AECL EACL

Licensing Submission

PIRT for Single-Channel Severe Flow Blockage in ACR-700

ACR USA

108US-03500-LS-002
Revision 0

Prepared by
Rédigé par
H. E. Sills
Consultant

Prepared by
Rédigé par
N. Popov
ACR Licensing - Canada

Prepared by
Rédigé par
E. Lemoine
ACR Licensing

Prepared by
Rédigé par
B.E. Boyack
Consultant

Reviewed by
Examiné par
D. Wren
ACR R&D

Approved by
Approuvé par
V.G. Snell
ACR Safety & Licensing

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2251 Speakman Drive
Mississauga, Ontario
Canada L5K 1B2

2251, rue Speakman
Mississauga (Ontario)
Canada L5K 1B2

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This report represents a US-style Phenomena Identification and Ranking Table (PIRT) activity undertaken by AECL. By its nature, the PIRT process is a group activity (i.e., resource intensive).

The facilitator, Brent Boyack, ably guided this PIRT effort and participated as a Panel member. Other PIRT Panel members, providing wide-ranging expertise, included Amad Abdul-Razzak (thermal hydraulics), Brock Sanderson (fuel, fuel channel, core damage), Darryl Dormuth (thermal hydraulics), Dave Wright (analyst), Elias Zariffeh (core damage), Glen McGee (thermal hydraulics), Hank Chow (core physics), Harve Sills (fuel, fuel channel), Lawrence Dickson (fuel, fission products), Nik Popov (thermal hydraulics), Samir Girgis (core damage) and Zorin Bilanovic (analyst). These people participated in a total of four meeting days spread over two separate meetings.

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EXECUTIVE SUMMARY

ACR-700 SINGLE FUEL CHANNEL FLOW BLOCKAGE ACCIDENT PHENOMENA IDENTIFICATION AND RANKING TABLE

This document provides the results of a Phenomena Identification and Ranking Table (PIRT) effort for the ACR-700™* undergoing a complete flow blockage of a high-powered fuel channel. The most important systems, components, and processes/phenomena occurring during each phase of the flow blockage are identified and tabulated. Rationales are provided to support the assigned importance-rankings.

The ACR-700 design is based on the use of modular horizontal fuel channels surrounded by a heavy water moderator, the same as with all CANDU®† reactors. The major innovation in ACR is the use of slightly enriched uranium fuel and light water as coolant. This results in a more compact reactor design and a reduction of heavy water inventory, both contributing to a significant decrease in cost compared to CANDU reactors, which employ natural uranium as fuel and heavy water as coolant.

An important effort in demonstrating the adequacy of the safety analysis code suite is the preparation of a Phenomena Identification and Ranking Table (PIRT). The PIRT is nuclear power plant (NPP) and scenario specific. Plant systems and components that may have an impact on the evaluation criteria are identified, as are the influencing phenomena. The identified phenomena are then importance-ranked relative to their influence on the Figure of Merit, or evaluation criteria. Once the PIRT is complete, the analysis code suite used to analyze the transient would then be reviewed to ensure that the component models are adequate. A high degree of adequacy is required for those models of the system/component behavior that most strongly impact the course of the transient as identified by the PIRT process.

The complete flow blockage of a single fuel channel is a limited core damage accident. At the time of the accident, the reactor is assumed to be operating at full power with equilibrium poison levels at the time of the LOCA. Design values are assumed for plant parameters. The scenario divides into three distinct phases:

- Channel geometry maintained during heat up;
- Channel geometry deforming, molten materials formed, and fuel channel failure; and
- Ejection of molten debris into the moderator fluid to firing of the emergency core cooling system (ECCS)

The following tables summarize the PIRT findings for the high importance-ranked processes / phenomena. Note that components are assumed to be available and to function as per design.

Channel Geometry Maintained (0 – 8 s)

System	Component	Processes/Phenomena
Fuel Channel (blocked)	Pressure Tube (blocked)	Convective heat transfer, radiant heat transfer
Fuel Bundle (blocked)	Fuel Element (blocked)	Conduction, gap conductance, forced convection to liquid, nucleate boiling, post-dryout heat transfer, Critical Heat flux (CHF), fission heating, axial power distribution, end power peaking, flow regime, pressure driven flow

Channel Geometry Deforming (8 s – 10 s)

System	Component	Processes/Phenomena
Fuel Channel (blocked)	Pressure Tube (blocked), Calandria Tube (blocked)	Convective heat transfer, conduction, radiant heat transfer, melt-to-pressure tube heat transfer, melt-to-calandria tube heat transfer, deformation, failure, melting, post-dryout heat transfer, jet impingement loading, ablation / erosion
Fuel Bundle (blocked)	Fuel Element (blocked)	Conduction, radiant heat transfer, post-dryout heat transfer, oxidation, UO_2 dissolution by molten Zircaloy, bundle slumping, melting, relocation, fission heating, radial power distribution, axial power distribution, end power peaking

Post-Channel Failure (10 s – 150 s)

System	Component	Processes/Phenomena
Moderator System	Calandria Vessel, Moderator Fluid, Ex-Channel debris	Impact loading, deformation, void generation from heat transfer, inter-phase condensation, pressure change, molten fuel moderator interaction
Fuel Channel (blocked)	End Fittings (blocked), Pressure Tube (blocked), Calandria Tube (blocked),	Critical flow, break characteristics
Fuel Channel (unaffected)	Calandria Tube (unaffected)	Pressure forming, jet impingement loading, ablation / erosion, impact loading
Fuel Bundle (blocked)	Fuel Element (blocked)	Void generation from heat transfer

ACRONYMS

ACR	Advanced CANDU Reactor
AECL	Atomic Energy of Canada Limited
ASDV	Atmospheric Steam Discharge Valve
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium
CANFLEX®*	CANDU FLEXible fuelling
CHF	Critical Heat Flux
CNSC	Canadian Nuclear Safety Commission
CSDV	Condenser Steam Dump Valve
CT	Calandria Tube
ECCS	Emergency Core Cooling System
ECI	Emergency Coolant Injection system
FOM	Figure Of Merit
HTS	Heat Transport System
LBLOCA	Large Break Loss-Of-Coolant Accident
LOCA	Loss-Of-Coolant Accident
LTC	Long-Term Cooling system
LWR	Light Water Reactor
MSIV	Main Steam Isolation Valve
MSSV	Main Steam Safety Valve
NPP	Nuclear Power Plant
NRC	(US) Nuclear Regulatory Commission
P&IC	Pressure and Inventory Control
PCT	Peak Clad Temperature
PDO	Post-DryOut
PHWR	Pressurized Heavy Water Reactor
PIRT	Phenomena Identification and Ranking Table
PT	Pressure Tube
PTR	Pressure Tube Reactor
PWR	Pressurized Water Reactor
RCW	Recirculated Cooling Water
RIH	Reactor Inlet Header
RRS	Reactor Regulating System
RWS	Reserve Water System
SDS	ShutDown System

* CANFLEX® is a registered trademark of AECL and the Korea Atomic Energy Research Institute (KAERI).

SDS1	ShutDown System 1 (shut off rods)
SDS2	ShutDown System 2 (poison injection)
SG	Steam Generator
TBD	Technical Basis Document
VM	Validation Matrix

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APPENDICES

1. INTRODUCTION

AECL has established a successful, internationally recognized line of CANDU pressure tube reactors (PTR) with heavy water moderator, in particular, the medium-sized CANDU 6 reactor. AECL has consistently adopted an evolutionary approach to the enhancement of CANDU nuclear power plant designs over the last 30 years. This approach, which has been applied to the current CANDU 6 reactor design being completed at the Qinshan CANDU Phase III site in People's Republic China[1], has now been extended further in the development of the Advanced CANDU Reactor (ACR).

Atomic Energy of Canada Limited (AECL) has developed the ACR-700 (Advanced CANDU Reactor-700) (Reference [1]) to meet customer needs for reduced capital cost, shorter construction schedule, higher capacity factor, lower operating cost, increased operating life, simpler component replacement and enhanced safety features. Currently, the ACR-700 is undergoing pre-application review by the United States Nuclear Regulatory Commission (NRC) and a pre-licensing review by the Canadian Nuclear Safety Commission (CNSC).

USNRC developed and demonstrated the Code Scaling, Applicability, and Uncertainty (CSAU) methodology (Reference [2]) by quantifying the uncertainty associated with the best-estimate calculation of key safety-related parameters for an accident in a nuclear power plant (NPP). Subsequently, the Code of Federal Regulations (CFR) was revised and the NRC issued guidance that applicants could license the ECCS of future plants using either the 10 CFR 50 Appendix K methodology, or they could use a best-estimate methodology, provided the uncertainty in key licensing parameters (e.g., the peak clad temperature (PCT)) was quantified.

Regardless of the approach chosen, conservative or realistic, the Phenomena Identification and Ranking Table (PIRT) method is an important step in the safety analysis process. The PIRT is plant and scenario specific.

AECL has completed a Technical Basis Document (TBD) for the CANDU 6 design and an ACR-specific TBD that reflects the ACR-700 specific design features and accident scenarios (Reference [3]). Both TBD documents cover high-level phenomena identification and ranking that is used in the Canadian computer code development and validation process (Reference [4]). The PIRT effort documented in this activity is aimed at performing a confirmatory phenomena identification and ranking process that follows the methodology developed in the US to confirm completeness of the phenomena identification and ranking documented in the TBD for the complete flow-blockage event of a single fuel channel in ACR-700.

The general PIRT process and its specific application to the single-channel flow blockage PIRT effort are documented in Section 2. A description of the ACR-700 plant and the key systems and components that respond to the selected scenario are described in Section 3. The single-channel complete flow-blockage scenario of an ACR-700 fuel channel is described in Section 4. The three phases of the accident for which PIRT assessments were made are described and include: the heatup of the fuel channel until molten material is formed in the blocked fuel channel, channel deformation and relocation of molten material onto the pressure tube, and the ejection of molten material/coolant/debris into the moderator fluid with the ensuing accident-generated

[1] Unit No. 1 went in-service in 2002 December, while Unit No. 2 produced first commercial power in 2003 June.

loadings of in-core structures. All ACR-700 components and their associated phenomena are ranked according to their influence on the loading of in-core structures. Summary PIRT results are presented in Section 5. Phenomena definitions are provided in Appendix A.

The severe (complete) single-channel flow blockage event is a small subset of flow blockage events that is caused by more than 95% of the flow area blocked, resulting in severe flow reduction, and fuel cladding melting. The severe single-channel flow blockage event is a beyond design basis event assessed as limited core damage event to demonstrate defense in depth, and provide assurance that the damage to the affected channel does not propagate to the neighboring channels in the core. A complete flow blockage of fuel channel results in superheated steam being formed in fuel channel and failure of that channel.

2. METHODOLOGY

2.1 Need for Identification and Ranking

The physical processes and phenomena that occur in nuclear reactors can be both complex and highly coupled. The ability to predict the behavior of nuclear reactors during normal operation as well as their response to accident conditions is of paramount importance. With predictability comes understanding. Both are required to ensure safe reactor operation.

Several fundamental elements form the basis for a safe design. The design itself is of paramount importance. An important recent trend in reactor design is the reliance on simplified, passive and/or inherent safety features to reduce the reliance on both active, complex hardware and systems, and operator interventions. The ability to accurately predict the behavior of the design under operational and accident conditions using qualified analytic methods is essential.

Predictability, including an understanding of safety margins, is based upon fundamental data from experiments, experiments in both scaled component and integral facilities, and calculations using analytic tools. However, it is not feasible to build a full-scale test reactor and then expose that reactor to the aggressive conditions of a spectrum of both design basis[2] and beyond design basis events. Therefore, analyses based upon qualified analytic methods have become essential to confirming the safety-related performance of a nuclear reactor design. The development and qualification of transient and accident analysis methods is central to both designing and demonstrating the safety of a reactor design.

Recently, the NRC has issued a draft regulatory guide, DG-1120, for "Transient and Accident Analysis Methods" (Reference [6]). Although specifically directed to analytic methods applied to the analysis of design basis events, the regulatory guide articulates six basic principles of evaluation model development and assessment that are also useful when applied to methods used to analyze beyond design basis events. The first of the six principles in DG-1120 is to "determine the requirements for the evaluation model." Central to this step is "identification of the . . . components, phenomena, physical processes, and parameters (hereafter collected under the general designation of 'phenomena') needed to evaluate event behavior relative to the figures of merit described in the Standard Review Plan and derived from the General Design Criteria in Appendix A to 10 CFR 50." This identification step is an essential element of the Phenomenon Identification and Ranking Table (PIRT) process. The second essential element is ranking each plausible phenomenon relative to a figure of merit (FOM), also called an evaluation criterion. The ranking step is based upon the reality that all processes and phenomena that occur during a transient or accident do not equally influence plant behavior. The PIRT process reduces candidate phenomena to a manageable set by identifying and ranking the phenomena with respect to their influence on the figure of merit.

As stated in Reference [6], the principal product of the process outlined above is a PIRT. Analytic model development and assessment for design basis events, and to the extent practical, for beyond design basis accidents, should be based upon a credible PIRT. The PIRT should be used to determine the requirements for physical model development, scalability, validation, and

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[2] Within this section, design basis accidents refer to those defined by the US NRC.

sensitivities studies. Given these importance statements, it is useful to recognize that “the PIRT is not an end in itself”, but is rather a “tool” to be used to guide and focus subsequent efforts.

2.2 PIRT Process

The PIRT process has evolved from its initial development and application (References [2], [7], and [8]) to its description as a generalized process (Reference [5]). A PIRT can be used to support several important decision-making processes. For example, the information can be used to support either the definition of requirements for related experiments and analytic tools, or the adequacy and applicability of existing experiments and analytic tools. This information is important because it is neither cost effective nor is it required to assess each feature of an experiment or analytic tool in a uniform fashion. The PIRT methodology brings into focus the phenomena that dominate, while identifying all plausible effects to demonstrate completeness.

A simplified description of the generalized PIRT process, as applied to the development of the PIRTs for thermal hydraulic transients and accidents in nuclear reactors, is illustrated in Figure 1 and described as follows:

Step 1: Define the issue that is driving the need, e.g., licensing, operational, or programmatic. The definition may evolve as a hierarchy starting with federal regulations or design or safety goals and descending to a consideration of key physical processes.

Step 2: Define the specific objectives of the PIRT. The PIRT objectives are usually specified by the sponsoring agency. A clear statement of PIRT objectives is important because it defines the focus, content, and intended applications of the PIRT product. The PIRT objectives should include a description of the final products to be prepared.

Step 3: Define the hardware, equipment and scenario for which the PIRT is to be prepared. Generally, a specific hardware configuration and specific scenario are defined. Usually, but not always, the scenario is divided into phases. This is done because the importance of a phenomenon often varies during the course of a scenario. In addition, some system components may not be activated throughout the scenario.

Experience obtained from previous PIRT efforts indicates that any consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed.

Step 4: Compile and review the contents of a database that captures the relevant experimental and analytic knowledge relative to the physical processes and hardware for which the PIRT is being developed. Each Panel member should review and become familiar with the information in the database.

Step 5: Define the Figure of Merit (FOM). The FOM is the primary evaluation criterion used to judge the relative importance of each phenomenon. Therefore, it must be identified before proceeding with the ranking portion of the PIRT effort. It is extremely important that all PIRT Panel members come to a common and clear understanding of the FOM and how it will be used in the ranking effort. The characteristics of a well-defined FOM are that it is: (1) directly related to the issue(s) being addressed; (2) directly related to the phenomena expected to occur during the scenario; (3) easily comprehended, (4) explicit; and (5) measurable. For design basis accident scenarios, the FOM is generally derived from regulatory requirements. For beyond design basis accident scenarios, the FOM may be derived from regulatory or design goals. As the PIRT process has rarely been applied to beyond design basis accidents, FOM development for such scenarios is evolving.

Step 6: Identify all plausible phenomena i.e., PIRT elements. A primary objective of this step is completeness. In addition to preparing the list of phenomena, precise definitions of each phenomenon should be developed and made available to the PIRT Panel to ensure that Panel members have a common understanding of each phenomenon. Within the context of this PIRT, the term “phenomenon” encompasses phenomena, processes, conditions, characteristics, and state variables. In each PIRT effort, there is a phenomenological hierarchy beginning at the system level and proceeding in turn through the component level, local level, microscopic level, atomic levels and so on. Each PIRT Panel must determine the appropriate phenomenological levels to include in its list of identified phenomena. Insights into the levels to be included can often be derived by considering the data needs for analytic methods and the level at which data from experiments are collected. Usually, there is no need to proceed further down the phenomenological hierarchy than (a) the level at which physical are processes modeled with analytic methods or (b) the level at which data, either direct or indirect, are acquired.

Step 7: Develop the importance-rank and rationale for each phenomenon. Importance is ranked relative to the FOM adopted in Step 5. Several ranking scales have been used in the past. However, consistent application of the scale is of equal importance as the specifics of the scale. A word-based scale, e.g., High, Medium, Low or Inactive / Insignificant importance, has proven useful. Numerical scales, e.g., 1-5, have also been used. Outcomes are closely associated with the ranking process and the members of the PIRT Panel should understand the outcomes as they embark on the ranking effort. For example, a phenomenon assigned an importance-rank of High must be simulated with a reasonable degree of accuracy in both experiments and analysis tools while a phenomenon with an importance rank of Low requires significantly less accuracy in both experimental and analytic simulations.

Step 8: Assess the level of knowledge regarding each phenomenon. This is a relatively new step in the evolving PIRT process. It was not included, for example, in a recent generalized description of the PIRT process (Reference [5]). As with importance ranking, several scales have been used in the past. Again, a consistent application of the scale is of equal importance as the specifics of the scale. A numerical scale, e.g., 1-4, which includes in its definitions a statement on uncertainty, has been used. A word-based scale, e.g., Known, Partially Known or Unknown, has also been used. By explicitly addressing uncertainty due to a lack of knowledge, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT Panel members to assign high importance to a phenomenon for which Panel members concluded that there was significantly less than full knowledge and understanding.

A consistent outcome of PIRT efforts has been that phenomena found to be highly important relative to the FOM, but for which the knowledge level is insufficient, are carefully examined to determine if additional experiments or analytic efforts are warranted.

Step 9: Document the PIRT results. The primary objective of this step is to provide sufficient coverage and depth that a knowledgeable reader can understand what was done (process) and the outcomes (results). The essential results to be documented are the phenomena considered and their associated definitions, the importance of each phenomena and associated rationale for the judgment of importance, the level of knowledge or uncertainty regarding each phenomenon and associated rationale, and the results and rationales for any assessments of extended applicability for the baseline PIRT. Other information may be included as determined by the Panel or requested by the Sponsor.

As presented in Figure 1, the PIRT process proceeds from start to end without iteration. In reality, however, the option to revisit any step is available and is often exercised during the PIRT development process.

2.3 PIRT Process Application: ACR-700 Complete Flow-Blockage Event of a Single Fuel Channel

Although the PIRT process has been generalized, there are numerous details that must be addressed for each PIRT application.

The initial pioneering PIRT application (References [2] and [7]) considered the response of a specific pressurized water reactor (PWR) design to a large break LOCA. Such plants have been built and operated for a number of years and both the experimental and analytic databases for PWR designs are large.

The current PIRT application focuses on the Advanced CANDU Reactor (ACR-700) undergoing a complete flow blockage event of a single fuel channel. Within the AECL accident categorization, this event is classified as a Limited Core Damage Accident and is a Class 5 event (Reference [9]). Limited Core Damage Accidents are improbable events beyond the US NRC's design basis, which must be accommodated within specified radiological dose limits to the public. The plant response to limited core damage accidents is analyzed using design-centered assumptions and detailed models.

Numerous specific decisions were made during the development of the ACR-700 single-channel complete flow blockage event PIRT. These are summarized in the following for each PIRT process step described in Section 2.2.

Step 1 – **Issue:** The United States (US) Nuclear Regulatory Commission (NRC) is conducting a pre-application review of the ACR-700. The NRC employs the PIRT process in both its work philosophy and licensing approach. An example of the latter is the extensive use of PIRT results and PIRT-related guidance provided to licensees regarding transient and accident analysis methods used to analyze the transient and accident behavior that are within the design basis of a plant (Reference [6]). The NRC has convened a large PIRT team to develop thermal hydraulic, severe accident, and nuclear analysis PIRTs. Atomic Energy of Canada Limited (AECL) has made extensive use of PIRT-like results in the validation of its computer programs used for safety analysis of the CANDU series and now the ACR design (Reference [3]).

