transient fluid acceleration and temporary increase of flow at certain locations will occur);
- increase in system temperature;
- decrease in system pressure;
- decrease in pressurizer level;
- increased humidity/moisture in the cavity vessel;
- reduction of cavity vacuum.

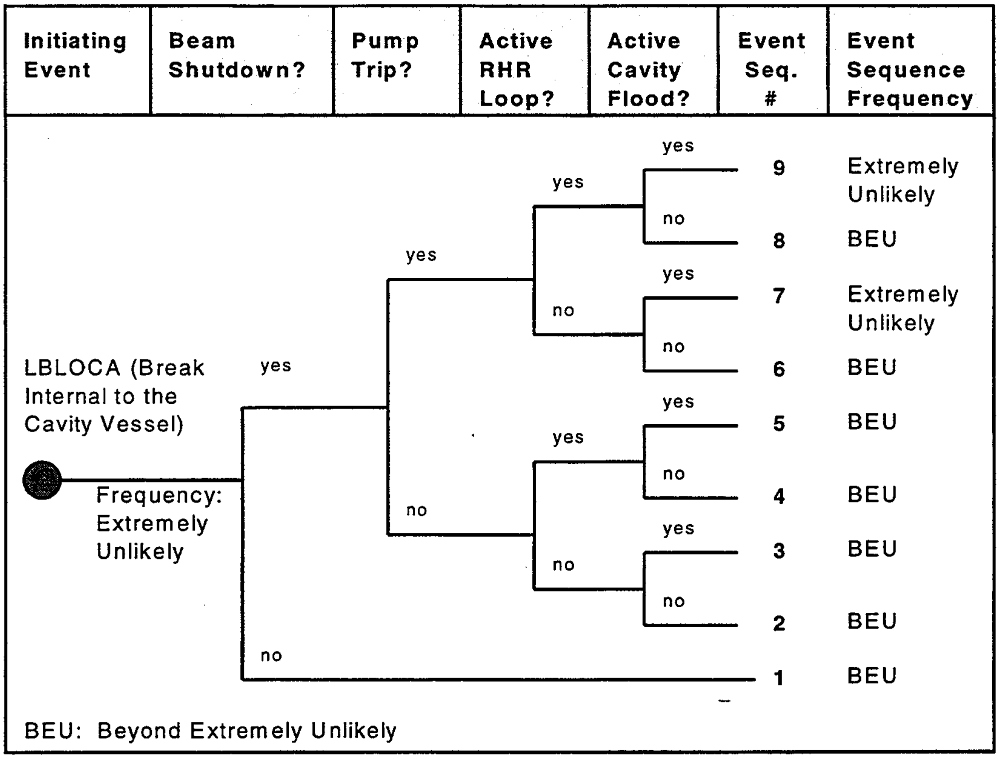

Figure BC-1 Event-tree for a LBLOCA internal to the cavity vessel.

Upon detection of the upset conditions, the following mitigative actions are taken:

- The beam is shutdown. The primary beam shutdown system is based on the LBLOCA detection measurements in the HRS. The reliability of the primary and back-up beam shutdown systems is discussed in Appendix RA. Based on this discussion, the frequency of failure to shutdown the beam given a LOFA with coastdown is in the Beyond Extremely Unlikely (BEU) range. In addition, there is a "passive" beam shutdown system that is automatically activated upon pressurizing the cavity vessel. The passive beam shutdown is automatically triggered after a LBLOCA inside the cavity.
- The pumps on the primary HRS are shutdown; however, for an internal break, the pump shutdown does not affect the thermal-hydraulic response. Thus, the pump shutdown is not included in the event tree shown in Fig. BC-1
- Following the beam shutdown, the Residual Heat Removal System (RHRS) pumps are started. There are two independent RHRS loops each being capable of removing the total decay heat in the blanket. The reliability of the RHRS is discussed in Appendix RB.
- Upon loss of pressurizer inventory or in the unlikely event that neither one of the RHRS pumps can be activated, the cavity flood is the next step in the mitigation. The reliability of the cavity flood system is discussed in Appendix RB.

It is important that the upset conditions that result in a LOCA do not result in loosing the detection and/or mitigation capabilities. In general, an independent power source is provided for the critical detection instruments. Furthermore, the detection instruments are designed to fail safe such that the failure of the instrument automatically results in beam shutdown. Finally, for the external events (such as a large facility fire) or natural phenomena hazards (e.g. seismic, flood), the beam is automatically shutdown without relying on the primary HRS signals for upset conditions.

In Fig. BC-1, sequences are numbered starting from fully unmitigated (Sequence #1) towards the mitigated sequences. Sequences numbered 3 and 5 in Fig. BC-1 are the design-basis event (DBE) sequences. The remaining sequences are the beyond-design basis event (BDBE) sequences. Once analyses are completed, an analytic discussion of all the sequences shown in Fig. BC-1 will be provided in the next revision of the PSAR. In the mean time, the accident sequences and consequences are discussed qualitatively.

2.1 Internal LBLOCA without a Beam Trip and without Pump Shutdown (Sequence Number 1 in Figure BC-1)

For an internal LBLOCA, the coolant inventory from the blanket primary loop will be drained into the cavity. The total coolant inventory is about 70 m^3 (excluding pressurizer inventory) and only 30 m^3 of water in the cavity vessel is needed to cover the blanket modules. Thus, the water in the cavity vessel must first be evaporated before extensive damage to the blanket modules can occur. The consequences of this event are bounded by an unmitigated external LBLOCA, discussed in Appendix BB. Similar to LOFA (discussed in Appendix BA) and External LBLOCA (discussed in Appendix BB), the beam shutdown system that responds to an internal LBLOCA is classified as a safety class system.

Because an internal LBLOCA will cause a passive beam shutdown as a result of cavity pressurization without postulating any additional internal failures, no BDBE sequence is analyzed for this accident. Such a scenario would be outside the realm of credible events and its analysis would not provide any meaningful insight for the residual risk.

2.2 Internal LBLOCA with Beam Trip and without Pump Shutdown (Sequence Number 2 in Figure BC-1)

During an Internal-LBLOCA, the system inventory will be drained into the cavity vessel. As discussed in Appendix DC, 30 m^3 of water is needed to flood the cavity above the top of the blanket modules. Thus, the pressurizer inventory (83 m^3) alone will be sufficient to keep the blanket modules covered with water.

In reality, the cavity flood is likely to prevent an internal dryout of the blanket as a result of recondensation for an extended period of time until the cavity flood water heats-up. If no further mitigative action is taken, one could postulate that after the water in the cavity boils off, the blanket could be dry. This duration is very long (on the order of XX days) and it is unrealistic to assume that the accident will be allowed to progress this long without additional administrative measures, such as activating the cavity flood manually if the automatic activation fails.

In this analysis, the ability of the cavity to retain the water is credited. The cavity vessel and the beam window are being designed to PC-3 requirements. The beam window is capable of withstanding the full hydrostatic pressure under cavity flood. Thus, the ability of the cavity to retain water is a design basis event.

2.3 Internal LBLOCA with Beam Trip and Cavity Flood without Pump Shutdown (Sequence Number 3 in Figure BC-1)

As discussed in the previous section, water drained from the pressurizer covers the blanket modules. During the time period when the pressurizer empties, the blanket plates remain cool. When the pressurizer is empty, the cavity flood is activated. Subsequently, the cavity flood water fills the cavity up to the fixed headers covering all potential break-locations.

2.4 Internal LBLOCA with Beam Trip and Active RHRS without Pump Shutdown (Sequence Number 4 in Figure BC-1)

For internal-LBLOCAs, no specific calculations have been performed with active RHRS and without cavity flood. As discussed in section 2.2 of this appendix, the water drained from the pressurizer covers the blanket modules. Thus, for this accident scenario the RHRS system is irrelevant but the pumps will probably be activated because early in the transient, it may not be feasible to differentiate between an external and internal LBLOCA. Instead of defining a complicated RHRS start-up logic, the RHRS pumps will be started automatically upon loss of pressure.

2.5 Internal LBLOCA with Beam Trip, Active RHRS and Cavity Flood without Pump Shutdown (Sequence Number 5 in Figure BC-1)

A number of TRAC calculations will be performed for the different break locations. In general, it is expected that these calculations will show that once the cavity is flooded, the system remains cool without overheating the blanket modules.

2.6 Internal LBLOCA with Beam Trip and with Pump Shutdown (Sequence Number 6 in Figure BC-1)

A number of TRAC calculations will be performed for the different break locations.

[TBA...]

2.7 Internal LBLOCA with Beam Trip and Cavity Flood with Pump Shutdown (Sequence Number 7 in Figure BC-1)

A number of TRAC calculations will be performed for the different break locations.

[TBA...]

2.8 Internal LBLOCA with Beam Trip and Active RHRS with Pump Shutdown (Sequence Number 8 in Figure BC-1)

A number of TRAC calculations will be performed for the different break locations.

[TBA...]

2.9 Internal LBLOCA with Beam Trip, Active RHRS and Cavity Flood with Pump Shutdown (Sequence Number 9 in Figure BC-1)

A number of TRAC calculations will be performed for the different break locations.

[TBA...]

3.0 Summary and Conclusions

In the next revision of the PSAR, internal LBLOCAs will be analyzed for different size breaks (leaks) at different locations in the HRS. The make-up water supply logic will be incorporated into these analyses to obtain a realistic system response to different types of internal LBLOCAs. Based on these analyses, TSRs for the shutdown functions will be developed. Also, a detailed discussion of the corrective actions will be provided.

No BDBE sequence without a beam shutdown will be analyzed for internal-LBLOCA. Such a sequence would require the failure of the active and passive beam shutdown systems, in addition to multiple break locations before any source term is generated.

3.1 Credited SSCs

For the internal LOCA analyses, the following SSCs are anticipated:

- Primary, back-up and "passive" beam shutdown systems are determined to serve a safety class function.
- Automatic cavity flood upon loss of pressurizer inventory is determined to be a safety significant function.

3.2 Summary of Control Logic and TSRs

The quantitative set of control logic for blanket internal-LOCA mitigation and the associated parameters are summarized in Table BC-2. This table is provided as an input for the development of the TSRs. Table BC-2 shows the signals based on the primary loop and cavity vessel measurements. For an internal-LOCA, the cavity flood is activated based on the pressurizer level and cavity pressure measurements.

Table BC-2 Shutdown and start-up set-points for the blanket internal LBLOCA mitigation.

SIGNAL	Beam Shutdown	Pump Shutdown	RHRS Start	Cavity Flood
PRIMARY LOOP				
Flow Rate				
- Pump Exit	75%	NA	NA	NA
- Pump Inlet	75%	NA	NA	NA
Pressure				
- Pump Inlet*	90%	NA	NA	NA
- Pressurizer*	90%	NA	NA	NA
Pressurizer Level	90%	NA	NA	25%
Temperature				
- HX Inlet	80°C	NA	NA	
- HX Exit	55°C	NA	NA	
CAVITY VESSEL				
- Pressure	25 torr	NA	NA	TBD

* These are the signals proposed to be used in the system analyses.

In addition, the beam will be shutdown based on high radiation measurements which is implemented as an administrative control.

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Appendix BD

Analyses of the Small-Break Loss-of-Coolant Accidents (SBLOCA) External to the Cavity Vessel in the Blanket Primary Heat Removal System

1.0 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal systems (HRS) identified the loss-of-coolant accident (LOCA) as a design basis accident (DBA).

The LOCAs are typically categorized as large-break (LB), intermediate-break (IB) or small-break (SB) LOCAs. In terms of consequences LBLOCAs are the most severe and they bound the consequences of IBLOCAs and the SBLOCAs. The external-LBLOCAs are analyzed in Appendix BB. In this appendix, IBLOCA and SBLOCA external to the cavity vessel are analyzed. These LOCAs are referred to as the external-SBLOCAs.

As discussed in Chapter 3 of this PSAR, for external SBLOCAs, the following initiators are identified:

- Failure of valve seals
- Failure of pump seals
- Erosion of heat exchanger tubes
- Material defects in piping (cracks)
- Assembly and welding defects
- Instrument line leaks or breaks

SBLOCA analyses will be performed in order to quantify the system response in comparison with the response of the corrective actions. For example, if the loss-of-water inventory or system depressurization is very slow compared to the response of the make-up water delivery or pressurizer recharge systems, a SBLOCA can proceed undetected for an extended period of time. Because the system response during a SBLOCA is slow in comparison with the transport time through the primary loop, the break location is not of primary importance. In the analyses, the main emphasis will be to quantify the effects of small leaks that can go undetected for an extended period of time.

Analyses of external SBLOCAs have not been completed. Results of these analyses will be presented and discussed in the next revision of the PSAR. In this appendix, a summary of the analyses to be performed for different size breaks at a limited number of locations outside the cavity vessel are provided. The consequences of unmitigated sequences are not discussed because such consequences would be bounded by the corresponding LBLOCA analyses presented in Appendix BB. An exception to this would be the release of the volatile radionuclides in the coolant. If a leak is allowed to proceed for an extended period of time, the consequences of coolant spills may exceed the coolant consequences during a LBLOCA.

Therefore, the main objectives of the analyses provided in this appendix are:

- to quantify the system response to various size leaks, and
- to develop detection and mitigation methodology to prevent a small break LOCA from evolving into a major loss-of-coolant accident.

2.0 SBLOCA Event Sequences and Analyses

The event tree for an external SBLOCA is similar to the external-LBLOCA event tree discussed in Appendix BB. The major difference is that the initiator frequency for a SBLOCA is in the anticipated range; however, because of the very slow progression of the accident, the mitigation is much easier and the unmitigated progression of the accident for an extended period is less likely.

Once initiated, an external SBLOCA can be detected by the following measurements:

- decrease in system pressure;
- decrease in pressurizer level;
- excessive increase in make-up system flow;
- increase in moisture in the confinement;
- increase in radiation field at the break location.

Upon detection of the upset conditions, the following mitigative actions are taken:

- The beam is shutdown. The beam shutdown for a SBLOCA is likely to be a manual function based on the make-up water inventory. For certain size breaks, the controls developed for the LOFA and LBLOCA may automatically terminate the beam operation.
- The pumps in the primary HRS are shutdown and the leak location will be isolated (if possible).
- Following the beam shutdown, the Residual Heat Removal System (RHRS) pumps are started. There are two independent RHRS loops each being capable of removing the total decay heat in the blanket.

If the leak is in the RHRS loop, the RHRS loop may have to be isolated while the primary loop is being used for removing the decay heat.

Upon loss of pressurizer inventory or in the unlikely event that neither one of the RHRS pumps can be activated, the cavity flood is the next step in the mitigation. However, it is not expected that an external SBLOCA will be allowed to proceed until the cavity flood would be needed.

The details of the operational controls to effectively deal with SBLOCAs without negatively impacting the plant availability considerations are currently being developed. Along with the details of the analyses for different size breaks at different locations, these controls will be included in the next revision of the PSAR.

3.0 Summary and Conclusions

In the next revision of the PSAR, external SBLOCAs will be analyzed for different size breaks (leaks) at different locations in the HRS. The make-up water supply logic will be incorporated into these analyses to obtain a realistic system response to different types of SBLOCAs.

Based on these analyses, TSRs for the shutdown functions will be developed. Also, a detailed discussion of the corrective actions will be provided.

Consequences of SBLOCAs will be bounded by the analyses provided in Appendix BB for external LBLOCAs, except more coolant may be spilled prior to detection.

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Appendix BE

Analyses of the Small-Break Loss-of-Coolant Accidents (SBLOCA) Internal to the Cavity Vessel in the Blanket Primary Heat Removal System

1.0 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal systems (HRS) identified the loss-of-coolant accident (LOCA) as a design basis accident (DBA).

The LOCAs are typically categorized as large-break (LB), intermediate-break (IB) or small-break (SB) LOCAs. In terms of consequences LBLOCAs are the most severe and they bound the consequences of IBLOCAs and the SBLOCAs. The internal-LBLOCAs are analyzed in Appendix BC. In this appendix, IBLOCAs and SBLOCAs internal to the cavity vessel are analyzed. These LOCAs are referred to as the internal-SBLOCAs.