However, the AECL PIRT practices and documentation differ in some important aspects from the PIRT results and documentation with which the NRC is familiar. Therefore, there is a need to produce one or more ACR PIRTs consistent with US practices and expectations. In general, these ACR PIRTs will serve several purposes. First, they will form the basis for responding to the "Evaluation Models" guidance provided by the NRC in DG-1120 (Reference [2]). As stated previously, the ACR single-channel complete flow blockage is a Class 5 event and, as such, the methods used to analyze this event do not fall under the guidance of DG-1120. Second, they will familiarize AECL staff with the PIRT process as practiced in the US. Third, they will assist and guide AECL staff as they provide support to the NRC as it independently develops PIRTs for the ACR in the US. Fourth, they will provide a basis for confirming the previously developed phenomena identification and ranking results for the ACR (Reference [3]). Fifth, AECL will identify and rank phenomena in a Class 5 or limited core damage event; a class of events for which there is limited PIRT experience in the US.

Step 2 - **Objectives:** The objectives of the ACR-700 complete flow blockage event PIRT effort were to: (1) confirm, or if necessary, improve the AECL understanding of ACR-700 complete flow blockage and the associated experimental and analytic needs, (2) prepare AECL staff to effectively interact with the NRC reviews of ACR-700 response to severe accidents, (3) continue efforts that inform AECL technical staff and management about the US approach to reactor- and event-based PIRT development, (4) prepare AECL staff to effectively interact with the experts engaged by the NRC to independently develop PIRTs for the ACR-700, and (5) provide a basis for evaluating the previously developed phenomena identification and ranking results for the ACR (Reference [3]).

Step 3 – **Hardware and Scenario:** This PIRT was developed for the ACR-700 design. A detailed description of the ACR-700 is provided in Reference [1]. A description of the ACR-700 design is also presented in Section 3, including a description of the key features of the ACR-700 design as they relate to the response of the design to a complete flow blockage event.

This PIRT was developed for a scenario in which there is a complete and instantaneous blockage of a single fuel channel in ACR-700. The blockage is assumed to affect a single feeder in an inlet header. The scenario is divided into three phases. Phase 1 begins with the blockage and ends at approximately 8 seconds when the fuel channel begins to deform and molten material is generated. Phase 2 ends at approximately 10 seconds when the molten materials relocate and causes the failure (rupture) of the pressure tube and calandria tube of the blocked channel. Phase 3 starts with the ejection of molten material/coolant/debris into the moderator and ends with the actuation of the Emergency Core Cooling System (ECCS). Events after Phase 3 are similar to a small-break LOCA. A detailed scenario description is provided in Section 4.

Step 4 – **Figure of Merit:** Each phenomenon was assessed relative to a single Figure of Merit. As the 100% single-channel flow blockage event is a severe accident; an explicit licensing criterion to guide the development of the FOM is not available.

However, an AECL design requirement for this event is that the failure of a single channel not propagate and cause more than limited damage to in-core structures such that the accident would continue rather than be terminated with the damage to only one blocked channel. For the complete flow blockage of a single channel, the FOM was defined to be the accident-generated loading of in-core structures. Included are loadings from direct pressure loading and pressure differences, calandria and pressure tube recoil, jet impingement, projectiles, etc.

Each phenomenon was assessed relative to the loadings during that phase. During Phase 1 and 2, all such loadings are internal to the blocked channel. Therefore, the relative importance of each phenomenon was evaluated relative to the loads generated on the pressure tube and calandria tubes. Precursor phenomena that affected the initial ejection pressure in Phase 3 were also considered. For Phase 3, each phenomenon was evaluated relative to the loads resulting from the ejection of molten material/debris into the moderator fluid or recoil of the failed pressure tube and/or calandria tube.

Step 5 – **Database:** Because AECL staff developed the PIRT documented herein; the experience base of the PIRT Panel was readily available. Specific information about the plant design and response of the design to accident conditions, applicable integral, component, and separate-effect experimental facilities and data, and analytic tools and results were available throughout the course of the PIRT development. The Panel had access to graphic results of a CATHENA simulation.

Panel members had access to data from experimental programs that assessed the response of the fuel channel and surrounding calandria vessel to a single-channel flow blockage event. This includes R&D programs on high-temperature fuel behavior (in particular UO_2/Zircaloy-4 alloying interactions), the deformation (including failure) behavior of pressure tubes and calandria tubes, hydrodynamic loads from a ruptured fuel channel, fuel channel debris coolability in the moderator, and molten fuel moderator interactions (Reference [10]).

Step 6 – **Identify Phenomena:** The general description for Step 6 in Section 2.2 stated that the objective was to identify a complete set of plausible phenomena and provide definitions for each phenomenon listed. As applied in this PIRT effort, it was stated that the term “phenomenon” encompasses phenomena, processes, conditions, characteristics, and state variables.

To support the phenomenon identification effort, a generalized list of PIRT phenomena was compiled by considering three potential elements of a component in a thermal-hydraulic system. These three elements are the structure, volume, and flow path associated with each component. Each element was further characterized by its physical characteristics, initial state at the start of the accident, and phenomena that could occur during the scenario. A fourth element, Equipment, was added to address several phenomena that could not easily be introduced into the structure, volume, and flow path construct.

The generalized PIRT phenomena list was assembled using phenomena lists from three sources. The first source was ACR-700 specific phenomena organized by discipline, several of which were reactor physics, fuel channel and system thermal hydraulics, fuel and fuel channel thermal-mechanical effects (Reference [3]). These phenomena are further identified in Table 1 with their unique identifier from Reference [3]. The identifier is shown in parenthesis and follows the phenomena entry. The second source was a consolidated list of phenomena of high importance from US PWR and BWR PIRTs (Reference [11]). The third source consisted of several large LOCA PIRTs conducted in the US. These PIRTs included complete lists of phenomena for the given plant and scenario. The PIRT for the AP600 large LOCA is an example (Reference [12]). The resultant consolidated PIRT phenomenon list is presented in Table 1.

The PIRT Panel developed a list of ACR-700 systems. Within each system, the components were listed. Finally, facilitators for this PIRT effort compiled a draft PIRT phenomena list by populating each component with plausible phenomena from the generalized PIRT phenomena list presented in Table 1. This draft PIRT phenomena list and accompanying definitions were then reviewed by the PIRT Panel and revised as needed. The final PIRT phenomena list considered by the Panel is presented in Section 5. The definitions for each phenomenon considered are presented in Appendix A.

Step 7 – **Importance Ranking:** The Panel ranked each phenomenon in the table relative to the single FOM as described in Step 4 of this section. A summary of the importance-rank assigned to each phenomenon is provided in Section 5.

Each phenomenon was assigned an importance-rank of “High,” “Medium,” “Low” or “Inactive/Insignificant.” The definitions associated with each of these importance-ranks are shown in the Table 2. The results of a PIRT effort are frequently used to focus attention on the areas in experimental facilities and analysis methods that are most important in accurately representing plant behavior. Thus, Table 2 also presents the “Application Outcomes” associated with each of the importance-ranks as an additional set of information to be used by the Panel members as they conduct their ranking efforts.

The Panel employed a hierarchical ranking process. During the first step of the importance-ranking effort, an importance-rank of H, M, L, or I was assigned for each system for each phase of the accident. Next, the importance of each component was evaluated for each phase. However, an important constraint[3] was applied to the component rankings for each phase, namely, that a component could not have a higher importance-rank than assigned to the associated system for the corresponding phase. Finally, an importance-rank for each phenomenon was assigned and the rationale documented. Again, a constraint[3] was applied to the phenomenon rankings for each phase, namely, that a phenomenon could not have a higher importance-rank than assigned to the associated component for the corresponding phase.

The hierarchical ranking process was employed because this approach has the benefit of limiting the number of phenomena identified as being of “High” importance. If the hierarchical ranking process is not followed, i.e., ranking of systems followed by

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[3] The rationale may indicate that the higher-level object(s) should have the assigned rank either increased or reduced.

components, followed by phenomena and with the constraints described above, the importance of each phenomena is evaluated in isolation and absent the insights offered by the rankings of the higher level systems and components.

Step 8 – **Knowledge Level:** Panel members assessed the current knowledge level for each phenomenon in the PIRT table. The knowledge level for each phenomenon was assessed relative to the impact of each phenomenon on the FOM. Numbers between 1 and 4 were assigned to reflect the knowledge level with the associated definitions shown in Table 3.

Step 9 – **Documentation:** This document represents the realization of the documentation step. An introduction to this PIRT effort is provided in Section 1. The general PIRT process and its specific application to the single-channel flow blockage effort are documented in Section 2. A description of the ACR-700 plant and the key systems and components that respond to the selected scenario are described in Section 3. The single-channel flow blockage scenario for the ACR-700 is described in Section 4. The three phases of the accident for which PIRT assessments were made are described. The three phases are the blocked channel heatup phase, deformation of the fuel channel and formation of molten materials, and failure of the fuel channel with ejection of molten material / coolant / debris into the moderator fluid. Summary PIRT results are presented in Section 5. Phenomena definitions are provided in Appendix A.

3. PLANT DESCRIPTION

The Phenomena Identification and Ranking Table (PIRT) is plant specific. Therefore, a brief description of the ACR-700 system is provided as a necessary element in this documentation of the PIRT evaluation (Reference [1]). Technical data for an ACR-700 reactor unit is provided in Table 4. In addition, a brief review of those systems and components having an impact on the course of the transient for a complete blockage of a single fuel channel is provided.

3.1 ACR-700 Description Overview

Atomic Energy of Canada Limited (AECL) has developed the ACR-700 (Advanced CANDU Reactor-700) to meet customer needs for reduced capital cost, shorter construction schedule, high capacity factor, low operating cost, increased operating life, simple component replacement, and enhanced safety features.

The ACR design is based on the use of modular horizontal fuel channels surrounded by a heavy water moderator, the same feature as in all CANDU reactors. The major innovation in ACR is the use of slightly enriched uranium fuel in CANFLEX fuel bundles, and light water as the coolant, which circulates in the fuel channels. This results in a more compact reactor design and a reduction of heavy water inventory, both contributing to a significant decrease in cost compared to CANDU reactors that employ natural uranium as fuel and heavy water as coolant.

The design also features higher pressures and temperatures of reactor coolant and main steam, thus providing an improved thermal efficiency over the existing CANDU plants. These thermal hydraulic characteristics further emphasize the ACR drive towards improved economics.

The above changes and other evolutionary design improvements are well supported by the existing knowledge base and build on the traditional characteristics of the CANDU system, including: proven, simple and economical fuel bundle design; on-power fuelling; separate cool, low-pressure moderator with back-up heat sink capability; and low neutron absorption for good fuel utilization.

The safety enhancements made in ACR encompass safety margins, performance and reliability of safety related systems. In particular, the use of the CANFLEX fuel bundle, with lower linear rating and higher critical heat flux, permits increased operating and safety margins of the reactor. Passive safety features draw from those of the existing CANDU plants (e.g., the two independent, reliable and diverse shutdown systems), and other passive features are added to strengthen the safety of the plant (e.g., a gravity supply of emergency feedwater to the steam generators).

The reactor consists of a set of 284 horizontally aligned fuel channels arranged on a square pitch. The fuel channels contain the fuel and the high-pressure light water coolant. They are mounted in a calandria vessel containing the heavy water moderator. An individual calandria tube surrounds each individual pressure tube.

The calandria vessel is enclosed by end shields, which support each end of the calandria. They are filled with steel balls and water to provide shielding. The fuel channels are located by adjustable restraints on the two end shields and are connected by individual feeder pipes to the Heat Transport System (HTS).

The calandria vessel is enclosed in a larger shield tank. The shield tank has a reactivity mechanisms deck mounted on its top and has horizontal penetrations for more reactivity systems. A series of thimbles are used to connect various reactivity and shutdown systems through to the calandria vessel.

3.2 Reactor Heat Transport System

The major components of the heat transport system are the 284 reactor fuel channels, two vertical steam generators, four motor driven pumps, two reactor inlet headers (RIH), two reactor outlet headers (ROH), and inter-connecting piping. The HTS is arranged in one closed circuit. A simplified heat transport circuit schematic is shown in Figure 2.

The fuel channels are horizontal and allow access to both ends by the fuelling machines. The headers, steam generators and pumps are located above the reactor to provide thermosyphoning if power is lost to the heat transport pumps. The general layout of the heat transport system in the reactor building is illustrated in Figure 3.

The fuel channel assemblies support and locate the fuel within the reactor core. They allow for flow of the heat transport coolant without leakage, and they also provide for shielding. Each fuel channel assembly consists of a pressure tube, calandria tube, two end fittings and associated hardware. Feeder pipes connect the inlet and outlet end fittings to the reactor inlet header and reactor outlet header, respectively, to complete the heat transport system loop. Each feeder pipe is connected to an end fitting sideport by a welded connection.

Light water coolant flows into the inlet end fitting, through the holes in the liner tube into the central circular section, then into the concentrically aligned shield plug in the end fitting and is directed into the pressure tube. Each end fitting incorporates a shield plug to provide shielding.

The outboard end face of each end fitting makes a sealed connection with the fuelling machine to perform on-power fuel insertion and removal. The channel closure is removed and stored by the fuelling machine during refueling and is re-installed in the end fitting before the fuelling machine moves off the channel.

3.3 Steam Generators

Two identical steam generators with integral preheaters transfer heat from the reactor coolant on the steam generator primary side to raise the temperature of, and boil, feedwater on the steam generator secondary side. The steam generator consists of an inverted vertical U-tube bundle installed in a shell. Steam-separating equipment is housed in the upper portion of the shell.

3.4 Heat Transport Pumps

The four heat transport pumps are vertical, single stage centrifugal pumps with single suction and double discharge. When maintenance of the shaft seals or the pump internals is required, the coolant level in the HTS can be lowered to a level below the pumps. The Long-Term Cooling system cools the HTS after a reactor shutdown to a temperature suitable for maintenance, maintains that temperature, and provides a means of draining, refilling and level control of the HTS to allow for this maintenance.

A gland seal external circuit supplies cooled and filtered water for lubricating and cooling the mechanical seals. A leakage recovery cavity takes the seal leakage to the leakage collection system. Each pump is driven by a vertical, totally enclosed, air and water-cooled squirrel cage induction motor. The motor has built-in inertia to prolong pump rundown on loss of power.

3.5 Feeders

The feeders at each end of the reactor run from the fuel channels horizontally or vertically up the face of the reactor and then horizontally across and above the fuelling machine area to the reactor headers. The feeders are sized to provide the necessary flow to each channel and to fit in the space between the end fittings. They are welded to the feeder connection provided on each end fitting. The lower portions of both the inlet and outlet feeders are stainless steel pipes to prevent flow-assisted corrosion. The headers and the upper portion of the feeders are carbon steel with 0.3% Cr.

3.6 Fuel Channel Assembly

The fuel channel assembly (Figure 4) comprises a pressure tube, a calandria tube, two end fittings (one at each end of the pressure tube), and various internal components. Each pressure tube is thermally insulated from the low temperature, low pressure moderator by a carbon dioxide (CO_2) filled gas annulus between the pressure tube and calandria tube. Spacers (garter springs), positioned along the length of the pressure tube, maintain the annular space and prevent contact between the two tubes.

The zirconium alloy (Zr-2.5% Nb) pressure tube is attached to the inboard end of the stainless steel end fitting by a roll-expanded joint.

A restraint mechanism, with a locking ring at each face of the reactor, allows the channel to be locked at one end and unlocked at the other to allow the channel to expand axially, due to irradiation and thermal-induced creep and expansion. A bellows assembly is used to seal the gas annulus while allowing movement of the end fitting at the free end of the fuel channel. To accommodate axial channel growth on both sides of the reactor, mid-way through the channel life, the unlocked end is locked and the locked end is unlocked.

The fuel channel is designed to achieve a target 30-year operating life with a 90 percent capacity factor. The fuel channel design will accommodate the predicted sag, axial and diametral growth due to irradiation of the pressure tube over this operating life. The fuel channel assemblies are designed to allow for replacement.

3.7 Fuel Bundle

Each fuel channel is fuelled with twelve CANFLEX fuel bundles fabricated from Zircaloy-4 components and sintered UO_2 fuel pellets (Reference [15]). The fuel bundles are short (approximately 50 cm long) and 103 mm in diameter. Each fuel bundle consists of 43 fuel elements arranged in concentric circles of 7, 14 and 21 fuel elements about a central fuel element. The fuel elements are welded at each end to thin, flexible end plates. Spacer pads are fixed to the fuel elements to maintain fuel element separation. Bearing pads are attached to the outer fuel elements to support the bundle in the fuel channel and avoid fuel element contact with the pressure tube. Flow turbulence buttons are also fixed to the sheath surface to improve heat transfer.

The fuel sheath is thin and creep collapses under coolant pressure onto the fuel pellet stack early in irradiation. Good fuel/sheath contact, low fission product gas release, and the use of a helium fill gas (filled at atmospheric pressure) all promote lower fuel operating temperatures.

3.8 Headers

There are two reactor outlet headers, one at each end of the reactor. Each of the reactor outlet headers receives the flow from the outlet feeders on one reactor face and conducts the flow to two steam generator inlet lines, which lead to a single steam generator.

There are two reactor inlet headers, one at each end of the reactor. Each of the reactor inlet headers receives the flow from two heat transport pumps through four discharge lines and channels the flow to the inlet feeders on one reactor face.

Design margin is provided in the steam generator to cater for fouling and tube plugging if required as the plant matures.

3.9 Pressurizer

The heat transport system is a pressurized light water closed loop. The heat transport pressure and inventory control (P&IC) system is designed to provide a means of pressure and inventory control for this closed loop as well as to provide adequate overpressure protection. The control of pressure and inventory is achieved using a distributed control system (DCS). Overpressure protection is independent of the DCS.

The pressurizer is a major component of the Pressure and Inventory Control System. The pressure vessel is partly full of coolant in liquid phase with the remainder being saturated vapor in equilibrium with the liquid. During normal operating condition, the pressurizer is connected to the HTS. This is called “normal mode” operation of the HTS pressure control system.

Controlling the pressure of the vapor space in the upper region of the pressurizer controls the reactor outlet header pressure at the setpoint. The pressure is increased by activating the heaters in the vessel and reduced by a controlled spray flow supplied by a line connected to a reactor inlet header. When the HTS is stable under normal conditions, one variable heater is used to compensate for pressurizer heat loss. During an upward maneuvering condition, the pressurizer spray is used to control increasing pressure.

The pressurizer level setpoint increases with reactor power and the water level is automatically controlled at the setpoint by the feed and bleeds circuit under the control of the unit computers. In “solid mode”, the pressurizer is isolated from the HTS circuit. In this case, the pressure control of the HTS is achieved by feed and bleed. Duplicated and instrumented steam relief valves connecting to the bleed condenser provide overpressure protection for the pressurizer. During a shutdown, the isolated pressurizer normally remains pressurized. Swell and shrinkage in the heat transport system, during warmup, startup, shutdown and cooldown, are accommodated in the pressurizer and the coolant storage tank, and are compensated for by bleeding from the system via the bleed circuit or feeding into the system via the feed circuit.

3.10 Feed and Bleed System

The feed and bleed circuit is provided for the inventory control of the HTS. The feed and bleed circuit is designed to handle the shrinkage and swell rates which take place during warmup and cooldown. Two high-pressure multi-stage pressurizing pumps are provided, one of which is normally operating with the other on standby.

The bleed flow is discharged from the HTS into the bleed condenser and cooled by a reflux tube bundle with a flow from the discharge of HTS pressurizing pumps. By passing through the bleed cooler, the coolant is further cooled down to 66°C (150°F). The water is routed to the heat transport purification system for filtering and purification.