As discussed in Chapter 3 of this PSAR, for internal SBLOCAs, the following initiators are identified:

- Failure of valve seals (the final design may not include any valves inside the cavity vessel)
- Material defects in piping
- Assembly and welding defects
- Instrument line leaks or breaks

SBLOCA analyses will be performed in order to quantify the system response in comparison with the response of the corrective actions. For example, if the loss-of-water inventory or system depressurization is very slow compared to the response of the make-up water delivery or pressurizer recharge systems, a SBLOCA can proceed undetected for an extended period of time. Because the system response during a SBLOCA is slow in comparison with the transport time through the primary loop, the break location is not of primary importance. In the analyses, the main emphasis would be to quantify the effects of small leaks that can go undetected for an extended period of time. However, the break location and size may affect the flow distribution among the many parallel flow channels that exist in the blanket design. A flow maldistribution may result in thermal failure in some of the channels.

Analyses of external SBLOCAs have not been completed. Results of these analyses will be presented and discussed in the next revision of the PSAR. In this appendix, a summary of the analyses to be performed for different size breaks at a limited number of locations inside the cavity vessel are provided. In general, the consequences of unmitigated sequences are not discussed because such consequences would be bounded by the corresponding LBLOCA analyses presented in Appendix BC. However, if a thermal failure caused by a SBLOCA results in a LBLOCA, the initial conditions assumed for the LBLOCA analyses may be different. These cases will have to be addressed specifically. Another exception to the consequence analyses being bounded by LBLOCAs would be the release of the volatile radionuclides in the coolant. If a leak is allowed to proceed for an extended period of time, the consequences of coolant spills may exceed the coolant consequences during a LBLOCA.

Therefore, the main objectives of the analyses provided in this appendix are:

- to quantify the system response to various size leaks, and
- to develop detection and mitigation methodology to prevent a small break LOCA from evolving into a major loss-of-coolant accident.

2.0 SBLOCA Event Sequences And Analyses

The event tree for an internal SBLOCA is similar to the internal-LBLOCA event tree discussed in Appendix BC. The major difference is that the initiator frequency for a SBLOCA is in the anticipated range; however, because of the very slow progression of the accident, the mitigation is much easier and the unmitigated progression of the accident for an extended period is less likely.

Once initiated, an external SBLOCA can be detected by the following measurements:

- decrease in system pressure;
- decrease in pressurizer level;
- excessive increase in make-up system flow;
- increase in moisture in the cavity vessel;
- increase in the cavity vessel pressure; and
- increase in radiation field at the break location.

Upon detection of the upset conditions, the following mitigative actions are taken:

- The beam is shutdown. The beam shutdown for a SBLOCA is likely to be a manual function based on the make-up water inventory. For certain size breaks, the controls developed for the LOFA and LBLOCA may automatically terminate the beam operation.
- The pumps in the primary HRS are shutdown.
- Following the beam shutdown, the Residual Heat Removal System (RHRS) pumps are started. There are two independent RHRS loops each being capable of removing the total decay heat in the blanket. Note that RHRS is needed for decay heat removal but it does not terminate the accident. Eventually the blanket module must be replaced after the necessary waiting period elapses. In the meantime, the leakage will continue possibly at a slower rate during RHRS operation.
- Upon loss of pressurizer inventory or in the unlikely event that neither one of the RHRS pumps can be activated, the cavity flood is the next step in the mitigation. However, it is not expected that an internal LBLOCA will be allowed to proceed until the cavity flood would be needed.

The details of the operational controls to effectively deal with SBLOCAs without negatively impacting the plant availability are currently being developed. Along with the details of the analyses for different size breaks at different locations, these controls will be included in the next revision of the PSAR.

3.0 Summary and Conclusions

In the next revision of the PSAR, internal SBLOCAs will be analyzed for different size breaks (leak) at different locations in the HRS. The make-up water supply logic will be incorporated into these analyses to obtain a realistic system response to different types of SBLOCAs. Also the interaction with the cavity vacuum system will be investigated.

Based on these analyses, TSRs for the shutdown functions will be developed. Also, a detailed discussion of the corrective actions will be provided.

Consequences of SBLOCAs will be bounded by the analyses provided in Appendix BC for Internal-LBLOCAs, except more coolant may be spilled prior to detection.

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Appendix BF

Analyses of the Loss-of-Heat Sink Accidents (LOHSA) in the Blanket Primary Heat Removal System

1.0 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal systems (HRS) identified the loss-of-heat sink accident (LOHSA) as a design basis accident (DBA). As discussed in Chapter 3 of this PSAR, multiple initiators are identified for a LOHSA in the blanket. Each initiator is discussed in Table BF-1.

As discussed in Table BF-1, there could be multiple initiators for the LOHSA in the blanket. A loss-of-coolant accident (LOCA) or a loss-of-flow accident (LOFA) in the tertiary or secondary loops will result in a loss-of-heat sink. The initiator determines the severity of the transient during which the heat sink to the primary HRS is lost. For instance, a LOFA in the secondary or tertiary loops is an anticipated event. However, accounting for the flow coastdown in these loops, the heat sink will be lost gradually allowing additional time to respond to the transient. On the other hand, a loss-of-coolant accident (LOCA) on the secondary side may result in a very rapid loss-of-heat sink. A large-break LOCA is a very unlikely event for the systems of interest.

Table BF-1 Discussion of the Initiators for LOHSA

Initiator	Discussion
LOCA on the secondary or tertiary loops	See initiators for the primary loop LBLOCA (Appendix BB).
LOFA on the secondary or tertiary loops	See initiators for the primary loop LOFA (Appendix BA).
Flow blockage in the heat exchangers, secondary or tertiary loops	See discussion of flow blockage accidents in Appendix BG.
Heat Exchanger Failure Between Primary and Secondary Loops or secondary and tertiary loops	• Leaks in heat exchanger (slow transient) • Pipe break in heat exchanger (rapid loss of heat sink)
Cooling tower failure	• Structural damage to cooling tower
Natural Events (Seismic, flood, etc..)	• Automatic beam shutdown upon detection of external events • Seismic discussed separately in Appendix TBD • Instruments must fail safe
External Events (Large Facility Fire)	• Beam shutdown upon detection of external events • Instruments must fail safe

In this appendix, the heat sink is assumed to be lost instantaneously, and the frequency of a LOHSA is assumed to be in the anticipated range. This treatment is conservative in assessing the risk associated with the LOHSA.

It is important that the upset conditions that result in a LOHSA do not result in losing the detection and/or mitigation capabilities. In general, an independent power source is provided for each critical instrument train, such that the loss-of site power does not disable the critical instruments. Furthermore, the detection instruments are designed to fail safe such that failure of the instrument automatically results in beam shutdown. Finally, for the external events (such as a large facility fire) or natural phenomena hazards (e.g. seismic, flood), the beam is automatically shutdown without relying on the primary HRS signals for upset conditions.

Analyses of LOHSAs have not been completed. Results of these analyses will be presented and discussed in the next revision of the PSAR. The objective of this appendix is to provide a summary of the analyses to be performed for the LOHSA event sequences. The event sequences are discussed qualitatively in the next section.

2.0 LOHSA Event Sequences

The event-tree for a LOHSA is shown in Fig. BF-1.

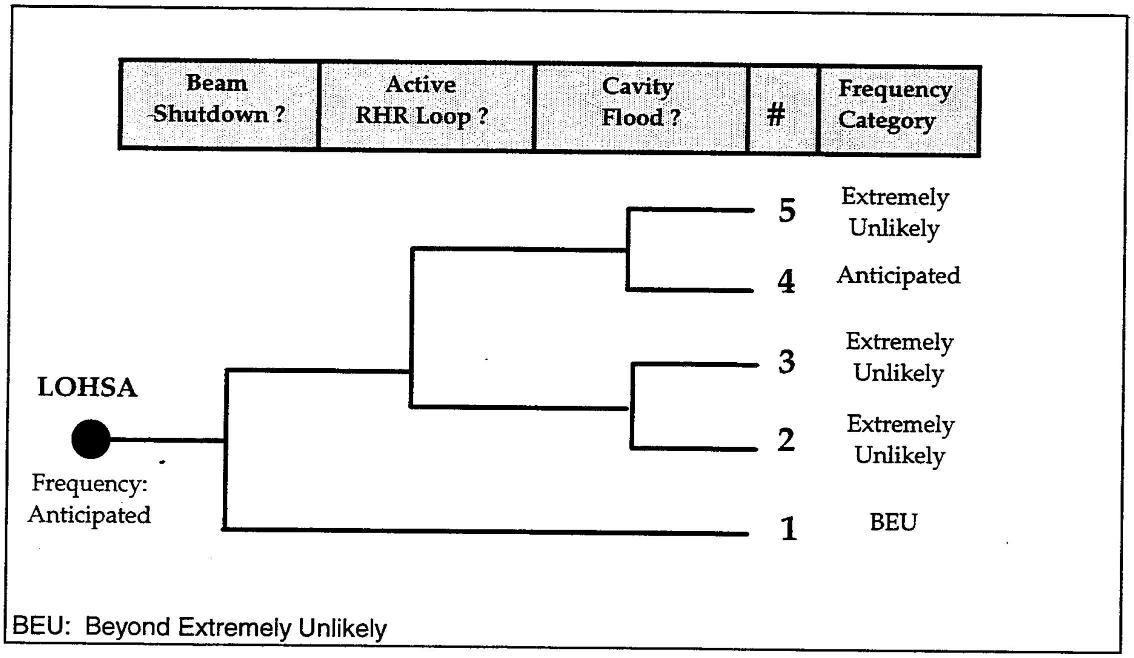

Figure BF-1 Event-tree for a LOHSA.