The normal feed flow is taken from HTS purification circuit and the coolant storage tank. During some abnormal situations (for example, design basis events such as relief valve failure, small loss of coolant accident, etc.), the heat transport system pressure falls and the HTS pressurizing pump flow subsequently increases. In order to avoid the pressurizing pump from tripping due to low suction pressure, override of the feed valves is provided such that the feed valves begin to throttle to reduce the flow.

During normal operation, the pressurizing pump also supplies purified coolant flow to the fuelling machines via a booster pump for the refueling operation.

3.11 Moderator Systems

The moderator system consists of a closed heavy water recirculating loop, which serves to cool and circulate the heavy water moderator through the calandria. The high purity D_2O moderator, used to slow fission neutrons to sustain criticality, is circulated through the main moderator circuit during normal operation. Heat generated within the moderator is removed in the moderator circuit to maintain a constant moderator temperature. The moderator circuit also acts as a medium for dispersion of reactivity control agents. During accidents, the moderator system acts as a heat sink.

3.12 Calandria Rupture Disc

The calandria rupture disc assemblies are not the principal pressure relief devices required by the ASME Code for the calandria vessel, the moderator system, or the moderator cover gas system.

They are backup devices to the normal means of pressure relief, which limit the magnitude of the peak pressure in the calandria for “emergency” conditions. Each rupture disc assembly consists of a weld neck mounting flange (suitable for welding to the relief duct), an inlet flange, a rupture disc, an outlet flange/knife blade holder, studs or bolts, and nuts. The rupture disc is clamped between the inlet and outlet flanges. The rupture disc is required to burst if the internal pressure in the calandria vessel reaches a specified level and causes a differential pressure of 150 kPa across the rupture disc.

3.13 Reactor Containment System

The containment system is an envelope around the nuclear components of the heat transport system where failure of these components could result in the release of a significant amount of radioactivity to the public. Because of the large amounts of energy stored in the heat transport system, the envelope must withstand a pressure rise. The criterion for determining the effectiveness of the envelope is the integrated leak rate for the period of the pressure excursion.

To meet the design leakage requirements two diverse principles are used. The first involves the detailed design of the envelope to minimize the leak rate. The envelope comprises a primary containment, and a system to automatically isolate or “button up” the reactor building after a loss-of-coolant accident. The second method involves a system that will absorb the energy released to the envelope, thus reducing the peak pressure and the duration of the pressure excursion. The building local air coolers do this.

3.14 Emergency Core Cooling System

The reactor shutdown and emergency core cooling systems (ECCS) acting together must, as a design target, prevent excessive fuel damage. Rupture of a fuel channel leads to a break discharge similar in magnitude to a small-break LOCA. The HTS slowly depressurizes in such an event. When the system pressure falls to a preset value, firing of the Emergency Coolant Injection (ECI) system initiates the ECCS.

The emergency core cooling system is designed to supply emergency coolant to the reactor in two stages. During the high-pressure stage, water is injected into the reactor core via the ECI system on a LOCA signal. To enhance the effectiveness of this high-pressure injection, the main steam safety valves are also opened on a LOCA signal to provide a rapid cooldown of the steam generators and depressurization of the heat transport system. When the HTS pressure drops below the rupture pressure of the one-way rupture discs, the rupture discs burst, thereby enabling ECI coolant injection to the reactor inlet headers. In addition, valves on the ECI interconnect line between the reactor outlet headers, open on a LOCA signal to assist in establishing a cooling flow path.

For complete flow blockage of a single fuel channel, the Long-Term Cooling (LTC) system is initiated following operation of the ECI system. On the LOCA signal, water is automatically introduced into the containment sumps and the LTC pumps start automatically. When the water accumulators are nearly empty, the ECI accumulator isolation valves close and the recovery stage begins by pumping water from the sumps into the HTS via the LTC heat exchangers and thus the LTC is initiated. The LTC delivers flow to the reactor inlet headers, thereby utilizing the cooling path already established by the high-pressure ECI system. The LTC system is also used for long-term cooling of the reactor after shutdown following other accidents and transients.

4. SINGLE-CHANNEL FLOW BLOCKAGE SCENARIO DESCRIPTION

The severe (complete) single-channel flow blockage event is a small subset of flow blockage events that is caused by more than 95% of the flow area blocked, resulting in severe flow reduction, and fuel cladding melting. The severe single-channel flow blockage event is a beyond design basis event assessed as limited core damage event to demonstrate defense in depth, and provide assurance that the damage to the affected channel does not propagate to the neighboring channels in the core.

A complete flow blockage of a single fuel channel results in superheated steam being formed in the fuel channel and failure of that channel. The sequence of events is as follows:

- Immediately after the channel flow blockage occurs, the heat transport system (HTS) remains essentially unaffected, except in the blocked channel.
- The fuel and pressure tube in the channel where the flow blockage occurs heat up rapidly as the stagnant coolant in the fuel channel superheats. Since the channel pressure is high, pressure tube circumferential strain begins as the pressure tube heats. Also, a non-uniform temperature distribution develops around the circumference of the pressure tube due to a combination of stratified two-phase flow and uneven steam flow.
- At full system pressure, a small non-uniform circumferential temperature distribution is sufficient to result in pressure tube failure.
- Sheath melting (Zircaloy-4) begins in the hotter fuel bundles augmented by UO_2-Zircaloy interaction (eutectic formation) and dissolution of UO_2 by molten Zircaloy.
- Slumping of the hot fuel bundles occurs as the bundle assembly weakens. Some fuel elements come into contact with the pressure tube.
- Pressure tube failure could occur as a result of circumferential strain or relocation of molten material onto the pressure tube. Failure by molten material is expected to occur prior to failure by circumferential strain.
- After pressure tube failure occurs, the gas annulus between the pressure tube and calandria tube pressurizes very rapidly and the calandria bellows rupture allowing discharge of reactor coolant into containment.
- Following pressure tube rupture, calandria tube failure occurs by thermal hydraulic loading and impact of molten material.
- After channel failure, the contents of the blocked channel consisting of superheated coolant and/or hydrogen, fission products, and overheated or molten fuel are rapidly discharged into the moderator.
- The discharge of light water coolant into the heavy water moderator introduces a large negative reactivity and accordingly initiates reactor self-shutdown.
- The rapid discharge of hot fuel and coolant into the calandria vessel produces a hydrodynamic transient that may cause damage to some in-core components (i.e., deformation of the calandria vessel, collapse of calandria tubes onto pressure tubes, bending of fuel channels, shut-off-rod guide tube structure) via pipe whip/recoil, jet impingement and pressure pulse.

- The increasing pressure in the calandria pushes moderator water up into the relief ducts at the top of the calandria. The moderator pressure and temperature continues to rise and the rupture discs in the relief ducts break open.
- The steam bubble formed by molten fuel moderator interaction collapses. For the unaffected channels, the event then progresses as any other small-break LOCA. The reactor trips within a few minutes of the initiating event on a process trip signal (e.g., moderator high level, HTS low pressure). In addition to the inherent reactor self-shutdown due to light water coolant discharge into the heavy water moderator, both of the independent shutdown systems remain capable to shut down the reactor and maintain it in a shutdown state. Neutron kinetics do not play a dominant role nor do shutdown system actions.
- The behavior of the HTS after the reactor has tripped is similar to that for a small-break LOCA. Eventually, the HTS pressure falls below the Emergency Core Cooling System (ECCS) initiation setpoint. The ECCS system is designed to prevent fuel sheath failures for small breaks in the HTS. Thus sheath temperatures in the intact fuel channels remain near the coolant temperature and systematic fuel failures are not expected.
- The HTS pumps continue to run in both loops until they are tripped by automatic pump trip.
- The ECCS restores coolant inventory and adequate fuel cooling is maintained.

To facilitate the Phenomena Identification and Ranking Table (PIRT) effort, the flow blockage scenario is subdivided into three time periods (or phases). Phase 1 addresses the time interval where fuel channel geometry is maintained (i.e., from the initiation of channel blockage to the onset of melting). Phase 2 covers the time period where the fuel channel geometry is deforming (i.e., onset of melting until fuel channel failure). Phase 3 initiates with channel failure and ends when the ECCS system is activated. After ECCS activation, the PIRT effort for small-break LOCA should be used.

The PIRT activity described in this document is specific to the ACR-700 reactor for the case of a 100% flow-blockage event in a single fuel channel. At the time of the transient, the reactor is operating at full power with equilibrium poison levels. The appropriate durations of each phase are:

Time Phase	Time Interval (s)	Scenario Phase
1	0 – 8	Channel geometry maintained
2	8 – 10	Channel geometry deforming
3	10 - 150	Post-channel failure

The events occurring during the channel flow blockage scenario are described in detailed point-form in Table 5. Figure 6 to 22 provide a gallery of results from the simulation and insight into the trends of some important parameters. Bundle location 1 (i.e., B1) is located at the inlet end of the channel while bundle B12 is at the outlet end location. The fuel channel failure occurs adjacent to the hottest fuel bundles at the middle of the fuel channel (i.e., B4 and/or B5). The thermal hydraulic data are from a single-channel CATHENA simulation (Figure 5).

4.1 Phase 1: Channel Geometry Maintained

Figure 6 to 9 are from a single-channel simulation that assumes the pressure tube (PT) remains intact. The purpose of these types of simulation is to identify specific component temperatures and thus times of component melting or failure. The simulations are then re-run with the break in the PT, the channel bellows, and the calandria tube properly timed.

The channel coolant flow drops rapidly to near zero (Figure 6) for the flow at the inlet end to the middle of the channel. Flow from the outlet is increased as steam is formed in the channel. Figure 7 shows that boil-off of the channel inventory occurs quite quickly and the coolant inventory is reduced quite rapidly.

With degraded cooling conditions, the fuel, sheath and pressure tube heat quickly (Figure 8). Zircaloy components (e.g., fuel sheath) start to reach their melting point (1760°C) at times between 8 to 10 seconds (the plateau in the sheath temperature curve). Pressure tube failure typically occurs within 2 seconds of sheath melting.

With the channel flow stagnated and the coolant boiling off, the pressure tube develops a non-uniform temperature around its circumference (Figure 9). A large temperature difference from the top to the bottom appears. With such large temperature gradients and high channel pressure (still above the normal operating pressure for the outlet header), the pressure tube can fail by local over-strain. The rupture of the pressure tube occurs at approximately 10 seconds at the high-power bundle locations, B4 and / or B5.

4.2 Phase 2: Channel Geometry Deforming

Zircaloy melting begins at approximately 8 seconds following the blockage[4] (Figure 8). The pressure tube in the blocked channel fails at approximately 10 seconds (Figure 9). Approximately 3.8 kg of molten material, primarily Zircaloy (Figure 16), is formed and relocates towards the bottom of the pressure tube prior to PT rupture. Slumping of the hot fuel bundles occurs as the bundle assembly weakens. Some fuel elements come into contact with the PT.

With pressure tube rupture, the channel flow stagnation is broken and the channel pressure re-distributes. The pressure is low near the pressure tube rupture location. The furthest downstream bundle, B12, still has a high channel pressure of about 10 MPa.

A large reverse flow (Figure 11) appears in the portion of the channel downstream of the break in the pressure tube.

Following PT rupture, there is a large break discharge flow into the annulus between the pressure tube and calandria tube (Figure 12). The gas annulus rapidly pressurizes and both bellows at the ends of the fuel channel rupture. The calandria tube ruptures almost immediately (i.e., within 0.5 seconds) from a combination of jet impingement, ablation, erosion and dryout. This initiates a large break flow into the moderator and a smaller break flow through the bellows into containment.

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4 The CATHENA simulation retains the molten material formed in-situ. The decline in molten material shown in Figure 4-14 represents freezing of this material.

4.3 Phase 3: Post-Channel Failure

The ejection of light water coolant into the moderator initiates self-shutdown of the reactor. (In the simulations shown, the channel power is assumed to remain high at 7.762 MW.)

The channel void fraction rapidly changes on pressure tube / calandria tube rupture (Figure 13). The remaining coolant in the channel (on the bottom) vaporizes immediately due to depressurization when the fuel channel ruptures. Even with a large reverse flow in the portion downstream of the break, the channel void fraction remains high. The coolant flowing from the reactor outlet header will vaporize in the channel where the pressure is much lower while the coolant temperature remains high (see steam and liquid temperatures in Figure 14 and 15 respectively).

With the large reverse flow (though with high void fraction and high temperature), the portion of the fuel channel downstream of the break (i.e., bundle 6 location) cools down. However, the portion of the fuel channel upstream of the break (i.e., bundle location 3) reheats (Figure 17).

Following fuel channel rupture, the molten material is expelled into the moderator. The molten debris, fuel fragments and steam/hydrogen form a steam bubble in the vicinity of the break (Figure 22). A significant portion of this steam comes from vapor generation during molten fuel moderator interaction (MFMI).

The hydrodynamic transient is relatively short-lived. Figure 19, from the TUBRUPT code, shows the pressure transient that develops across the calandria vessel wall. Figure 20 indicates the sensitivity of this transient to the amount of molten material expelled from the ruptured fuel channel. The moderator rupture disk opens in less than 0.05 seconds after the rupture of the calandria tube (Figure 21). A steady discharge flow then develops with the flow coming from the outlet header. The accident proceeds in a similar fashion to a small-break LOCA.

A number of potential damage mechanisms can occur subsequent to a channel rupture. Jet forces load adjacent structures. Pressure tube and calandria tube recoil may cause impact with adjacent structures. Hydrodynamic forces apply impulse loads on adjacent structures and pressurize the calandria vessel. Fuel bundles and debris may also be ejected from the ruptured channel and impact other structures. A brief description of the damage mechanisms that may occur during this phase follows.

Hydrodynamic Loads:

The magnitude of the hydrodynamic loads is determined by the dynamics of the bubble expansion. Bubble expansion is governed by the discharge rate from the break, condensation at the bubble interface with the moderator fluid, compression of the liquid moderator, and dimensional changes of in-core structures (e.g., collapse of calandria tubes in the unaffected channels onto their pressure tubes, deformation of the calandria vessel).

The impulse loadings on adjacent structures only exist during the first 20 milliseconds following fuel channel failure. The impulse loads are caused by the transient pressure differences across the adjacent structures from the rapid expansion of the two-phase bubble. The transient pressure gradients persist until the bubble pressure equilibrates with the moderator pressure, at which point all structures see a uniform pressure.

Jet Impingement Loads:

Jet forces come into play in 1) failure of the calandria tube following pressure tube failure, and 2) in the moderator following calandria tube failure and when the hydrodynamic transient has subsided (typically a few hundred milliseconds). In both cases, thrust loads (i.e., reaction forces) act on structures in the opposite direction.

Impact Loads:

Following fuel channel rupture, fuel elements or fuel fragments may be ejected as projectiles from the ruptured channel and impact adjacent structures. The worst potential response is perforation of the adjacent structure. Another response is permanent, rather than elastic, deformation of the adjacent structure.

Impact loads are also generated by recoil (pipe whip) as a reaction to break discharge: first by the rupture of the pressure tube, then by the rupture of the calandria tube.

5. PIRT RESULTS

As indicated in the acknowledgements, this Phenomena Identification and Ranking Table (PIRT) exercise involved a number of domain experts. For each phase of the complete flow blockage scenario, a hierarchy of importance-ranking evaluations was developed by consensus[5]. The importance-rank was assigned on the basis of the potential impact of associated, credible phenomena on the Figure of Merit (FOM). The top-down assessment logically proceeds from system, to components, and finally processes / phenomena. A bottom-up re-evaluation follows to ensure consistency for the assigned importance-ranks.

This section summarizes the results of the ACR-700 complete flow blockage of a single fuel channel. The reactor is assumed to be operating at full power with equilibrium poison levels. Design values are assumed for plant parameters. All components are assumed to be available and to function as per design.

The following summarizes the four importance-ranks used in this exercise.

High (**H**)	The phenomenon has a controlling impact on the Figure of Merit
Medium (**M**)	The phenomenon has a moderate impact on the Figure of Merit
Low (**L**)	The phenomenon has a minimal impact on the Figure of Merit.
Inactive (**I**)	The phenomenon has no impact on or is insignificant with respect to the Figure of Merit.

The highest potential importance-rank assigned to a component during a particular phase of the scenario is limited to the highest importance-rank of the associated system during that same phase. A similar logic is applied to processes / phenomena with respect to their associated component. A definition of the PIRT term for a process / phenomenon[6] is provided in Appendix A.

It is understood that a phenomenon ranked High (**H**), Medium (**M**) or Low (**L**) must, at a minimum, be modeled within the Evaluation Model (Reference [6]).

A detailed scenario description is provided in Section 4 of this report. Much of the description is based upon a code-calculated sequence (e.g., Table 5). Excessive reliance on the code-calculated result could lead to erroneous importance-rankings. However, the PIRT exercise is only a portion of an iterative process to ensure that the Evaluation Model is applicable to the accident scenario in question. Deficiencies identified during the PIRT process would lead to Change Control as required by software Quality Assurance (References [13] and [14]). Significant changes to the analysis code(s) would require a re-assessment of the PIRT.

5.1 ACR-700 Complete Flow Blockage PIRT

The complete flow blockage of a single fuel channel in ACR-700 is described in Section 4 of this report. Table 6 provides a PIRT Summary recording the PIRT Panel's importance-rank

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5 Achieving consensus had at least two advantages: 1) ensuring side-effects/phenomena interactions were properly noted; and 2) a shared appreciation of overall system response.

6 It has proven difficult to clearly differentiate between processes and phenomena. The word "phenomenon", as used in this report, is intended to include phenomena, processes and, in some cases, key output parameters that would be used in Evaluation Model validation (Reference 5-1).

evaluations. Note that a "phenomenon", Availability, indicating the importance of the component functioning as designed, is used only for completeness.

The Figure of Merit is accident-generated loadings of in-core structures. In Phases 1 and 2, precursor phenomena that affect the ejection pressure in Phase 3 as well as loadings in the blocked channel are considered.

5.1.1 Channel Heatup Period

The early channel heatup period covers the period from feeder blockage until the onset of sheath melting at 8 seconds. During this period, the following systems have a controlling impact (***H****igh*) on the Figure of Merit:

- Fuel Channel (blocked)
- Fuel Bundle (blocked)

5.1.1.1 Fuel Channel (Blocked)

The Fuel Channel (blocked), as defined within this document, consists of the end fittings (blocked)[7], **pressure tube (blocked)**, gas annulus (blocked), calandria tube (blocked), bellows (blocked) and the fixed spacers (blocked).

The blocked channel rapidly heats and becomes mostly steam filled. Significant circumferential temperature gradients develop around the pressure tube leading to non-uniform deformation at temperatures above 600°C. Convective and radiant heat transfers to the pressure tube are governing phenomena.

5.1.1.2 Fuel Bundle (Blocked)

The fuel bundle (blocked), as defined within this document, consists of the **fuel elements (blocked)[8]** and end plate (blocked).

Heating of the fuel elements is key to the timing and amount of molten materials formed in the blocked channel. Heat loss is governed by conduction out of the fuel (conduction, gap conductance) and heat loss to the coolant (forced convection to liquid, nucleate boiling, Critical Heat Flux (CHF), post-dryout heat transfer). Heat input is by fission heating and sheath oxidation.

Sheath temperatures are sensitive to the local heat generation rate (fission heating) which is controlled by the axial power distribution for fuel bundles within the blocked channel, the radial power distribution between rings of fuel elements within fuel bundles, and the end power peaking which occurs near the ends of each fuel bundle.

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7 Within Section 5.1, components with a high importance-rank are shown in bold font.

8 Captures the phenomenological aspects of CANLUB, Fuel Pellet, Fuel Sheath, End Cap, Spacer Pad, Filling Gas and CHF Enhancers.

5.1.2 Channel Deformation Period

The channel deformation period lasts from the onset of Zircaloy melting until rupture of the pressure tube / calandria tube. During this period, the following systems have a controlling impact (***High***) on the Figure of Merit:

- Fuel Channel (blocked)
- Fuel Bundle (blocked)

5.1.2.1 Fuel Channel (Blocked)

The Fuel Channel (blocked) consists of the end fittings (blocked), **pressure tube (blocked)**, gas annulus (blocked), **calandria tube (blocked)**, bellows (blocked) and the fixed spacers (blocked).

Convective heat transfer, radiant heat transfer and conduction through contacting components govern general heating of the pressure tube. Local heating is strongly influenced by the relocation of molten material onto the pressure tube surface (melt-to-solid contact heat transfer). The locally elevated temperatures produce deformation / straining in the pressure tube and finally, melting / failure of the pressure tube.

The calandria tube temperature is controlled by convective heat transfer and thermal conduction. When the molten material is ejected from the ruptured pressure tube, the calandria tube is heated locally (melt-to-calandria tube heat transfer) and the jet impingement onto its surface causing ablation / erosion, deformation and eventually failure. The local heating of the calandria tube is strongly influenced by its dryout and post-dryout heat transfer to the moderator fluid.

5.1.2.2 Fuel Bundle (Blocked)

The fuel bundle (blocked), as defined within this document, consists of the **fuel elements (blocked)** and end plate (blocked).

Heating of the fuel bundles in the blocked channel is still occurring leading to further Zircaloy melting and dissolution of UO_2 by the molten Zircaloy. Heat loss from the fuel elements is by conduction, radiant heat transfer and post-dryout heat transfer. Heat input is by fission heating (axial power distribution, radial power distribution, end power peaking) and Zircaloy oxidation.

The hot fuel bundles begin to lose their structure as molten material relocates to the pressure tube, fuel elements and end plates lose structural rigidity, and the bundle slumps onto the pressure tube surface.

5.1.3 Post-Channel Failure

Channel failure occurs at 10 seconds. At 150 seconds the Emergency Core Cooling System (ECCS) is activated. During the period from 10 – 150 seconds, the following systems have a controlling impact (***High***) on the Figure of Merit:

- Moderator System
- Fuel Channel (blocked)
- Fuel Channel (unaffected)
- Fuel Bundle (blocked)

5.1.3.1 Moderator System

The Moderator System consists of the **calandria vessel**, moderator piping/header, **moderator fluid**, moderator pump, moderator heat exchanger, moderator rupture disc, ion exchanges and **ex-channel debris**.

The rapid pressure change in the moderator fluid from molten fuel moderator interaction and steam bubble formation is the major load-generating phenomenon. Steam bubble dynamics (i.e., size and pressure) are controlled by void generation from heat transfer from hot debris and interfacial condensation at the bubble/moderator fluid interface.

The calandria vessel is elastically deformed by the pressure pulse of the hydrodynamic transient resulting from hot debris/coolant ejection into the moderator fluid. Vessel deformation helps to attenuate the pressure pulse.

5.1.3.2 Fuel Channel (Blocked)

The Fuel Channel (blocked) consists of the **end fittings (blocked)**, **pressure tube (blocked)**, gas annulus (blocked), **calandria tube (blocked)**, bellows (blocked) and the fixed spacers (blocked).

Critical flow can occur either in the end fitting or, depending upon the break characteristics, the rupture in the pressure tube, the rupture in the calandria tube, or the bellows.

5.1.3.3 Fuel Channel (Unaffected)

The Fuel Channel (unaffected) consists of the end fittings (unaffected), pressure tube (unaffected), gas annulus (unaffected), **calandria tube** (unaffected**)**, bellows (unaffected) and the fixed spacers (unaffected).

The calandria tubes in channels adjacent to the blocked channel can be deformed onto their pressure tubes by the pressure of the hydrodynamic transient. The resulting volume change helps attenuate the pressure pulse in the moderator.

Jet impingement and impact by projectiles or the ruptured channel can cause further damage to adjacent fuel channels. The molten material associated with jet impingement can also lead to ablation / erosion of adjacent channels.

5.1.3.4 Fuel Bundle (Blocked)

The fuel bundle (blocked) consists of the **fuel elements (blocked)** and end plate (blocked).

Although the reactor is shutting down as a result of the plume of light water entering the moderator fluid, bundle decay-power in the blocked channel remain sufficiently high to cause further void generation by heat transfer.

6. SUMMARY

Atomic Energy of Canada Limited (AECL) has made extensive use of phenomena ranking results in the validation of its computer programs used for safety analysis of the CANDU reactors, and recently the ACR design. This report documents the US-style PIRT process that was conducted with the objective of confirming the phenomena identification and ranking results for the ACR previously developed using the Canadian methodology.

This document provides the results and a detailed assessment of a PIRT effort for the ACR-700 reactor. The most important systems, components, and processes/phenomena occurring during each phase of a complete flow blockage of a single fuel channel are identified and tabulated. The scenario was divided into three phases: (1) heat up of the blocked channel until melting of Zircaloy in fuel elements begins (interval 0 – 8 s); (2) fuel channel deformation, melt relocation, failure of the pressure tube and calandria tube (interval 8 s – 10 s); (3) ejection of molten material / debris / coolant into the moderator fluid until the Emergency Core Cooling System (ECCS) is initiated (interval 10 s – 150 s). Each phenomenon is assessed relative to its impact on a Figure of Merit (FOM) or evaluation criterion. The FOM for this PIRT effort is accident-generated loadings on in-core structures (i.e., consequential damage).

In the Technical Basis Document (TBD) for the ACR-700 reactor phenomena identification and ranking for each accident scenario is done in a generic fashion using several Figures of Merit simultaneously. The PIRT approach addresses phenomena at the component / phase level and uses a single FOM. Despite these differences, the agreement in the high importance-ranked phenomena between the TBD and the PIRT activity was excellent.

Table 7 provides a summary of the high importance-ranked phenomena for each component during each phase of the ACR-700 channel flow blockage scenario. These PIRT results can be used to support several important decision-making processes that are used in support of code validation and qualification.

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Table 1 Generalized PIRT Phenomena List

(The codes in brackets are phenomena designators from the TBD document [3])

STRUCTURE
Physical Properties (examples)
• Density
• Heat capacity
• Thermal conductivity
• Hardness
• Yield strength
 	
Initial State (examples)
• Thickness
• Surface area
• Orientation
• Temperature
• Stored energy
• Reactivity
 	
Phenomena
• Stored energy release (FC2)(TH6)
• Conduction (TH6)
• Radiant heat transfer (TH11)(RC21)
• Contact heat transfer
• Conductance (gap)
• Embrittlement
• Fragmentation
• Debris generation
• Fuel-coolant interaction (FCI)
• Ablation/erosion
• Post dryout heat transfer (TH12)
	• Rewet (TH12)
	• Critical heat flux (CHF) (TH9)
	• Departure from nucleate boiling (DNB)
	• Temperature distribution
	• Condensation
	• Oxidation (FC9)(FC10)(FC20)
	• Reduction (FC10)
	• Thermal-chemical reaction (Zircaloy/water) (TH13)
	• Jet impingement loading (TH22)
	• Deformation (FC6)(FC18)(FC19)(TH19)
	• Mechanical interaction (TH19)
	• Relocation (FC11)
	• Relocated melt surface area
	• Failure (FC7)
	• Melting (FC11)
	• Gas release (FC5)
	• Decay heating (FC1)
	• Fission heating (FC1)
	• Reactivity
	    • Fuel temperature change (PH7)
	    • Coolant temperature change (PH2)(PH4)
	    • Void (PH1)
	    • Density / void (PH1)(PH3)
	    • Purity (PH6)(PH16)
	    • Poison concentration (PH5)
	    • Isotopic concentration change (PH8)
	    • Lattice distortion (PH15)

VOLUME
Physical Properties (examples)
• Density
• Heat capacity
• Thermal conductivity
• Viscosity
• Chemical reactivity
 	
Initial State (example)
• Phase (liquid, vapor, two-phase)
• Temperature
• Pressure
• Concentration (poison, non-condensable gas)
• Level
• Velocity
 	
Phenomena
• Pressure change
	• Phase separation / stratification (TH3)
	• Level change
	• Conduction (TH6)(MH43)
	• Convection (TH7)(MH44)
	    • Forced to liquid
	    • Forced to vapor
	• Radiant heat transfer (TH11)(MH45)
	• Boiling
	    • Subcooled (TH2)
	    • Nucleate (TH8)(TH2)
	    • Transition (TH2)
	    • Film (TH2)
	• Entrainment
	• De-entrainment
	• Flashing (TH2)(FC23)
	• Void generation from heat transfer
	• Evaporation (TH2)

<table>
<tr><td>

- Condensation (TH3)
  - Surface
  - Inter-phase
- Interfacial shear
- Swelling (MH42)(TH4)
- Natural circulation (TH17)
- Multi-dimensional flow
- Mixing (multiple fluid streams) (MH19)
- Non-condensable gas effect (TH23)
- Degassing (MH46)
- Cavitation (MH9)
- Oscillation (TH16)

</td><td>

- Turbulence (MH11)
- Steam binding
- Poison
  - Transport (MH15)
  - Mixing
  - Diffusion
- Deflagration (MH34)
- Burning
- Waterhammer
  - Steam condensation induced (PH11)
  - Mechanically induced (PH12)

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FLOW PATH

Physical properties (examples)

- Resistance (form loss)
- Surface roughness
- Length
- Diameter
- Blockage

Initial State (examples)

- Path/state (open/close)
- Volume
- Phase (liquid, vapor, two-phase)
- Temperature
- Pressure
- Concentration
- Level
- Velocity

</td><td>

Phenomena

- Pressure drop
- Change in path/state (open/close)
- Flow
  - Blockage
  - Bypass
  - Distribution (multiple channels)
  - Counter-current (TH15)
  - Gravity driven (draining)
  - Gravity driven (natural circulation)
  - Interrupted (valve action)
  - Pressure driven
  - Flow regime at break
  - Critical (TH1)
  - Stalled (stagnation)
  - Reverse
  - Transport
  - Debris
  - Poison
  - Non-condensable gas

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EQUIPMENT

Phenomena

- Break orientation
- Pump coastdown
- Pump performance (single and two-phase) (TH5)
- Power
  - 3D distribution
  - 3D kinetics
  - End power peaking
  - Radial distribution

</td><td>

- Flux distribution (PH14)
- Core physics response to moderator level (PH16)
- Asymmetries (loop-to-loop)
- Device-movement induced reactivity (PH11)
- Class I, II, III or IV power-availability

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Table 2
Importance-Ranks and Definitions

Rank	Definition	Application Outcomes
High (H)	Phenomenon has a controlling impact on the Figure of Merit	Simulation of experiments and/or analytic modeling with a reasonable degree of accuracy (includes scaling) is required.
Medium (M)	Phenomenon has a moderate impact on the Figure of Merit	Simulation of experiments and/or analytic modeling with a moderate degree of accuracy is required.
Low (L)	Phenomenon has a minimal impact on the Figure of Merit	Simple models may be needed to preserve functional dependencies
Inactive or Insignificant (I)	Phenomenon has either an insignificant or no impact on the Figure of Merit	Simulation of experiments not required. Analytic modeling not required unless functional dependencies needed.

Table 3
Knowledge Levels and Definitions

Rank	Definition
4	Fully known, small uncertainty
3	Known, moderate uncertainty
2	Partially known, large uncertainty
1	Very limited knowledge, uncertainty cannot be characterized

Table 4
Technical Data for Each ACR-700 Unit

Reactor	
Type	Pressure Tube Reactor (PTR)
Thermal Output to Steam Generators [MWth]	1982
Coolant	Pressurized Light Water
Moderator	Heavy Water
Calandria Vessel Diameter [m]	5.2
Fuel Channel	Horizontal, concentric pressure tube/calandria tube with 403 SS end fittings
Number of fuel channels	284
Lattice Pitch [mm]	220
Reflector Thickness [mm]	510
Fuel	
Fuel	Sintered pellets of slightly enriched UO_2 and natural UO_2 in central element; Zircaloy-4 sheaths
Enrichment Level	2.1 wt% ^{235}U in 42 pins, and central pin NU with 7.5 wt% Dysprosium
Fuel Burnup [MWd/te U]	21,000
Fuel Bundle Assembly	43 element CANFLEX
Length of Bundle [mm]	495.3
Outside Diameter (maximum) [mm]	103
Bundle Weight [kg]	22.7 (includes 18 kg U)
Bundles per Fuel Channel	12
Bundle Power (maximum time-averaged) [kW]	870
Channel Power (maximum time-averaged) [MW]	7.5
Fuel Channel	
Pressure Tube Outer Radius [mm]	58.2
Pressure Tube Inner Radius [mm]	51.7
Pressure Tube Material	Zircaloy - 2.5 wt% Nb
Calandria Tube Outer Radius [mm]	78.0
Calandria Tube Inner Radius [mm]	75.5
Calandria Tube Material	Zircaloy-2
Heavy Water	
Moderator System [Mg D_2O]	129
Reserve [Mg D_2O]	2
Heat Transport System	
Reactor Outlet Header Pressure [MPa(g)]	11.9
Reactor Outlet Header Temperature [°C]	325
Reactor Inlet Header Pressure [MPa(g)]	13.1
Reactor Inlet Header Temperature [°C]	278.5
Reactor core coolant flow (total) [Mg/s]	6.9
Single Channel Flow (Maximum) [kg/s]	26
Steam Generators	
Number	2
Type	Vertical U-tube with integral preheater
Steam Temperature (Nominal) [°C]	281
Steam Quality	0.999
Steam Pressure [MPa(g)]	6.4

Heat Transport Pumps	
Number	4
Pump Type	Vertical, centrifugal, single suction, double discharge
Motor Type	AC, vertical, squirrel cage induction
Rated Flow [L/s]	2250
Rated Head [m]	230
Motor Rating [MWe]	6.9
Containment	
Type	Pre-stressed concrete with steel liner
Inside Diameter [m]	39.5
Height (top of base slab to inside of dome) [m]	59
Design Pressure [kPa(g)]	250
Turbine Generator	
Steam Turbine Type	Impulse type, tandem compound double exhaust flow, reheat condensing turbine with a last-stage blade length of 132 cm (52 inches).
Steam Turbine Composition	One single flow, high-pressure cylinder, two external moisture separators/reheaters and two double flow, low pressure cylinders.
Net Heat to Turbine [MWth]	1980
Gross/Net Electrical Output* (nominal) [MWe]	731/680*
Gross Turbine Generator Efficiency	36.9%
Steam Temperature at Main Stop Valve [°C]	279
Steam Pressure at Main Stop Valve [MPa(g)]	6.2
Final Feedwater Temperature [°C]	218
Condenser Vacuum [kPa(a)]	4.9*
* Gross electrical output is dependent on cooling water temperature, the turbine generator and condenser design, and the grid frequency.	

Table 5
Event Sequence for Complete Flow Blockage of a Single Fuel Channel

Elapsed Time (s)	Event Description
Phase 1 (channel geometry maintained)	
0	• Sudden and complete (100%) flow blockage occurs at feeder inlet • All systems operating normally (100% full power; equilibrium poisons) • Heat Transport System (HTS), with the exception of the blocked channel, is unaffected
	• Coolant flow in the blocked channel decreases to near zero • Blocked channel coolant stratifies • Stagnant coolant in blocked channel superheats • Fuel and pressure tube heat up rapidly
~1.7	• Boil-off in blocked channel produces non-uniform temperature distribution around pressure tube • Sheath oxidation/hydrogen production occur • Channel power declines slightly with channel void formation (i.e., by 4.5% as coolant void reactivity coefficient is –3 mk for a fully voided core)
~8	• Blocked channel mostly steam filled
Phase 2 (deforming channel geometry)	
~8	• Sheath inside surface at bundle ends begin to melt; progressive bundle sag (top-down) • UO_2-Zircaloy interaction (eutectic formation) • Dissolution of UO_2 in molten Zircaloy • Subchannel flow area reduction
>8	• Central portions of hot bundle(s) begin to melt; approximately 3.5 kg molten Zircaloy formed; fuel melting not predicted • Central portions of hot bundle(s) undergo UO_2-Zircaloy interaction (eutectic formation) • Fuel element-pressure tube contact

Elapsed Time (s)	Event Description
	• Molten material (i.e., 3.8 kg Zircaloy plus eutectic) starts to relocate
10	• PT ruptures (e.g., ballooning, FE/PT contact, melt) by localized over-strain • Channel bellows[9] rupture (gas annulus pressure > 4.5 MPa) • Flow path through PT rupture through ruptured bellows to containment; alarm indications • Molten material[10] contacts PT/CT
~10.5	• CT dryout and failure
Phase 3 (blocked channel failed)	
~10.5	• Superheated coolant/hydrogen, fission products, and overheated / molten fuel / debris ejected into moderator • Pipe whip (i.e., recoil) of failed channel • Jet impingement (e.g., molten material ablation / erosion, coolant, projectiles) onto adjacent channels • Molten fuel moderator interaction (MFMI); steam bubble formed in moderator • Pressure pulse in moderator fluid • Elastic deformation of the calandria vessel • Some SOR guide structure damage occurs • Some CT collapse onto their PT in adjacent intact channels • Bending of fuel channels in a moderator pressure gradient • Moderator temperature and pressure increase • Moderator purity (i.e., downgrading with light water) decreases rapidly, effectively rendering the reactor subcritical • Increasing moderator pressure pushes moderator into relief ducts • Blocked end of channel under degraded cooling conditions; unblocked end receiving adequate cooling by reversed flow • Blocked end of channel still heating at reduced power levels

9 Both bellows rupture due to the high pressure differential

10 Once the bellows fail, sufficient cooling may be available to cool the fuel and any molten material present; consequent failure of the CT may be precluded. However, CT failure is assured for melts > 1 kg even with liquid coolant in the bottom of the fuel channel.

Elapsed Time (s)	Event Description
~120	• Reactor trips on a process trip (e.g., moderator high level); LOCA signal conditioned by the moderator high level or high containment pressure • SDS1/SDS2 actuated; both SDS1 and SDS2 remain capable of shutting down the reactor.
	• Moderator temperature and pressure continue to increase • Small reactivity loss with increasing moderator temperature • Moderator rupture discs fail at 150 kPa pressure differential • Steam bubble collapses
~150	• Emergency Core Cooling System (ECCS) signal initiated on HTS low pressure; adequate fuel cooling maintained • Steam Generator (SG) crash cooldown initiated and adequate fuel cooling maintained on effective ECCS injection • Reserve Water System (RWS) activated • HTS pumps continue to run in both loops until they are tripped by automatic pump trip • Sheath temperatures in unaffected channels remain near the coolant temperature; no systematic fuel failures expected

Table 6
PIRT Summary for ACR-700 100% Flow Blockage of a Single Fuel Channel

Figure of Merit (FOM) Accident-generated loading[11] of in-core structures		
Rank		
High (**H**)	Phenomenon has a controlling impact on the Figure of Merit. Simulation of experiments and analytic modeling with a reasonable degree of accuracy (major/minor trends reasonably within range of data (includes scaling)).	
Medium (**M**)	Phenomenon has a moderate impact on the Figure of Merit. Simulation of experiments and/or analytic modeling with a moderate degree of accuracy (major trends generally within range of data) is required.	
Low (**L**)	Phenomenon has a minimal impact on the Figure of Merit. Modeling must be present to preserve functional dependencies.	
Inactive (**I**)	Phenomenon has no impact on or is insignificant with respect to the Figure of Merit. Modeling must be present if the functional dependencies are required.	
Time Phase		
1	0 – 8s	Initiation of blockage to the generation of molten material.
2	8s – 10s	Relocation of molten material to rupturing of the pressure tube / calandria tube.
3	10s – 150s	Molten material / coolant /debris ejected from the blocked channel to firing of the ECI.