Once initiated, this event can be detected by the following measurements:

- loss of flow in the tertiary or the secondary loop;
- loss-of-pressure in the secondary or the tertiary loop;
- increase in the heat exchanger inlet and outlet temperatures in the primary or the secondary loop, or increase in cooling tower exit temperature in the tertiary loop;

Upon detection of the upset conditions, the following mitigative actions are taken:

1. The beam is shutdown. The primary beam shutdown system is based on the above measurements in the primary, secondary or tertiary HRS. The reliability of the primary beam shutdown system is discussed in Appendix RA. Based on this discussion, the frequency of failure to shutdown the beam given a LOHSA is in the Beyond Extremely Unlikely (BEU) range. In addition, there is a back-up beam shutdown system that is automatically activated upon pressurizing the cavity vessel. If the LOHSA progresses to a point where a failure in the pressure boundary of the HRS occurs inside the cavity, the back-up system shuts the beam down.

2. Following the beam shutdown, the Residual Heat Removal System (RHRS) pumps are started. There are two independent RHRS loops each being capable to remove the total decay heat in the blanket. The RHRS pumps are battery operated. If extended service is required, diesel generators also are available for continued use of the RHRS pumps. Failing to activate either one of the RHRS pumps is believed to be extremely unlikely unless the initiating event results in a complete facility blackout (large facility fire). This case is discussed in Appendix TBA along with combined target and blanket LOFAs. The reliability of the RHRS is discussed in Appendix RB.

3. In the unlikely event that neither of the RHRS pumps can be activated, the cavity flood is the next step in the mitigation. Independent and diverse means are available to actuate the cavity flood valves. As discussed later, after beam shutdown, there is ample time to actuate the cavity flood before the blanket LOHSA progresses to a point where radiological source term generation becomes an issue. Thus, the sequence frequency of needing a cavity flood actuation and failing to actuate the cavity flood after a blanket LOHSA is in the BEU frequency range. The reliability of the cavity flood system is discussed in Appendix RB.

It is important that the upset conditions that result in a LOHSA do not result in losing the detection and/or mitigation capabilities. Some of the initiating events discussed in Table BF-1 may challenge the detection and control instruments. In general, an independent power source is provided for each critical instrument train. Furthermore, the detection instrument are designed to fail safe such their failure automatically results in beam shutdown. Finally, for the external events (such as a large facility fire) or natural phenomena hazards (e.g. seismic and flood), the beam is shutdown without relying on the primary HRS signals for upset conditions.

In Fig. BF-1, sequences are numbered starting from fully unmitigated (Sequence #1) and progressing through the mitigated sequences. An analytic discussion of all the sequences shown in Fig. BF-1 is provided below.

2.1 LOHSA without a Beam Shutdown (Sequence Number 1 in Figure BF-1)

This sequence represents the unmitigated LOHSA. The discussion of this scenario is very similar to the discussion, provided in Appendix BA, of the unmitigated LOFA in the blanket primary HRS. The frequency of this sequence is in the beyond extremely unlikely range and the consequences are identical to those given in Appendix BA.

Based on the conservative assessment of this sequence, the beam shutdown system following a LOHSA is determined to perform a safety class function. The safety class beam shutdown system is triggered if:

- Heat exchanger inlet temperature is 80°C (in the primary loop); or
- Heat exchanger exit temperature is 55°C (in the primary loop).

In addition, the following back-up systems for the beam shutdown are available:

- secondary and tertiary low flow signals
- secondary and tertiary low pressure signals
- secondary and tertiary high or low coolant temperatures

The back-up signals in the secondary and tertiary loops are assumed to perform a safety significant function as a back-up to the safety class function that uses the primary loop temperatures signals.

2.2 LOHSA with a Beam Shutdown (Sequence Number 2 in Figure BF-1)

Similar to the LOFA case analyzed in Appendix BA, there is no loss of coolant inventory as a result of this accident. The coolant transport time around the loop is ~30 s. Thus, there is ample time to detect a heat sink failure and shutdown the beam without recirculating the uncooled coolant through the blanket. Once the beam is shutdown, it will take a long time to dry-out the blanket flow channels and create a potential for loss of coolable geometry, slumping of the blanket modules into the target ladders and radiological releases. This sequence is bounded by the similar sequence analyzed for the LOFA in Sec. 2.2. of Appendix BA.

2.3 LOHSA with Beam Shutdown and Cavity Flood (Sequence Number 3 in Figure BF-1)

This analysis is bounded by the equivalent LOFA sequence discussed in Appendix BA. There is no radiological release as a result of this event sequence.

2.4 LOHSA with Beam Shutdown and Active RHR (Sequence Number 4 in Figure BF-1)

Because of the 30 s transport time in the primary loop, there is ample time to detect this accident and start the RHRS pumps without significant overheating in the blanket modules. Once the RHRS pumps are started, the decay heat can be effectively removed by the RHRS (see Appendix BA).

2.5 LOHSA with Beam Shutdown, Active RHR and Cavity Flood (Sequence Number 5 in Figure BF-1)

The desired mitigation for a LOHSA is the decay heat removal with the RHRS after the beam shutdown. Cavity flood is activated only if the RHRS does not work. The use of RHRS along with cavity flood is not a design choice and can happen accidentally. However, this sequence is bounded by sequence numbers 3 and 4 and has no further consequences.

3.0 Summary and Conclusions

In this appendix, qualitative discussions of LOHSAs initiated by loss-of-power or mechanical pump failure are presented. The discussions show that, the unmitigated consequences of this accident are bounded by the unmitigated consequences of the LOFA presented in Appendix BA.

3.1 Credited SSCs

For the LOHSA analyses, the following SSCs are credited:

- Primary and back-up beam shutdown is determined to serve a safety class function.
- Beam shutdown based on secondary and tertiary loop, flow, pressure and temperature measurements are safety significant as they back-up the safety class-beam shutdown
- RHRS pumps activation is determined to be a safety significant function.
- Manual cavity flood based on extended inability to restore forced circulation to the blanket is determined to be a defense-in-depth function, even though the cavity flood is a safety significant system being deigned to safety class standards.

3.2 Summary of Control Logic and TSRs

The quantitative set of control logic for blanket LOHSA mitigation and the associated parameters are summarized in Table BF-2. This table is provided as an input for the development of the TSRs. Table BF-2 shows the signals based on the primary, secondary and tertiary loops and cavity vessel measurements. For a LOHSA, the cavity flood is activated based on the RHR loop measurements. The cavity flood is manually activated after a maximum waiting time of 900 s if either one of the following conditions occurs.

- Total RHR flow (considering both RHRS) is less than 4% of the nominal flow.
- The RHR loop heat exchanger inlet temperature is xx (TBD).

3.3 Discussion of Conservative Analyses Assumptions and Future Plans for Analyses and Experiments

In the LOHSA analyses, the discussion and the needs for future analyses and experiments are identical to those discussed in Appendix BA for LOFA.

3.4 Main Design Features Used in the Analyses

In the LOHSA analyses, the main design features are the same as the main design features used for the LOFA analyses.

Table BF-2 Shutdown and start-up set-points for the LOHSA mitigation.