11 Includes pressure/pressure gradients in the moderator fluid, pipe recoil, jet impingement, projectiles, etc.

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
Reactor System[12]											
				Shield Tank	I	I	I	Available			
				End Shield	I	I	I				
				Structure				Pressure loading	I	I	I
								Deformation	I	I	I
Moderator System	I	I	**H**	**Calandria Vessel**	I	I	**H**				
				Structure				Ablation/erosion	I	I	L
								Jet impingement loading	I	I	L
								Impact loading	I	I	**H**
								Pressure loading	I	I	L
								Deformation	I	I	**H**
				Moderator Piping / Header	I	I	I	Available			
				Moderator Fluid	I	I	**H**				
				Volume				Reactivity – moderator purity	I	I	L
								Reactivity – moderator temperature	I	I	L
								Void generation from heat transfer	I	I	**H**
								Condensation (inter-phase)	I	I	**H**
								Level change	I	I	L
								Pressure change	I	I	**H**
				Moderator Pump	I	I	I	Available			
				Moderator Heat Exchanger	I	I	I	Available			
				Moderator Rupture Disc	I	I	M				
				Flow Path				Change in path/state (open/close)	I	I	M
				Ion Exchanges	I	I	I	Available			
				Ex-Channel Debris	I	I	**H**				
				Structure				Fragmentation (≥ pellet)	I	I	L
								Molten fuel moderator interaction	I	I	**H**
								Relocation	I	I	L
				Volume				Criticality	I	I	I
Emergency Cooling	I	I	I								

[12] Most subsystems are treated as separate systems

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
Injection (ECI)											
				Nitrogen Charging System	I	I	I	Available			
				Injection Water Storage Tank	I	I	I	Available			
				H_2O Injection Valve	I	I	I	Available			
				ECI Piping	I	I	I	Available			
				Large Header Interconnect	I	I	I	Available			
				Rupture Disc	I	I	I	Available			
				Floating Ball Seal	I	I	I	Available			
Long Term Cooling (LTC)	I	I	I								
				Sump	I	I	I	Available			
				Debris Screen	I	I	I	Available			
				Recovery Pump and Piping	I	I	I	Available			
				Heat Exchanger	I	I	I	Available			
				LTC Valves	I	I	I	Available			
Reserve Water System (RWS)	I	I	I								
				Reserve Water Tank	I	I	I	Available			
				Reserve Water Piping	I	I	I	Available			
				Reserve Water Valve	I	I	I	Available			
Electrical Supply	I	I	I								
				Class IV Power Supply	I	I	I	Available			
				Class III Power Supply	I	I	I	Available			
				Class II Power Supply	These components are assumed to be available with a very high reliability						
				Class I Power Supply							
Reactor Regulating System (RRS)	I	I	I								
				Zonal Control Rod	I	I	I	Available			
				Mechanical Control Absorber (MCA)	I	I	I	Available			
Heat Transport System (HTS)	I	M	M								
				Inlet Header	I	I	I	Available			
				Outlet Header	I	M	M				
				Structure				Stored energy release	I	I	I

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
				Volume				Flashing	I	I	L
								Condensation (inter-phase)	I	I	I
								Water hammer - condensation induced	I	I	I
								Oscillations	I	I	I
								Flow regime	I	I	I
								Entrainment	I	I	I
								De-entrainment	I	I	I
								Multi-dimensional flow	I	I	L
								Mixing - multiple fluid streams	I	I	I
				Flow Path				Flow - pressure driven	I	M	M
								Flow - gravity driven (draining)	I	I	I
								Distribution (multiple channels)	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	I
								Flow reversal	I	M	I
				Feeder	I	M	M				
				Structure				Stored energy release	I	I	I
				Volume				Flashing	I	I	L
								Condensation (inter-phase)	I	I	I
								Water hammer - condensation induced	I	I	I
								Oscillations	I	I	I
								Flow regime	I	I	I
				Flow Path				Flow - pressure driven	I	M	M
								Flow - gravity driven (draining)	I	I	I
								Pressure drop (1-phase, 2-phase)	I	M	M
								Flow reversal	I	M	I
								Flow – counter current	I	I	I
				Permanent Header Interconnect	I	I	I	Available			
				SG Inlet Piping/Plenum	I	I	I				
				Structure				Stored energy release	I	I	I
				Volume				Flashing	I	I	I
								Reflux condensation	I	I	I

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
								Flow regime	I	I	I
								Multi-dimensional flow	I	I	I
								Entrainment	I	I	I
								De-entrainment	I	I	I
				Flow Path				Flow – pressure driven	I	I	I
								Flow – gravity driven (draining)	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	I
								Flow reversal	I	I	I
				SG – Primary Side	I	L	L				
				Structure				Stored energy release	I	I	I
								Forced convection to liquid	I	L	L
								Forced convection to vapor	I	I	I
				Volume				Flashing	I	I	I
								Level	I	I	I
								Condensation (inter-phase)	I	I	I
								Reflux condensation	I	I	I
				Flow Path				Flow – pressure driven	I	I	I
								Flow – gravity driven (draining)	I	I	I
								Flow – counter current	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	I
								Flow reversal	I	I	I
				Pump Suction Piping/SG Outlet Plenum	I	I	I				
				Structure				Stored energy release	I	I	I
								Flashing	I	I	I
								Flow regime	I	I	I
								Multi-dimensional flow	I	I	I
								Entrainment	I	I	I
								De-entrainment	I	I	I
				Flow Path				Flow – pressure driven	I	I	I
								Flow – gravity driven (draining)	I	I	I
								Floe – counter current	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	I
								Flow reversal	I	I	I

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	**2**	**3**		**1**	**2**	**3**		**1**	**2**	**3**
				HTS Pump	I	I	I				
				Structure				Stored energy release	I	I	I
				Volume				Flashing	I	I	I
								Pump performance / characteristics	I	I	I
				Flow Path				Pressure drop (1-phase, 2-phase)	I	I	I
				Pump Discharge Piping	I	I	I				
				Structure				Stored energy release	I	I	I
				Volume				Flashing	I	I	I
								Reflux condensation	I	I	I
								Flow regime	I	I	I
								Entrainment	I	I	I
								De-entrainment	I	I	I
				Flow Path				Flow – pressure driven	I	I	I
								Flow – gravity driven (draining)	I	I	I
								Flow – counter current	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	I
								Flow reversal	I	I	I
Fuel Channel (blocked)	**H**	**H**	**H**								
				End Fittings (blocked)	I	L	**H**				
				Structure				Stored energy release	I	I	I
				Volume				Flashing	I	I	L
								Flow regime	I	I	L
								Condensation (inter-phase)	I	I	I
								Entrainment	I	L	L
								De-entrainment	I	I	L
				Flow Path				Flow - pressure driven	I	I	L
								Flow – counter current	I	I	I
								Critical flow	I	I	**H**
								Flow - gravity driven (draining)	I	I	I
								Pressure drop (1-phase, 2-phase)	I	I	L
								Flow reversal	I	I	I
				Pressure Tube (blocked)	**H**	**H**	**H**				
				Structure				Stored energy release	L	L	L
								Convective heat transfer	**H**	**H**	M

System	**Rank by Time Phase**			**Component**	**Rank by Time Phase**			**Process/Phenomenon**	**Rank by Time Phase**		
	1	**2**	**3**		**1**	**2**	**3**		**1**	**2**	**3**
								Conduction	L	**H**	M
								Radiant heat transfer	**H**	**H**	M
								Solid-to-solid (fuel element-to-pressure tube) contact heat transfer	L	M	L
								Melt-to-solid contact heat transfer	I	**H**	M
								Solid-to-solid (debris-to-pressure tube) contact heat transfer	L	M	L
								Recoil (pipe whip)	I	L	L
								Deformation/straining	L	**H**	I
								Melting	I	**H**	I
								Failure	I	**H**	L
				Flow Path: break				Critical flow	I	L	**H**
								Flow - pressure driven	I	I	L
								Break characteristics (shape, location, size)	I	L	**H**
				Gas Annulus (blocked)	I	I	I				
				Flow Path				Flow - pressure driven	I	I	I
				Calandria Tube (blocked)							
				Structure	I	**H**	**H**	Stored energy release	I	I	I
								Convective heat transfer	L	**H**	L
								Conduction	L	**H**	L
								Radiant heat transfer	L	L	L
								Solid-to-solid (calandria tube-to-pressure tube) contact heat transfer	I	M	M
								Melt-to-calandria tube heat transfer	I	**H**	M
								Solid-to-solid (debris-to-calandria tube) contact heat transfer	I	L	L
								Boiling - nucleate	I	L	I
								Post-dryout heat transfer	I	**H**	I
								Jet impingement loading	I	**H**	I
								Ablation/erosion	I	**H**	L
								Deformation (includes failure)	I	**H**	L
				Flow Path: break				Critical flow	I	I	**H**
								Flow - pressure driven	I	I	L

System	Rank by Time Phase 1	2	3	Component	Rank by Time Phase 1	2	3	Process/Phenomenon	Rank by Time Phase 1	2	3
								Break characteristics (shape, location, size)	I	I	**H**
				Bellows (blocked)	I	L	L				
				Flow Path				Change of path/state (open/close)	I	L	L
								Critical flow	I	L	L
								Flow - pressure driven	I	I	I
								Break characteristics (shape, location, size)	I	L	L
Fuel Channel (unaffected)	I	I	**H**								
				End Fittings (unaffected)	I	I	I	Available			
				Pressure Tube (unaffected)	I	I	M				
				Structure				Stored energy release	I	I	I
								Convective heat transfer	I	I	I
								Conduction	I	I	I
								Radiant heat transfer	I	I	I
								Solid-to-solid (fuel element-to-pressure tube) contact heat transfer	I	I	I
								Deformation (includes failure)	I	I	M
				Gas Annulus (unaffected)	I	I	I	Available			
				Calandria Tube (unaffected)	I	I	**H**				
				Structure				Stored energy release	I	I	I
								Convective heat transfer	I	I	I
								Pressure forming	I	I	**H**
								Solid-solid calandria tube-to-pressure tube) contact heat transfer	I	I	I
								Jet impingement loading	I	I	**H**
								Ablation/erosion	I	I	**H**
								Impact loading	I	I	**H**
								Boiling - nucleate	I	I	I
				Bellows (unaffected)	I	I	I	Available			
Fuel Bundle[13] (blocked)	**H**	**H**	M								

13 Captures the phenomenological aspects of CANLUB, Fuel Pellet, Fuel Sheath, End Cap, Bearing Pad, Spacer Pad, Filling Gas, CHF Enhancers

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	**2**	**3**		**1**	**2**	**3**		**1**	**2**	**3**
				Fuel Element (blocked)	**H**	**H**	M				
				Structure				Stored energy release	I	I	L
								Conduction	**H**	**H**	M
								Radiant heat transfer	L	**H**	M
								Gap conductance	**H**	M	L
								Forced convection to liquid	**H**	L	L
								Boiling - nucleate	**H**	L	M
								Post-dryout heat transfer	**H**	**H**	M
								Rewet	L	L	M
								Critical Heat Flux (CHF)	**H**	L	L
								Oxidation	M	**H**	M
								UO_2/Zircaloy interaction (alloying)	L	M	L
								UO_2 dissolution by molten Zircaloy	L	**H**	L
								Embrittlement	L	L	L
								Deformation - ballooning	L	M	L
								Failure	L	L	L
								Bundle slumping	L	**H**	L
								Melting	L	**H**	L
								Relocation	L	**H**	L
								Fragmentation	I	I	I
								Decay heating	L	L	L
								Fission heating	**H**	**H**	M
								Reactivity - fuel temperature change	M	M	L
								Reactivity - coolant temperature change	L	L	I
								Reactivity - density/void	L	L	I
								Swelling - fuel	L	M	L
								Radial power distribution	M	**H**	M
								Axial power distribution	**H**	**H**	M
								End power peaking	**H**	**H**	L
				Volume				Flow regime	**H**	M	L
								Void generation from heat transfer	I	I	**H**
								Entrainment	L	L	L
								De-entrainment	L	L	L

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
								Flashing	I	L	M
								Hydrodynamic loading	I	L	L
								Swelling – level	M	L	I
								Multi-dimensional flow	L	L	I
				Flow Path				Flow - pressure driven	**H**	M	M
								Pressure drop (1-phase, 2-phase)	L	L	L
				End Plate (blocked)	M	M	L				
				Structure				Deformation	M	L	L
								Melting	M	M	L
								Oxidation	L	L	L
Reactor Protection System	I	I	I								
				Flux Detectors	I	I	I	Available			
Shutdown System (SDS)	I	I	L								
				SDS1 (shut off rods)	I	I	L				
								Reactivity effect of firing SDS1	I	I	L
				SDS2 (poison injection)	I	I	L				
								Reactivity effect of firing SDS2	I	L	L
Pressure and Inventory Control System (P&IC)	I	I	I								
				Liquid Relief Valve (LRV)	I	I	I	Available			
				Feed and Bleed System	I	I	I	Available			
Secondary and Feedwater System	I	I	I								
				SG – Secondary Side	I	I	I	Available			
				Main Steam Line/Header	I	I	I	Available			
				Stop Valve	I	I	I	Available			
				Turbine	I	I	I	Available			
				Steam Reheater	I	I	I	Available			
				Condenser	I	I	I	Available			
				SG Feedwater	I	I	I	Available			
				Main Steam Safety Valve (MSSV)	I	I	I	Available			
				Main Steam Isolation Valve (MSIV)	I	I	I	Available			

System	Rank by Time Phase			Component	Rank by Time Phase			Process/Phenomenon	Rank by Time Phase		
	1	2	3		1	2	3		1	2	3
				Atmospheric Steam Discharge Valve (ASDV)	I	I	I	Available			
				Condenser Steam Dump Valve (CSDV)	I	I	I	Available			
Containment System											
				Containment	I	I	I	Available			
				Local Air Coolers	I	I	I	Available			

Table 7
Summary of High Importance-Ranked Systems, Components and Phenomena

System	Component	Process / Phenomenon
Channel Geometry Maintained (0 – 8 s)		
Fuel Channel (blocked)	Pressure Tube (blocked)	Convective heat transfer Radiant heat transfer
Fuel Bundle (blocked)	Fuel Element (blocked)	Conduction Gap conductance Forced convection to liquid Boiling – nucleate Post-dryout heat transfer Critical Heat Flux (CHF) Fission heating Axial power distribution End power peaking Flow regime Flow – pressure driven
Channel Geometry Deforming (8 s – 10 s)		
Fuel Channel (blocked)	Pressure Tube (blocked)	Convective heat transfer Conduction Radiant heat transfer Melt-to-solid contact heat transfer Deformation / straining Melting Failure
	Calandria Tube (blocked)	Convective heat transfer Conduction Melt-to-calandria tube heat transfer Post-dryout heat transfer Jet impingement loading Ablation / erosion Deformation (includes failure)

System	Component	Process / Phenomenon
Fuel Bundle (blocked)	Fuel Element (blocked)	Conduction Radiant heat transfer Post-dryout heat transfer Oxidation UO_2 dissolution by molten Zircaloy Bundle slumping Melting Relocation Fission heating Radial power distribution Axial power distribution End power peaking
Post-Channel Failure (10 s – 150 s)		
Moderator System	Calandria Vessel	Impact loading Deformation
	Moderator Fluid	Void generation from heat transfer Condensation (inter-phase) Pressure change
	Ex-Channel Debris	Molten fuel moderator interaction
Fuel Channel (blocked)	End Fittings (blocked)	Critical flow
	Pressure Tube (blocked)	Critical flow (at break) Break characteristics
	Calandria Tube (blocked)	Critical flow (at break) Break characteristics
Fuel Channel (unaffected)	Calandria Tube (unaffected)	Pressure forming Jet impingement loading Ablation / erosion Impact loading
Fuel Bundle (blocked)	Fuel Element (blocked)	Void generation from heat transfer