SIGNAL	Beam Shutdown	RHRS Start	Comment
PRIMARY LOOP			
Temperature			
- HX Inlet	80°C	85°C	Not used in the analysis. Slowest LOFA indication
- HX Exit	55°C	60°C	Not used in the analysis. Slowest LOFA indication.
SECONDARY or TERTIARY LOOPS			
Pump parameters	75%	NA	Not used in current assessment.
Pressure	TBD	NA	Not used in current assessment.
Flow Rate	TBD	50%	Not used in current assessment.
Temperature	TBD	NA	Not used in current assessment.
CAVITY VESSEL			
- Pressure	25 torr	NA	Used in the BDBE sequence

Appendix BG

Analyses of the Flow Blockage Accidents (FBA) in the Blanket Primary Heat Removal System

1.0 Introduction and Objective

The hazard analysis (HA) performed for the blanket identified flow blockage accidents (FBA) as a subset of the loss-of-flow accidents (LOFA) which is a design basis accident (DBA).

In the blanket primary heat removal system (HRS), partial or full flow blockages may occur at the following locations

- Main loop including pumps and heat exchangers;
- Supply and return headers;
- Supply and return jumpers;
- Supply and return manifolds;
- Decoupler flow channels; and
- Coolant flow channels in the blanket plates.

The following may result in flow blockages:

- Debris left behind during the assembly process: Administrative procedures and post assembly hydraulic testing will be the main protection against this type of flow blockage.
- Inadvertent partial or full closure of a valve: All the valves will be locked open during beam operations.
- Dislocated or loose parts during operations: Strainers will be included at the inlet or exit of the blanket modules to prevent loose parts entering the modules during operations. However, loose parts may be left in the main loop.
- Erosion and corrosion products during operations: The continuous water purification system is the main defense against this type of flow blockage. The potential use of strainers at the blanket module inlets also would prevent small particles from recirculating back into the flow channels.

Currently, the blanket design places all the flow and pressure measurement systems outside the cavity vessels in various sections of the HRS and the blanket primary residual heat removal system (RHRS). The reliability of the flow and pressure instrumentation inside the cavity vessel is suspect especially near the beam region, because of high radiation fields. Inclusions of thermocouples within the blanket modules is being considered. The feasibility of temperature measurements to detect flow blockages in the cooling channels is being considered.

The objective of this appendix is to provide a summary of the analyses performed for the FBA event sequences. This summary includes:

- Analyses methodology and assumptions;
- Summary of the results;
- Quantification of the shutdown and control logic; and
- Conclusions including
  - the safety classification of the mitigation equipment, and/or
  - radiological consequences of the event sequence.

The accident analyses for the FBAs are not complete. In this revision, the discussion is focused on the analyses methodology and identification of the engineering systems to prevent or mitigate FBAs. The results of the accident analysis will be included in the next PSAR revision upon completion of the analyses.

2.0 FBA Event Sequences

The generic event-tree for flow blockage accidents is provided in Fig. BG-1. As shown in Fig. BG-1, the primary question with respect to flow blockage accidents is whether or not the blockage can be detected. Unfortunately, not all blockages can be detected, especially partial or local blockages in the cooling channels of the blanket modules within the primary HRS.

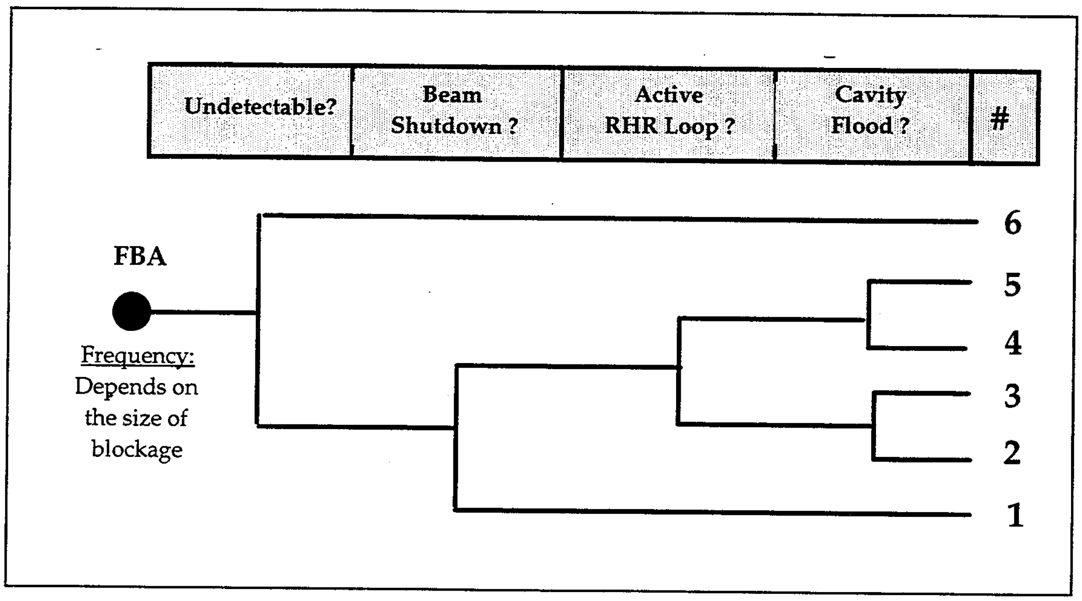

Fig. BG-1 Event tree for the FBA.

If the flow blockage is not detectable, the objective of the analyses would be to quantify the consequences. If the consequences are not acceptable, engineering means of detection must be implemented.

If the flow blockage is detected, the beam is shutdown. For partial flow blockages, the primary loop flow may be more than adequate to remove the decay heat. However, if the blockage in the primary loop is outside the cavity vessel and if it severely constrains the flow, the RHRS pumps are activated. If either one of the pumps in the two RHRS loops cannot be activated, cavity flood provides the final mitigation option to prevent blanket overheating and potential radioactive material releases to the environment. Cavity flood may be necessary even if the RHRS pumps are activated if the flow blockage is located inside the cavity vessel where the coolant piping for the HRS and RHRS is common.

The following measurements may be used in detecting partial or full flow blockages:

- Flow rate measurements at various locations along the primary HRS (outside the cavity vessel);
- Temperature measurements at various locations along the primary HRS (outside the cavity vessel);
- Differential pressure across the pumps; and
- Temperature measurements at various locations (inlet, exit, and intermediate plenums) within individual module units (inside the cavity vessel);

The first series of analyses that will be included in the next PSAR are system calculations to determine the detectable blockages using the above set of measurements and the required precision and uncertainty associated with these measurements. The system models will include a realistic pump supply curve such that decisions can be made in terms of increase of pressure and/or decrease of flow rate as a means of blockage detection for varying demand curves as a function of blockage. At the individual module level more detailed analyses will be performed to determine the number and arrangement of flow blockages among the discrete flow channels that remains acceptable.

After this series of analyses are completed and the detectable versus undetectable sets of flow blockages are sorted, the sequences shown in Fig. BG-1 will be analyzed for consequences.

2.1 Detectable Flow Blockage with Failure to Shutdown the Beam (Sequence 1 in Figure BG-1)

A sufficiently large flow blockage may result in thermal failure of multiple blanket plates if the beam is not shutdown. The result would be a LBLOCA inside the cavity vessel. The bounding analysis provided for LOFA also applies to this case, leading to the conclusion that beam shutdown based on flow blockage signals would perform a *safety class* function.

The BDBE analyses provided for a LOFA without beam shutdown should bound most cases of flow blockage without beam shutdown.

2.2 Detectable Flow Blockage with Beam Shutdown (Sequence 2 in Figure BG-1)

The analysis will be similar to the identical event for the LOFA analysis. However, the increased system friction as a result of flow blockage may impact the natural circulation and passive cooling used in the LOFA with beam shutdown. The analysis will be reevaluated under the specific conditions of a worst-case detectable flow blockage.

2.3 Detectable Flow Blockage with Beam Shutdown and Cavity Flood (Sequence 3 in Figure BG-1)

The cavity flood will mitigate the accident (see Appendix BA for LOFA analysis). However, the conditions under which the cavity will be flooded must be quantified to develop the necessary controls.

2.4 Detectable Flow Blockage with Beam Shutdown and RHR Cooling (Sequence 4 in Figure BG-1)

The analysis will be similar to the identical event for the LOFA analysis. However, if the flow blockage is inside the cavity vessel, the RHR may not be able to remove the decay heat. In this case, the analyses in Section 2.2 would apply to this sequence as well.

2.5 Detectable Flow Blockage with Beam Shutdown, Cavity Flood and RHR Cooling (Sequence 5 in Figure BG-1)

This will be bounded by the cases analyzed in Sections 2.3 and 2.4.

2.6 Undetectable Flow Blockage (Sequence 6 in Figure BG-1)

At this time, it is expected that even a complete blockage of a module coolant flow may go undetected until an internal LBLOCA is created as a result. The consequences must be analyzed similar to internal LBLOCA analyses presented in Appendix BC, recognizing that the initial conditions at the time of failure may be different. An internal break LOCA will result in triggering the passive beam shutdown in addition to the variety of signals that would trigger the primary and back-up beam shutdown system. Thus, after the creation of the LOCA, the beam will be assumed to be shutdown. Thereafter, the event can be analyzed with or without cavity flood.

3.0 Summary and Conclusions

In this appendix, the results of the analyses for flow blockages will be presented. Current conclusions are based on qualitative assessment and are preliminary. Detailed analyses and the conclusions will be included in the next PSAR revision.

3.1 Preliminary List of Credited SSCs

For the FBA analyses, the following SSCs are credited:

- Primary, back-up, and "passive" beam shutdown systems are determined to serve a *safety-class* function.
- RHRS pump activation is determined to be a *safety-significant* function.
- Manual cavity flood based on extended inability to restore forced circulation to the blanket is determined to be a defense-in-depth function even though the cavity flood is a safety *significant-system* being deigned to *safety-class* standards. Cavity flood activation upon an internal LBLOCA caused by flow blockage serves a *safety-significant* function.

3.2 Summary of Control Logic and TSRs

These will be developed and quantified in the next PSAR revision upon completion of the analyses.

3.3 Main Design Features Used in the Analyses

A detailed list will be provided upon completion of the analyses. However, some of the design features that are likely to be necessitated by these analyses are listed below:

- Strainers at various locations are likely to be needed;
- These accidents may have more stringent requirements on the temperature, flow, and pressure measurements in terms of accuracy and number of locations; and
- A quantitative set of requirements will be developed for the water purification system.

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Appendix BH

Analyses of the Loss-of-Helium-Gas Accidents (LOHGA) Inside the Target/Blanket Building

1 Introduction and Objective

The hazard analysis (HA) performed for the blanket primary heat removal (HR) systems identified the loss-of-helium gas accident (LOHGA) due to a compromise in the integrity of the helium gas supply system inside of the Target/Blanket building as a design basis accident (DBA). There are two types of Target/Blanket building LOHGAs: (1) those internal to a blanket module (i.e., internal break (IB) LOHGAs) where helium gas enters the blanket system's primary HRS coolant; and (2) those external to a module (i.e., external break (EB) LOHGAs) where helium gas does not enter the blanket system's primary HRS coolant. LOHGAs vary from slow pin-hole leaks (Small Break LOHGAs) to a catastrophic failure of a helium tube resulting in the sudden release of a large volume of gas (Large Break LOHGAs). The initiating events are briefly summarized in Table BH-1.

Table BH-1 Discussion of initiators for LOHGA

Initiator	Discussion
Material defects in piping	All materials will be selected, procured and inspected consistent with the PC-3 requirements.
Assembly and welding defects	All the assemblies and welds will be performed and inspected according to PC-3 requirements.
Flow induced vibrations	The system will be designed to minimize the FIV phenomenon. Pumps and compressors will be mechanically isolated from the piping. FIV will be monitored during operations.
Excessive internal pressure	There is continuous pressure monitoring and pressure relief valves.
Drop or impact of heavy equipment	There will be no lift or transport of heavy equipment over or near the HRS. Piping will be protected against collisions.
Seismic Event	Discussed separately in Appendix TBD.
Building collapse caused by external or natural events	Examples are large fires, flood, helicopter crash, etc. The potential for losing the detection instruments must be addressed.

2 Blanket Internal Break (IB) LOHGAs

Blanket IBLOHGAs with two scenarios are considered:

1. LOHGAs with the pressurizer relief valve remaining closed during the event.
2. LOHGAs with the pressurizer relief valve opening during the event.

When the relief valve remains closed, the helium/tritium gas mixture is contained within the blanket HRS. This gas can subsequently be recovered without release to the environment. If the relief valve opens, helium/tritium gas released into the blanket HRS could be vented to the environment. Therefore, this accident scenario would have on-site and possibly off-site consequences.

The event tree shown in Fig. BH-1 is applicable to all the LOHGAs, regardless of the rupture locations or relief valve status. The objective of this appendix is to provide a summary of the LOHGA analyses performed.

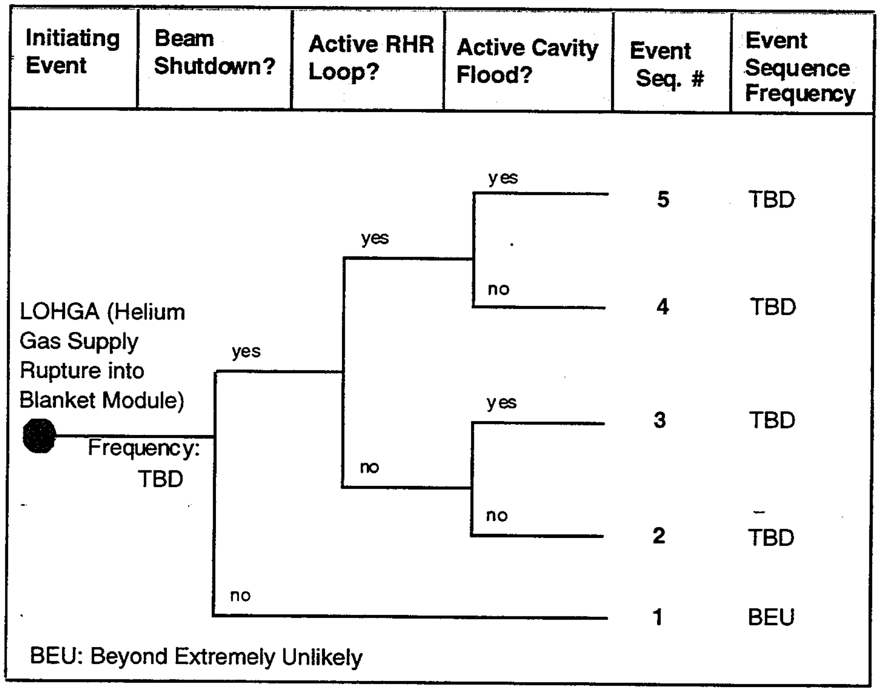

Figure BH-1 Event tree for a LOHGA initiated by a helium gas system rupture that leaks gas into the blanket HRS.

2.1 IBLOHGA With Relief Valve Closed

In this section LOHGA simulations in which the pressurizer relief valve remains closed are discussed. The IBLOHGAs are subdivided into large (LB) and small (SB) helium tube ruptures at several different break locations.

Once initiated, LB IBLOHGA events can be detected by the following parameter changes:

- increase in blanket HRS pressure;
- decrease in helium reservoir pressure;
- decrease in blanket HRS flowrate;
- increase in blanket HRS temperatures; and
- increase in monitored radiation near the rupture location.

2.1.1 LB IBLOHGA With Helium Supply Rupture Near Decoupler Inlet/Outlet

Figure BH-2 shows the break locations of the two LB IBLOHGAs that were analyzed, breaks near the inlet and outlet plenums of the decoupler in a lateral Row-1 module (Ref. BH-2). The two break locations selected for the LB IBLOHGA simulations are assumed to be bounding. Table BH-2 provides the pipe break size for each break location. Initial conditions for the helium reservoir are assumed to be 1.0 m^3 helium gas at 200 psia, and 40°C.