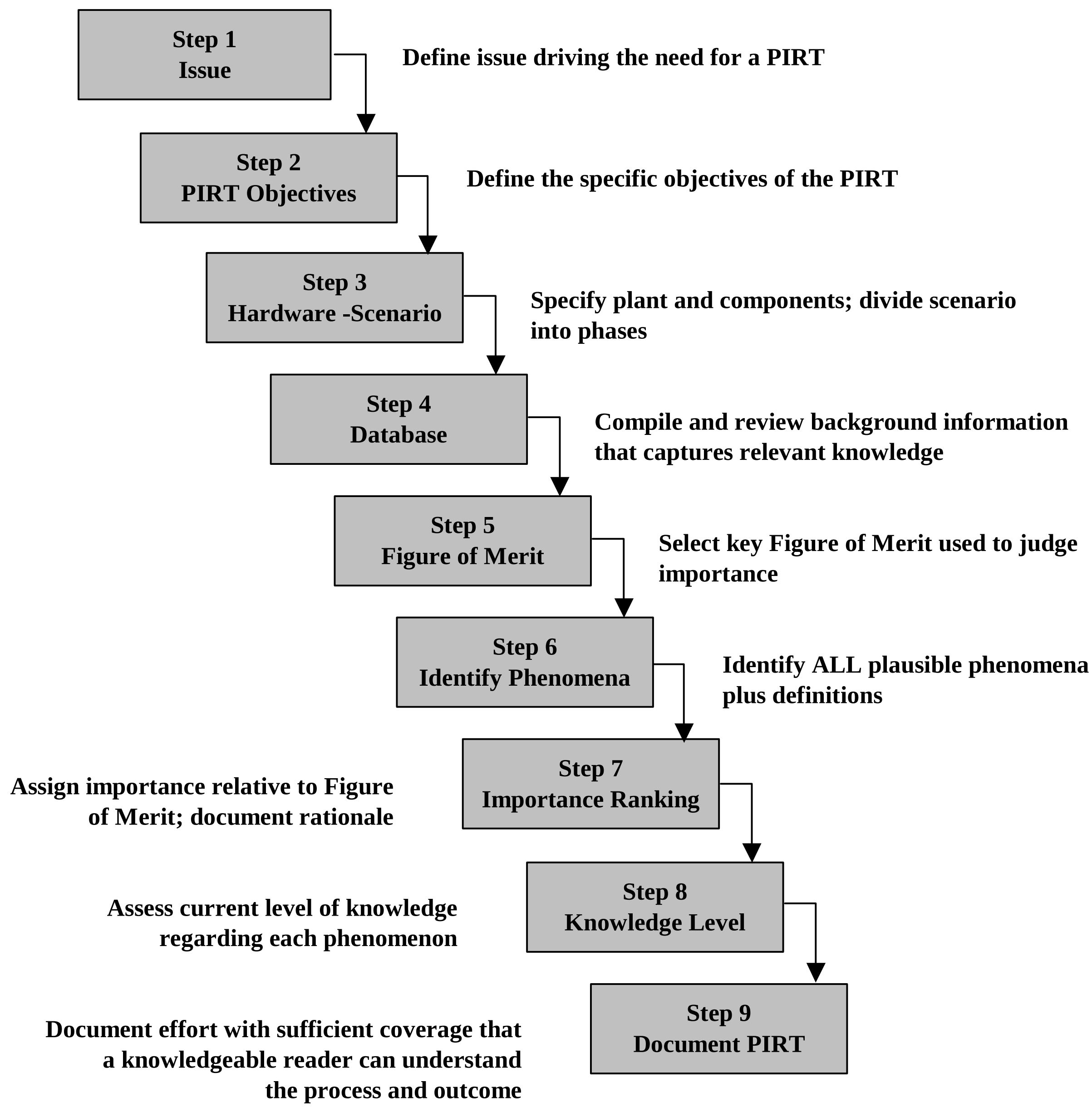

Figure 1 General PIRT Process

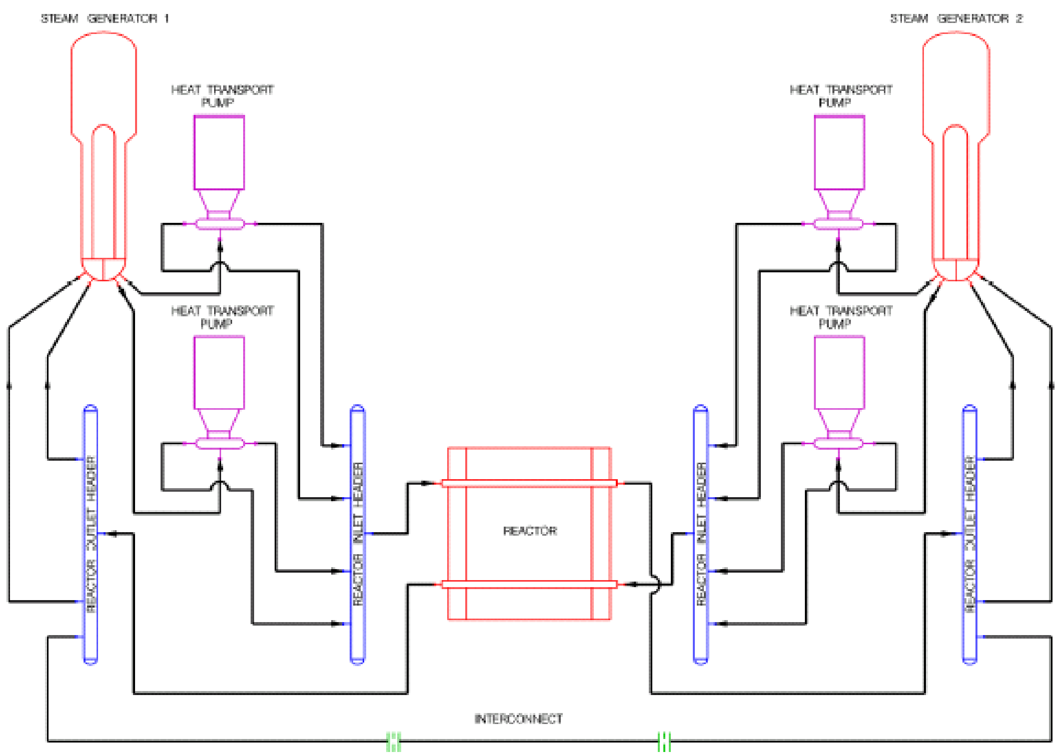

Figure 2 ACR-700 Simplified Heat Transport Circuit Schematic

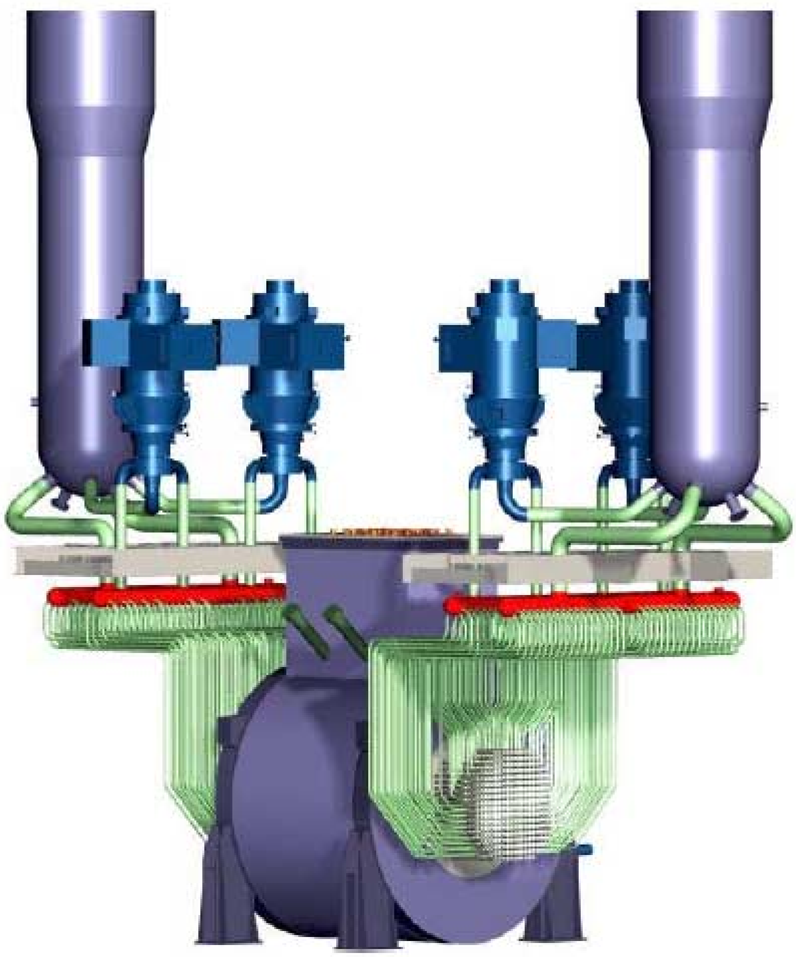

Figure 3 ACR-700 Heat Transport System Layout

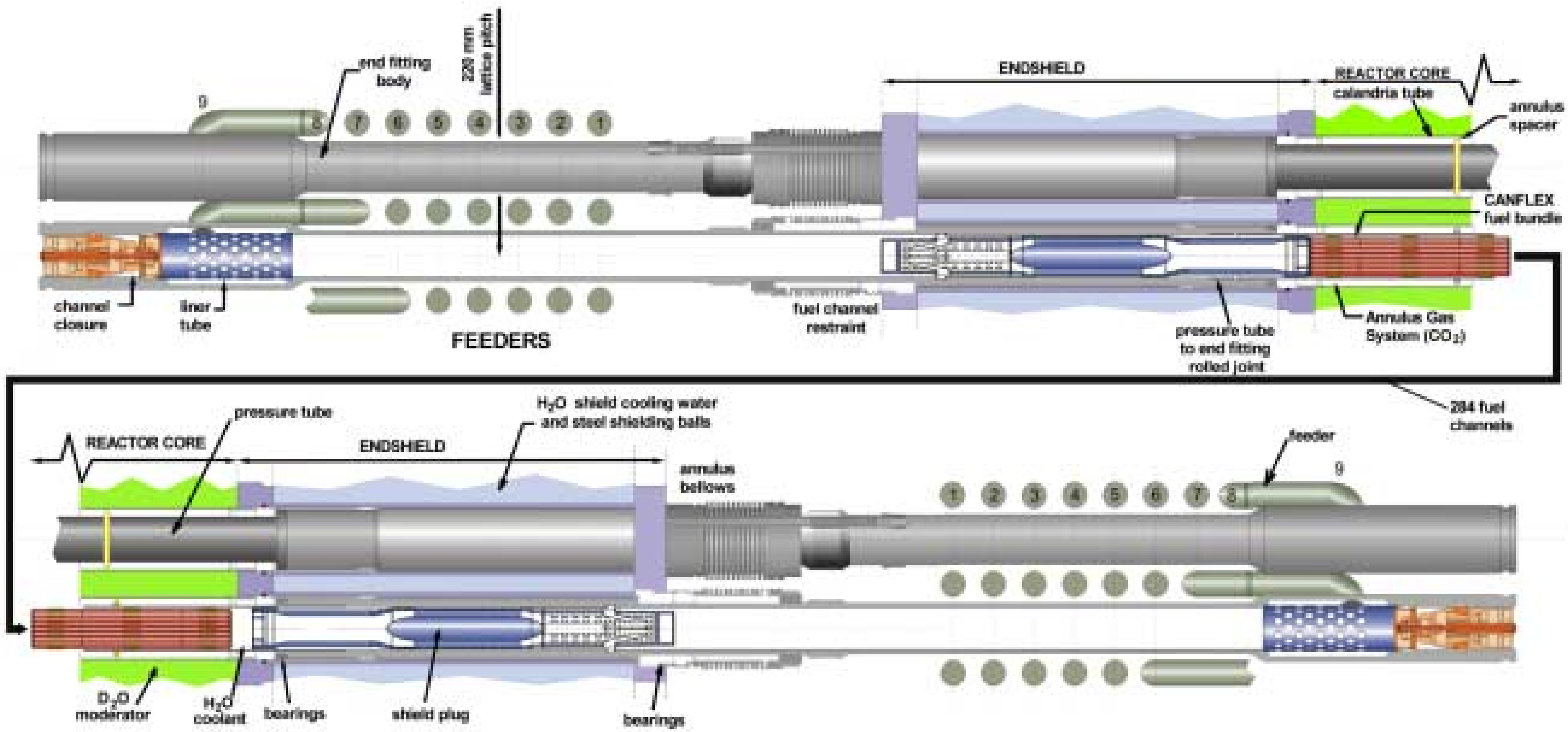

Figure 4 Fuel Channel Assembly

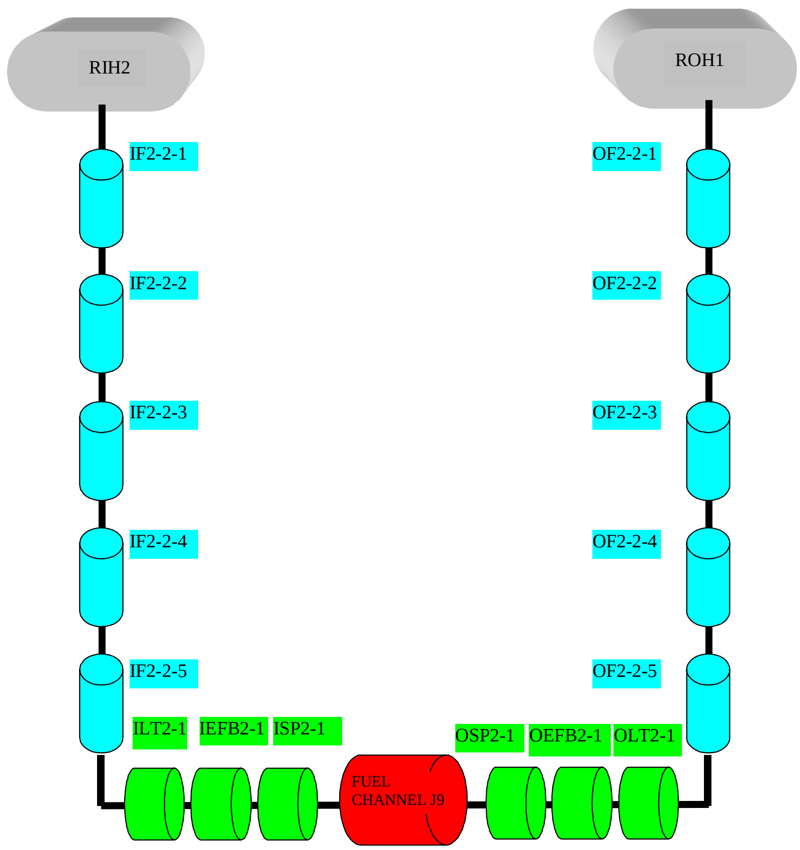

Figure 5 ACR-700 Single Channel Nodalization Diagram

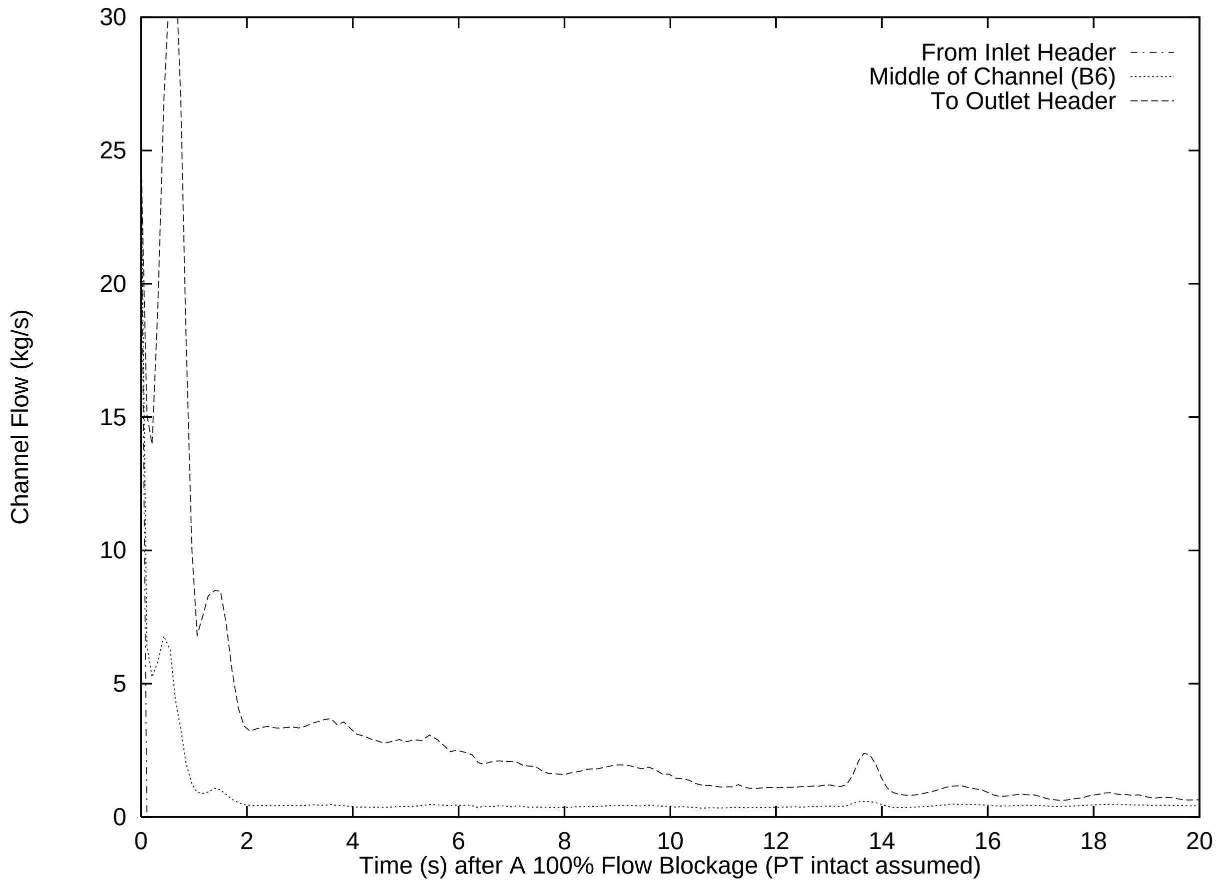

Figure 6 Channel Flow (PT intact)

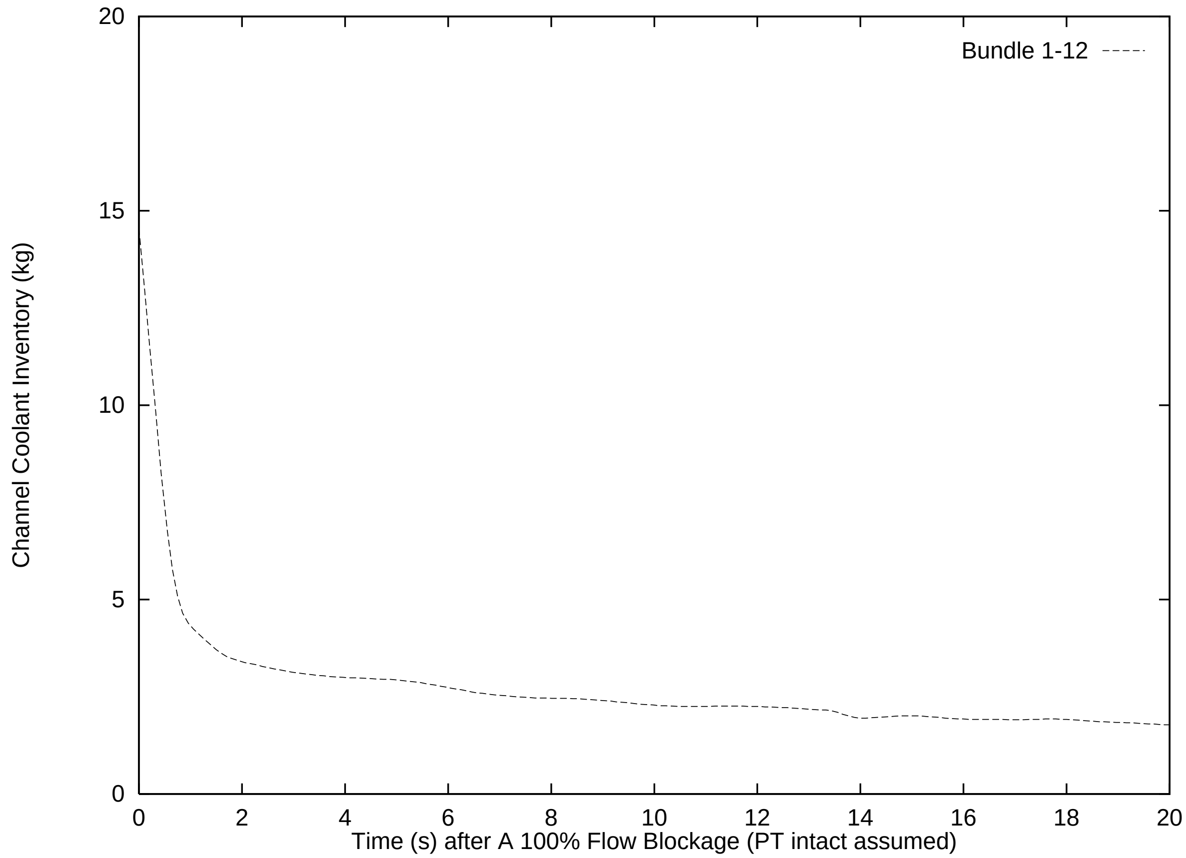

Figure 7 Channel Inventory (PT intact)

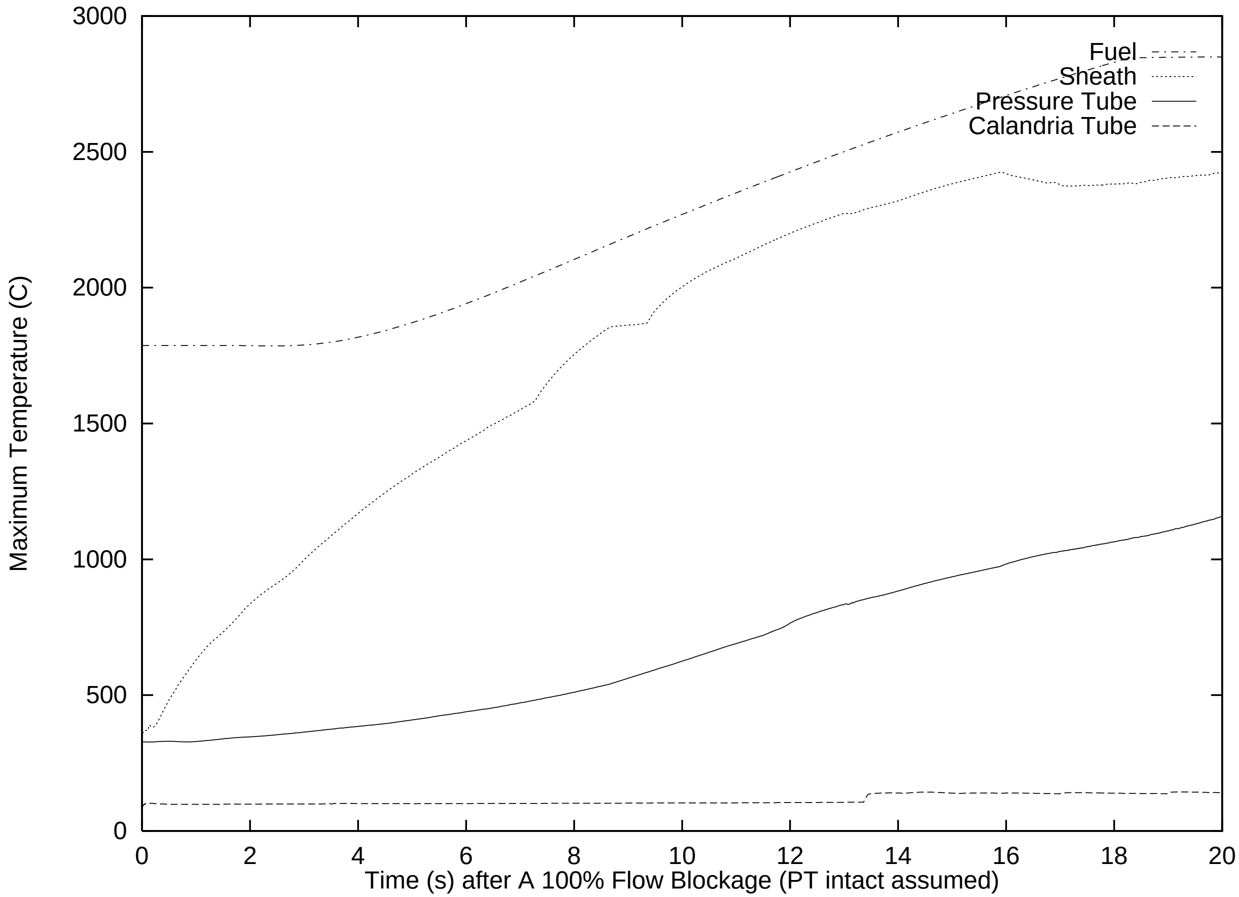

Figure 8 Channel Temperatures (PT intact)

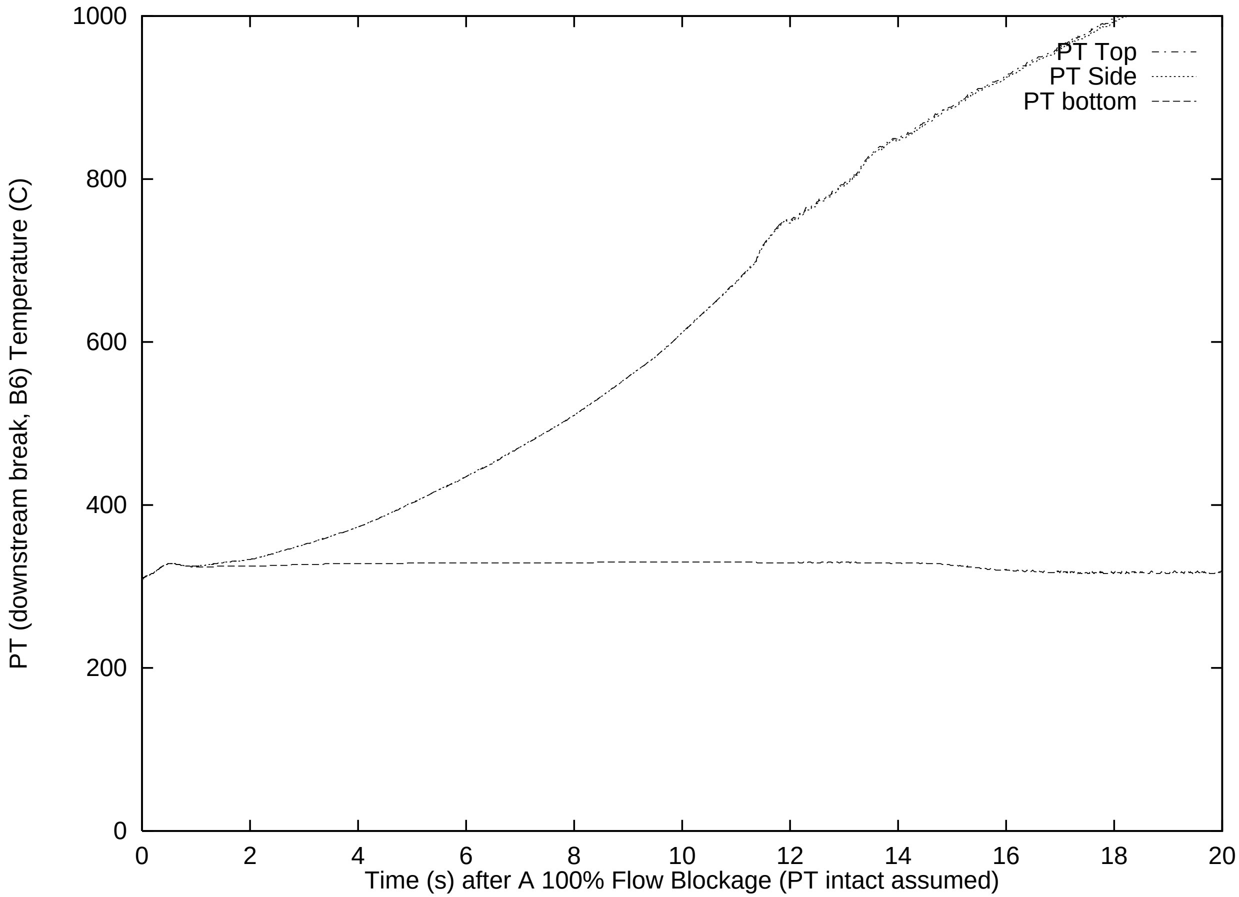

Figure 9 Non-uniform Pressure Tube Temperature around PT Circumference (PT Intact)

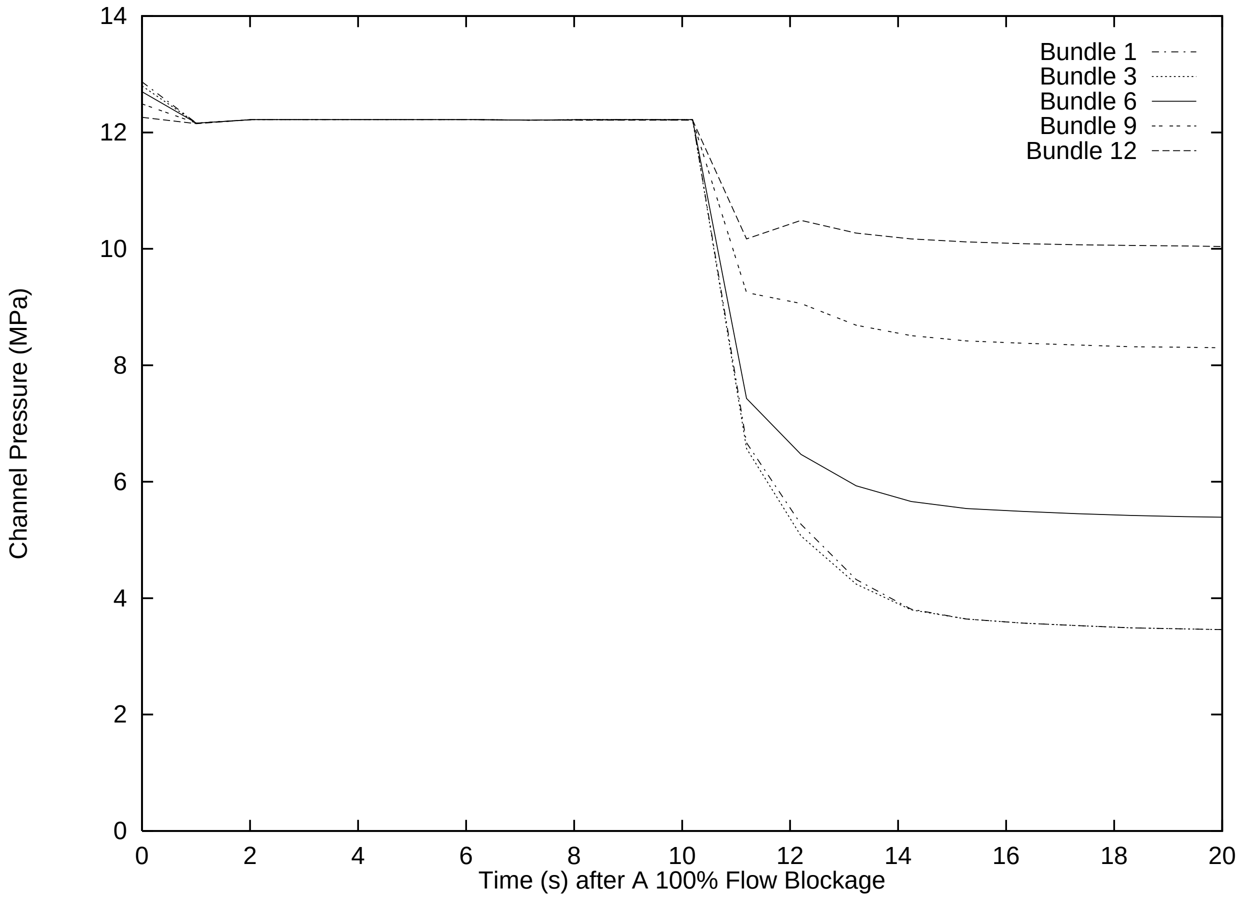

Figure 10 Channel Pressure at Typical Bundle Locations (PT Failed)

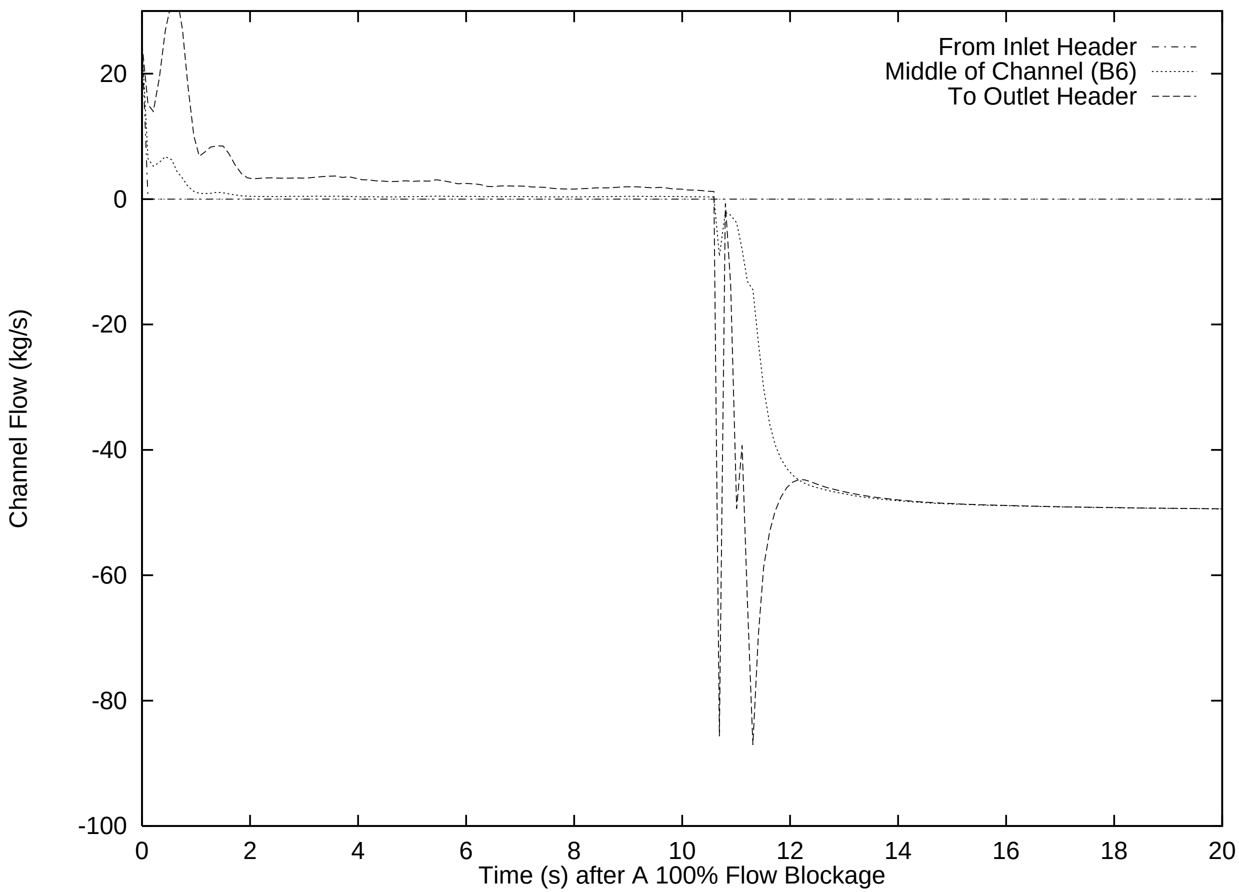

Figure 11 Channel Flow (PT Failed)

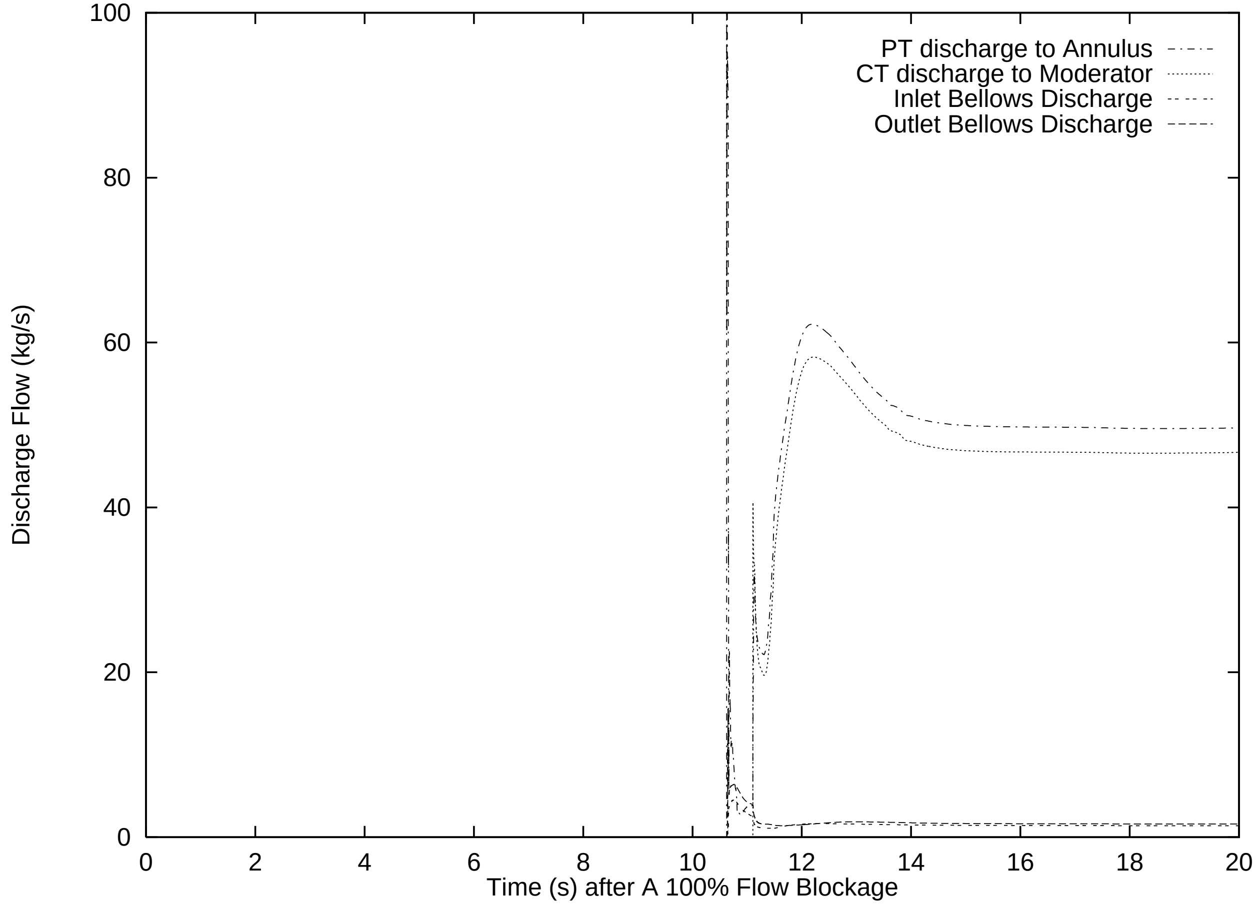

Figure 12 Break Discharge (PT/CT Failed)

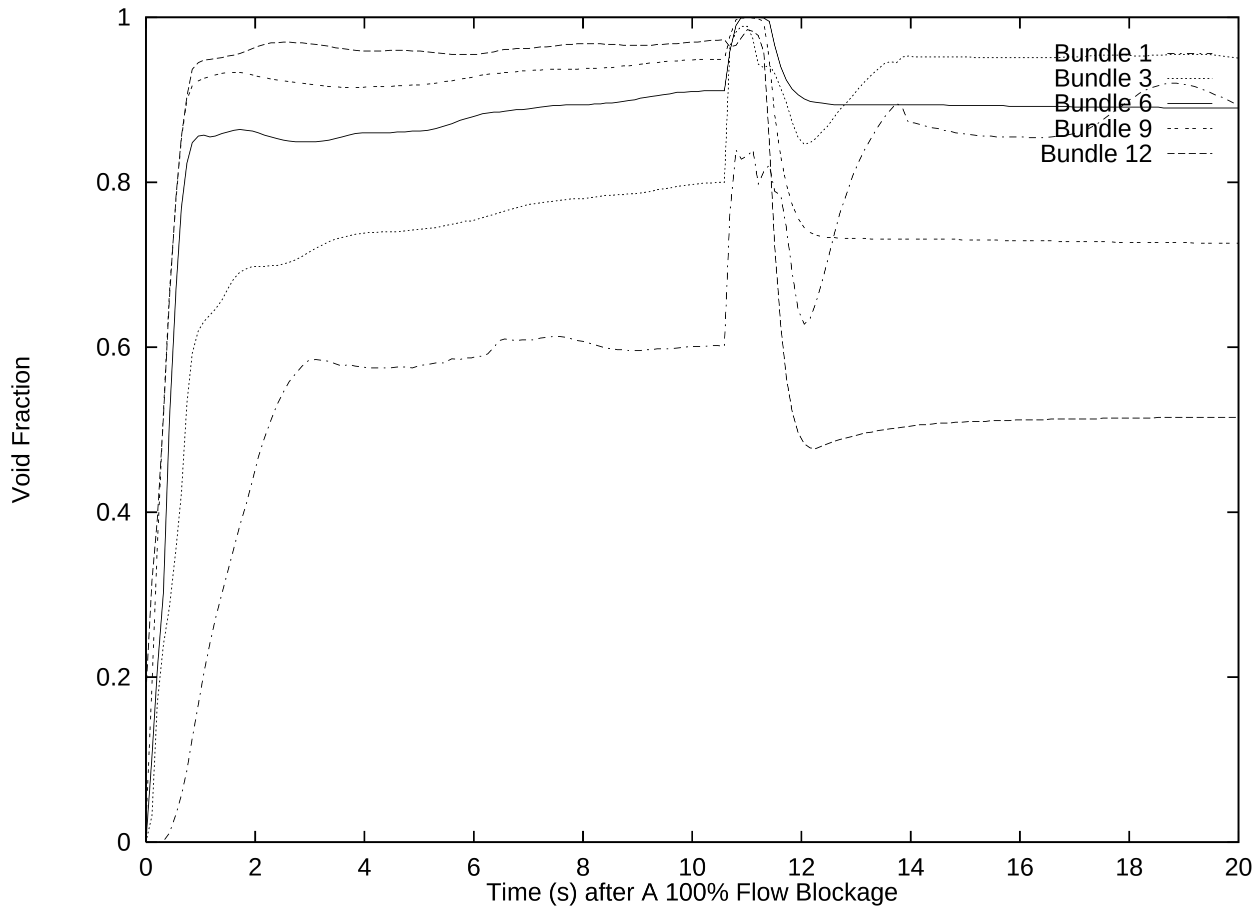

Figure 13 Channel Void Formation (PT/CT Failed)

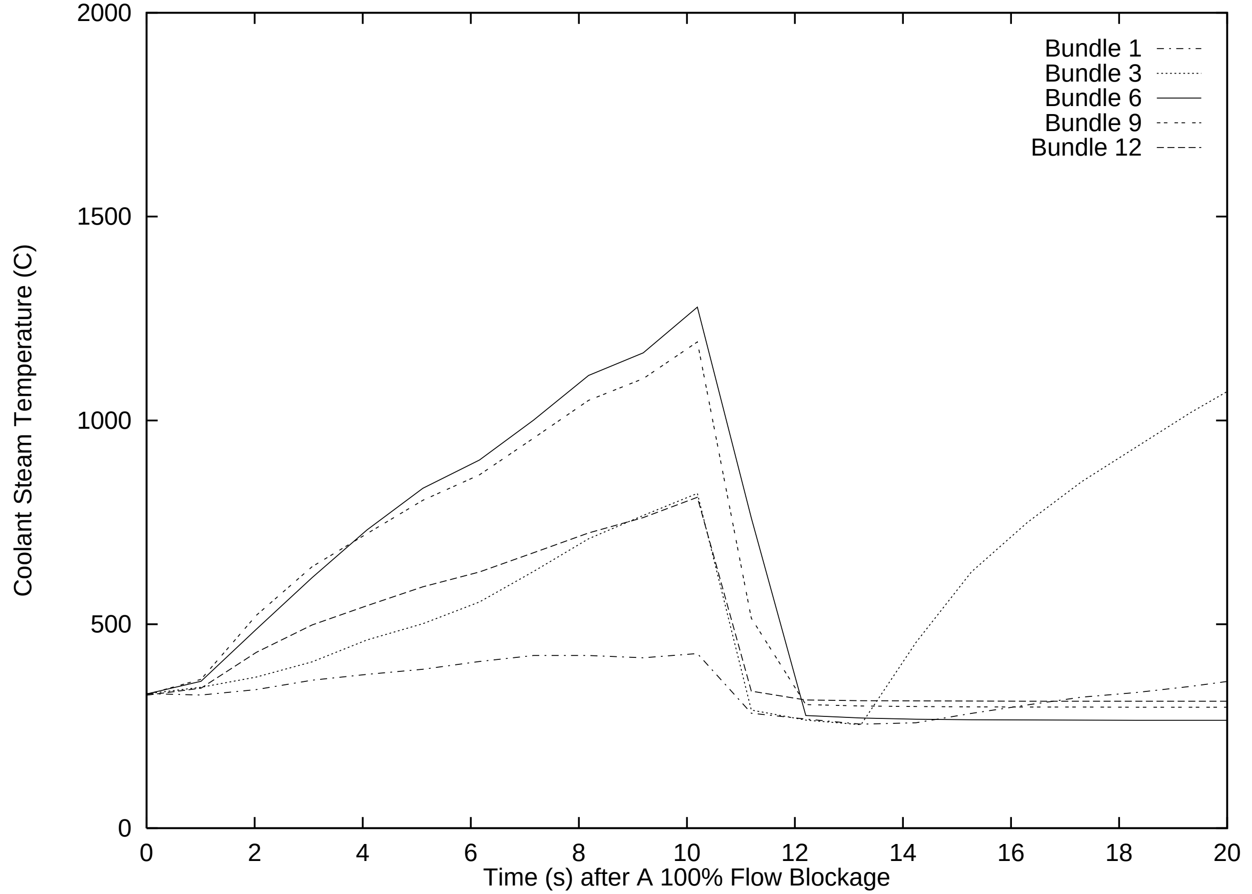

Figure 14 Channel Steam Temperature (PT/CT Failed)