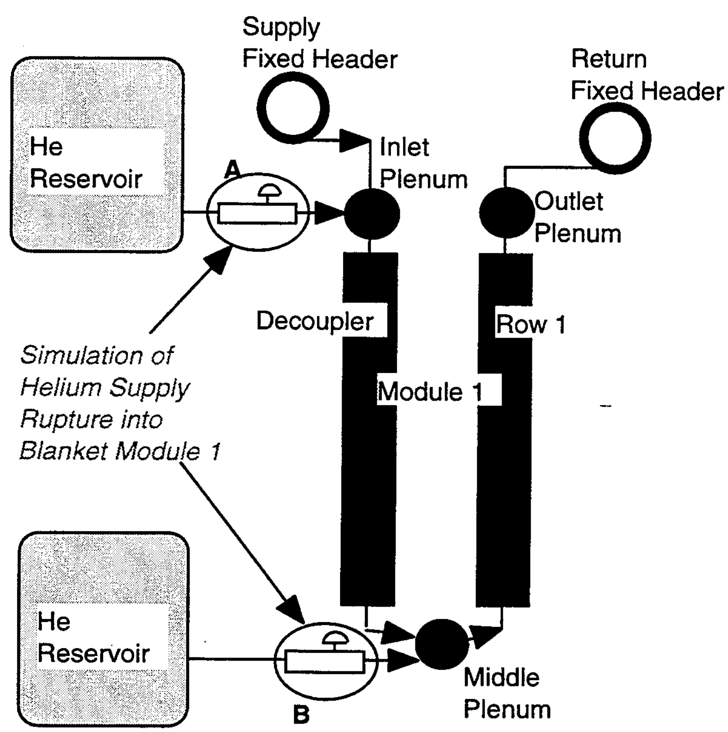

Figure BH-2 Schematic flow diagram for the APT blanket Module 1 and the helium tube rupture locations for IBLOHGA analyses.

Table BH-2 Break location pipe sizes for the IBLOHGAs analyzed.

Break Location in Fig. BH-2	Reference Name used in Appendix BH	Pipe break size for LOHGA simulations (ID)
A	Helium gas leak at decoupler inlet	3.0"
B	Helium gas leak at decoupler outlet	3.0"

2.1.1.1 LB IBLOHGA Near Decoupler Inlet/Outlet Without Beam Shutdown (Event Sequence #1 in Figure BH-1)

This event sequence represents a completely unmitigated helium gas release into the blanket HRS as a result of large break rupture in the helium supply system. A one-dimensional TRAC model, with 6 lumped modules, of the blanket HRS was used to simulate the LB IBLOHGA (Ref. BH-2). Reference BH-3 contains detailed descriptions of the simulations and presents and discusses results.

2.1.1.1.1 LB IBLOHGA Near Decoupler Inlet Without Beam Shutdown

This is event sequence 1 in Fig. BH-1, with the break location at point "A" in Fig. BH-2. In the TRAC simulation of this accident, the initial condition of the blanket HRS is normal operating conditions (Ref. BH-4). Following initiation of this LB IBLOHGA, there is a rapid drop in pressure in the helium reservoir (Fig. BH-3), and the inlet header experiences a spike in pressure to about 167 psia within the first few seconds (Fig. BH-4). This pressure surge could be used to detect the accident. The inlet header pressure quickly drops back to the pre-incident value as gas is convected to the heat exchangers. Figure BH-5 shows the accumulation of gas within the heat exchangers (the high point in the primary cooling system).

Results from the TRAC LB IBLOHGA transient were used to supply boundary conditions to the FLOWTRAN-TF model (Refs. BH-5, BH-6) for detailed calculations of the thermal-hydraulic behavior of a single Row 1 module plate. Maximum metal temperatures from the FLOWTRAN-TF calculations are shown in Fig. BH-6. The maximum aluminum temperature found anywhere in the plate cladding and the maximum lead temperature anywhere in the plate are plotted as functions of time after the start of the accident. The decrease in coolant flow in the early part of the transient leads to a temperature increase in the metal of only 2.5°C. As expected, the metal temperature returns to its initial value as the flow disturbance passes. It is clear from the plotted metal temperatures that surface temperatures in the flow channels, even without beam trip, do not approach local boiling conditions. At typical module pressures, the local saturation temperature is approximately 165°C. At no time in the transient does the flow channel become completely voided.

Since there is no damage to the blanket system from the LB IBLOHGA at this location, and it is assumed that the released gas is contained within the heat exchangers and can eventually be recovered, there are no on-site or off-site radiological consequences from this event.

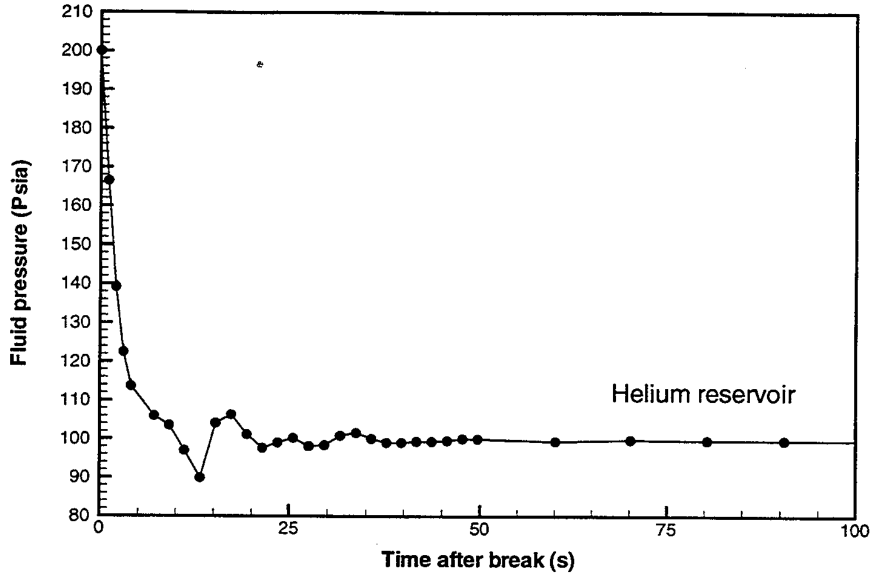

Figure BH-3 Transient pressure in the helium reservoir.

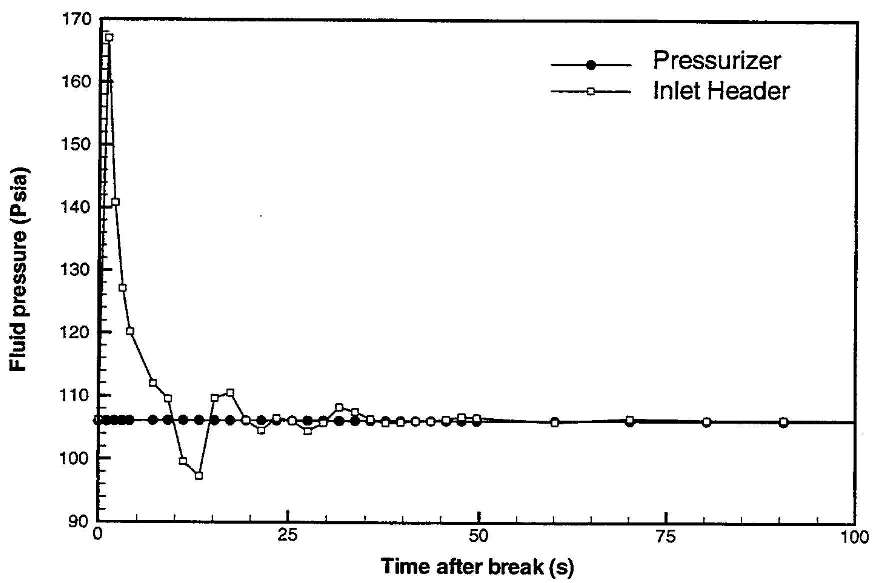

Figure BH-4 Transient fluid pressures in the inlet header and pressurizer.

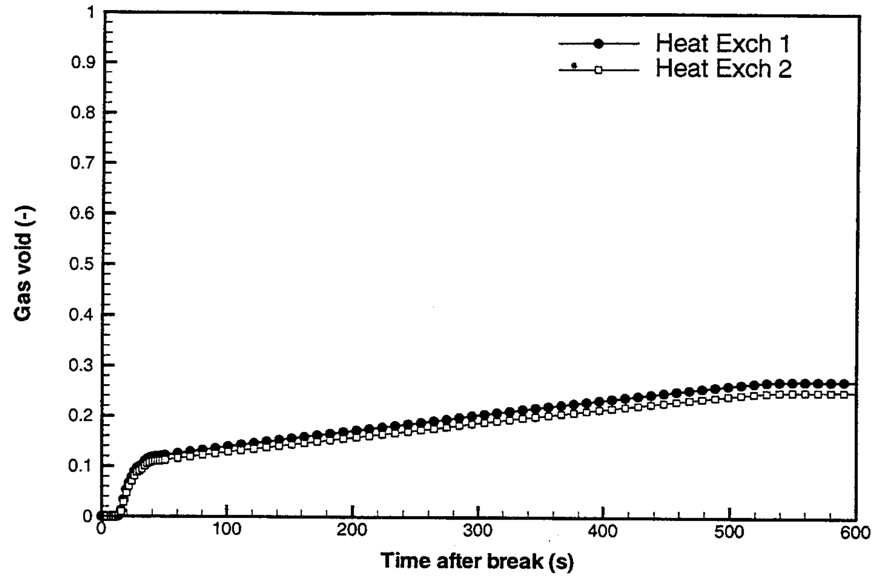

Figure BH-5 Transient void fractions at the heat exchanger outlet.

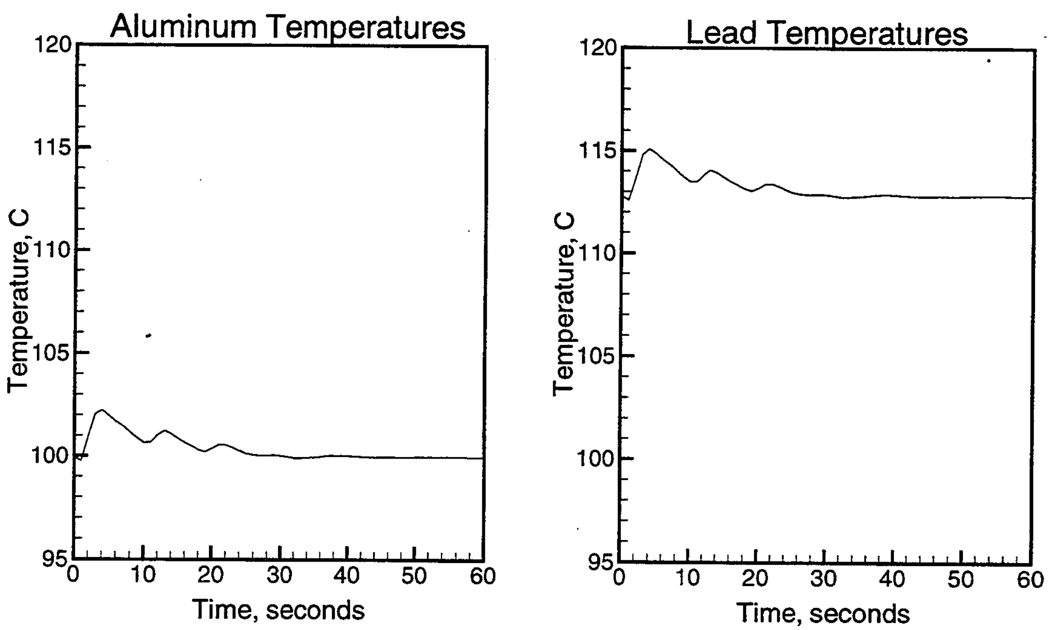

Figure BH-6 Maximum metal temperatures in a lateral Row 1 blanket module plate.

2.1.1.1.2 LB IBLOHGA Near Decoupler Outlet Without Beam Shutdown

The second LB IBLOHGA break location considered is a rupture in a helium system near the decoupler outlet, location "B" in Fig. BH-2. The transient response of the system to a rupture of the helium gas supply at this break location is essentially the same as that for a break at the decoupler inlet. The conclusions from the analysis are identical to those presented in the previous section, and are not repeated.

2.1.1.2 LB IBLOHGA Near Decoupler Inlet/Outlet With Beam Shutdown and Inactive RHR and/or Cavity Flood (Event Sequence #2 in Figure BH-1)

This accident is bounded by the analyses provided in Sec. 2.1.1.1.

2.1.1.3 LB IBLOHGA Near Decoupler Inlet/Outlet with Beam Shutdown and Active RHR and/or Cavity Flood (Event Sequence #3 in Figure BH-1)

The accident is bounded by the analyses provided in Sec. 2.1.1.1.

2.1.2 SB IBLOHGA With Helium Supply Rupture Near Decoupler Inlet/Outlet

While a small leak of helium gas into the blanket coolant system may be difficult to detect, it is anticipated that the consequences on this type of accident are bounded by those of the large break accidents. If a small gas leak goes undetected for an extended period of time, accumulated gas could generate significant void in the HRS and block flow. That is, an undetected SB IBLOHGA could eventually initiate a LOFA. The LOFA events are addressed in Appendix BA.

2.2 IBLOHGA With Relief Valve Open

If the pressurizer relief valve opens in response to a IBLOHGA, the gas entering the coolant system can be released to the environment. This accident scenario will therefore have some on-sit and off-site radiological consequences. Due to frequent batch extraction of tritium from the helium system, the tritium inventory at any point in time is minimized. This reduces the potential radiological consequences of this class of accidents. No analyses have been done for these accidents.

3 Blanket External Break (EB) LOHGAs

Blanket EBLOHGAs would not affect the operation of the blanket HRS, and therefore beam shutdown is not necessary to protect the blanket coolant system. These types of events release gas into the building and potentially into the environment. These accidents will therefore have some on-sit and off-site radiological consequences. No analyses have been done for these accidents.

4 Summary and Conclusions

In this appendix, results are presented for the accident analyses of unmitigated (no beam shutdown) LB IBLOHGA events, with no system pressure relief, at the following locations:

- Decoupler inlet

- Decoupler outlet.

The analyses demonstrate that the HRS can withstand unmitigated accidents of this type. For these design basis accidents, analysis results show that no radioactive material releases, either on-site or to the environment, will occur.

Once initiated, these events can be detected by the following parameter changes:

- increase in blanket HRS pressure;
- decrease in helium system pressure;
- decrease in blanket HRS flowrate;
- increase in blanket HRS temperatures; and
- increase in monitored radiation at the rupture location.

A short duration high amplitude pressure pulse occurs in the inlet header and can be used to detect LB IBLOHGAs. The pressurizer pressure remains essentially constant during the accident and could not be used for event detection. This also means that the relief valve probably would not open.

With the relief valve closed, helium released into the coolant system accumulates in the heat exchanger headers, which are the high points in the system. The helium reservoir pressure decreases from its initial value of 200 psia to the coolant system pressure of 100 psia in approximately 10 seconds and stabilizes within about 50 seconds. The HRS transient last for approximately 60 seconds, with system parameters returning to pre-incident values.

For a LB IBLOHGA with the relief valve remaining closed, beam shutdown is not necessary to protect the blanket coolant system. Therefore, no credit needs to be taken for any SSC. Similarly, no technical safety requirements (TSRs) are identified from these analyses. The released helium is collected in the heat exchanger. Since it is assumed that the this gas can be retrieved, there are no radiological consequences of these accidents.

The following are planned analyses to supplement the results presented in this appendix:

- Sensitivity analyses to support quantification of safety margins and uncertainties.
- Further analyses of accident scenarios with the relief valve open. These analyses will serve to specify the safety function of the pressurizer relief valve.
- Further analyses of SB IBLOHGAs to demonstrate that they are bounded by the LB IBLOHGA and LOFA analyses.

5 References

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BH-3. L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Loss-Of-Helium-Gas Accident (LOHGA) Based On Initial Conceptual design - Helium Supply Rupture Into Blanket Module", WSRC-TR-98-00177 (July 1998).

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BH-7. L. L. Hamm, S. Y. Lee, M. A. Shadday, and F. G. Smith, III, "APT Blanket System Safety Analysis Methodology," Westinghouse Savannah River Company, Westinghouse Savannah River Company, WSRC-TR-98-0052 (May 1998).

BH-8. Safety Code Development Group, "TRAC-PF1/MOD2: An Advanced Best Estimate Computer Program for Pressurized Water Reactor Thermal-Hydraulic Analysis," Los Alamos National Laboratory report LA-12031-M, Vol. 1 (NUREG/CR-5673), (July 21, 1993).

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