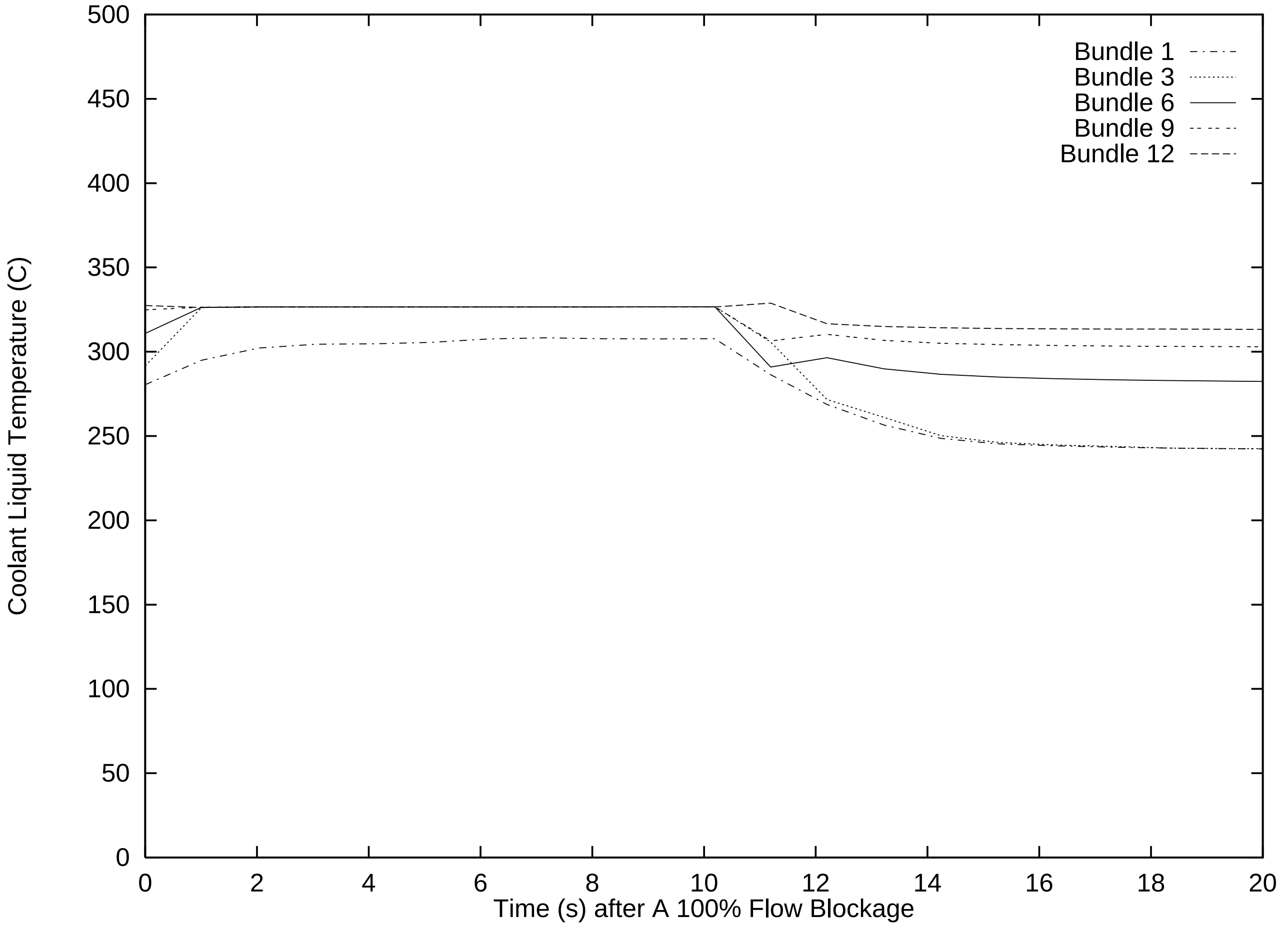

Figure 15 Channel Liquid Temperature (PT/CT Failed)

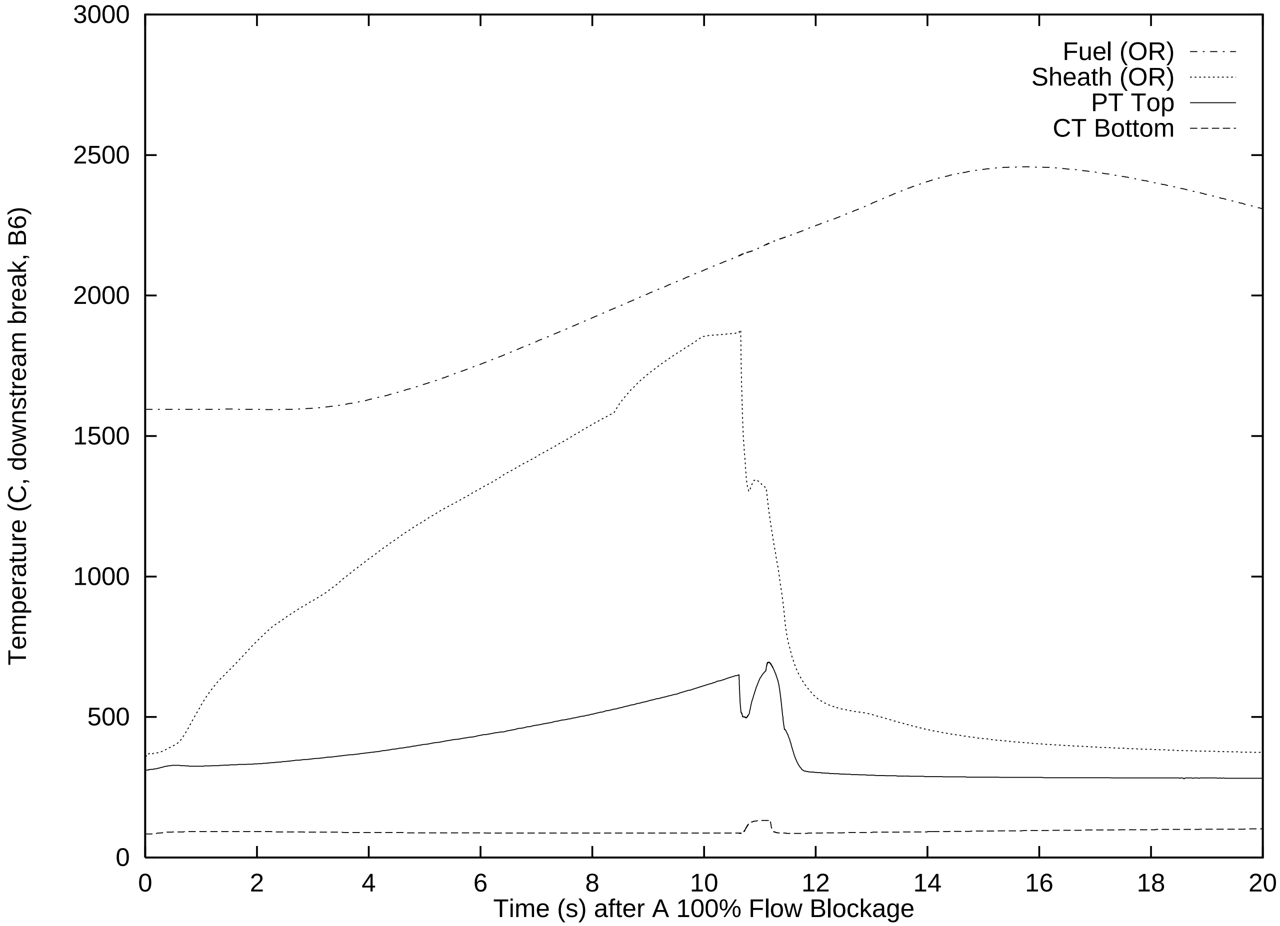

Figure 16 Channel Temperatures Downstream of Break (PT/CT Failed)

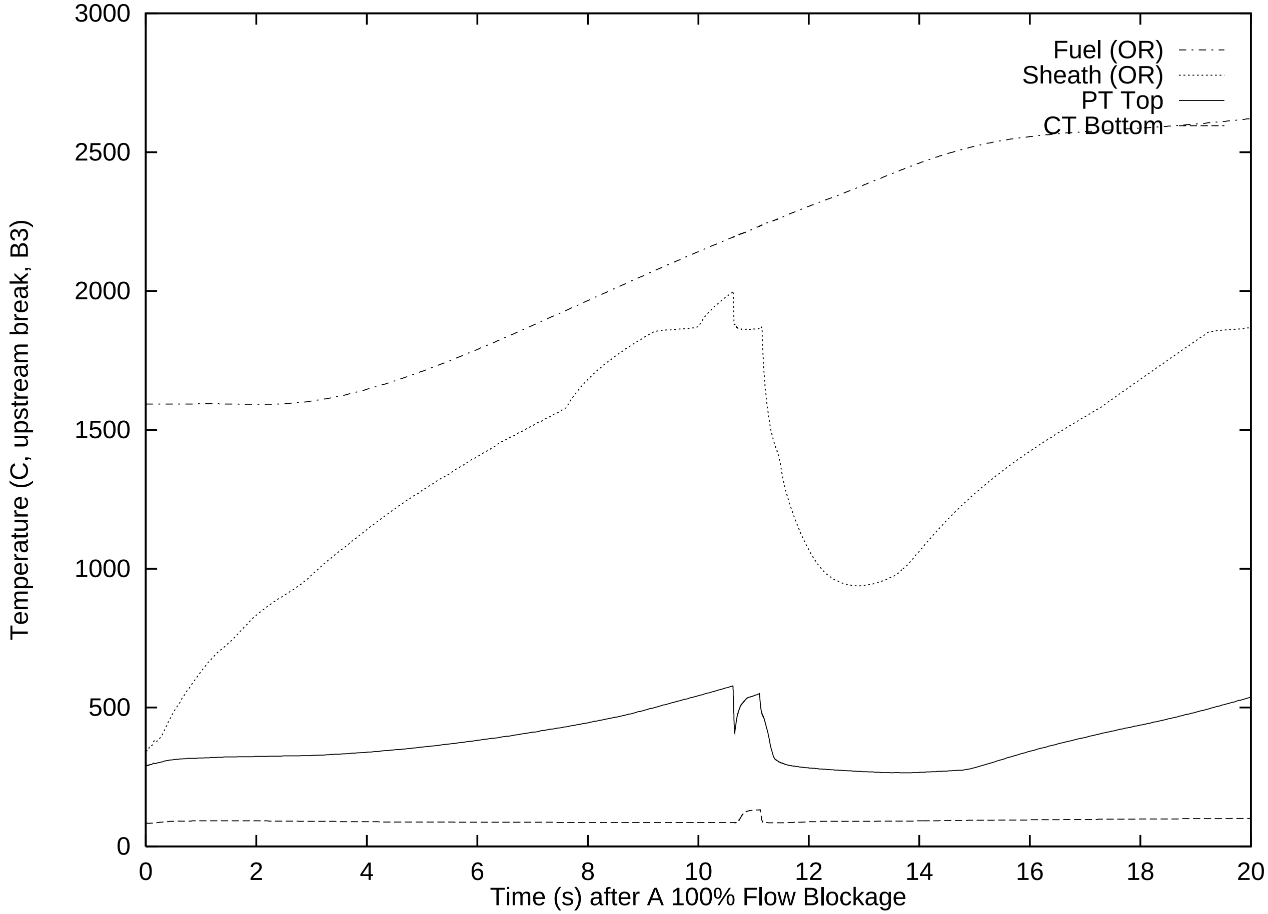

Figure 17 Channel Temperatures Upstream of Break (PT/CT Failed)

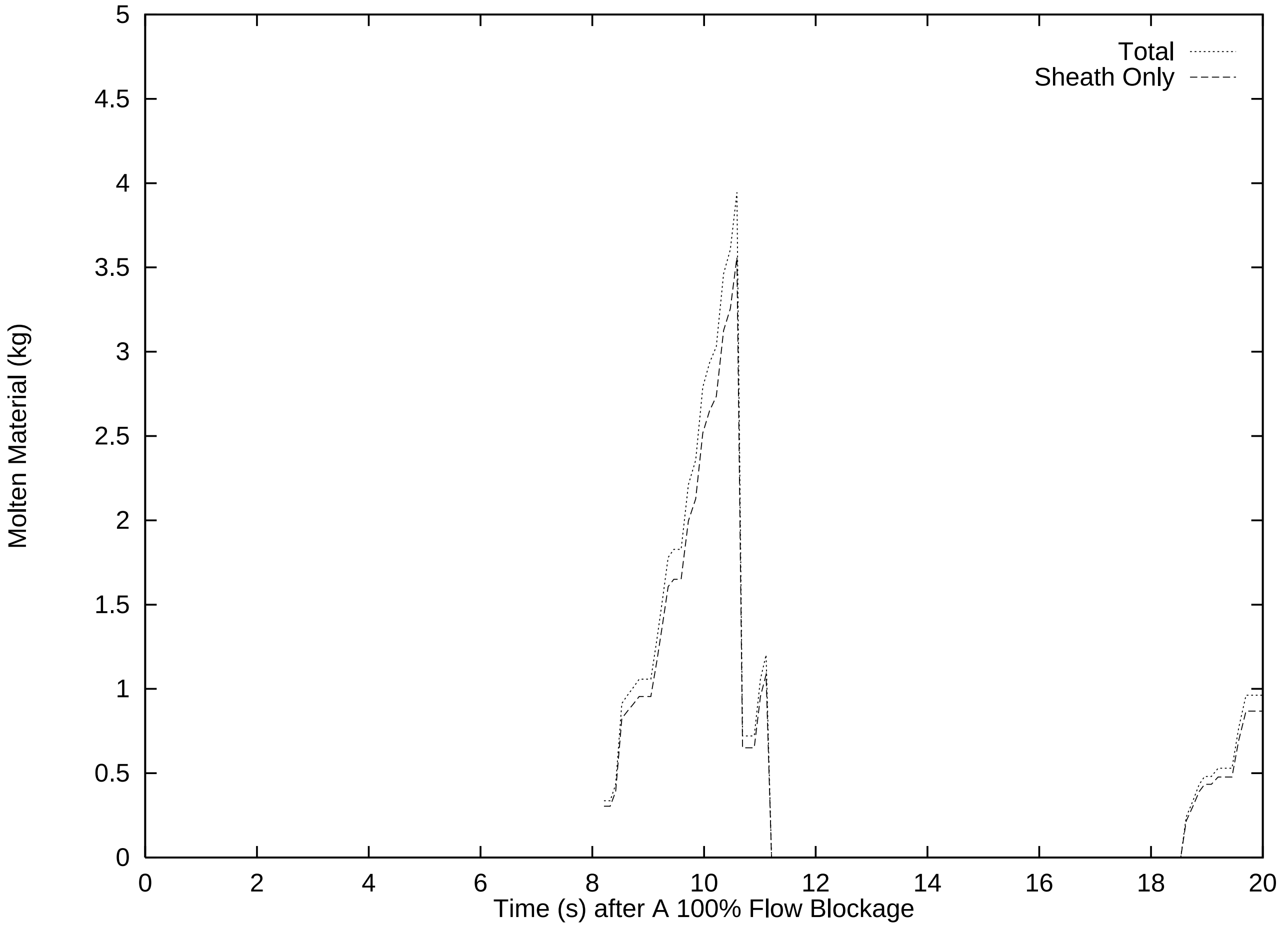

Figure 18 Molten Material Formation

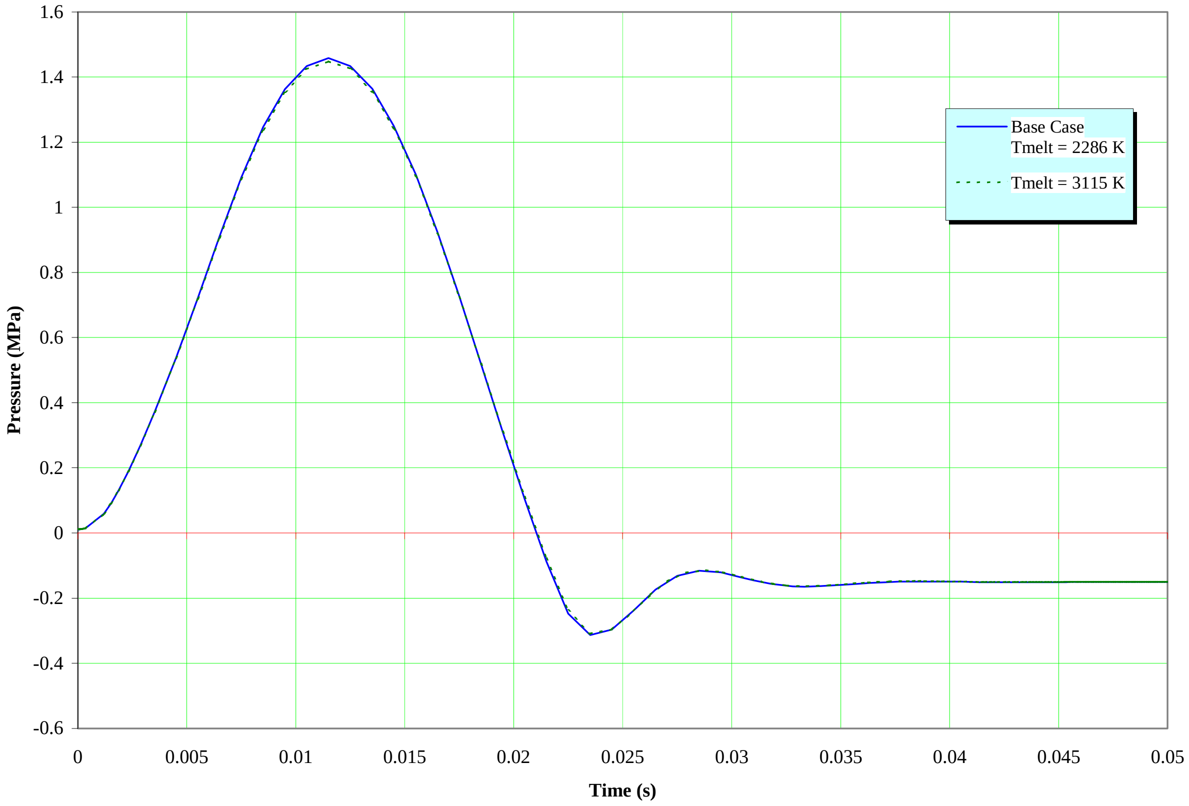

Figure 19 Pressure Across the Calandria Vessel Wall Following Channel Failure

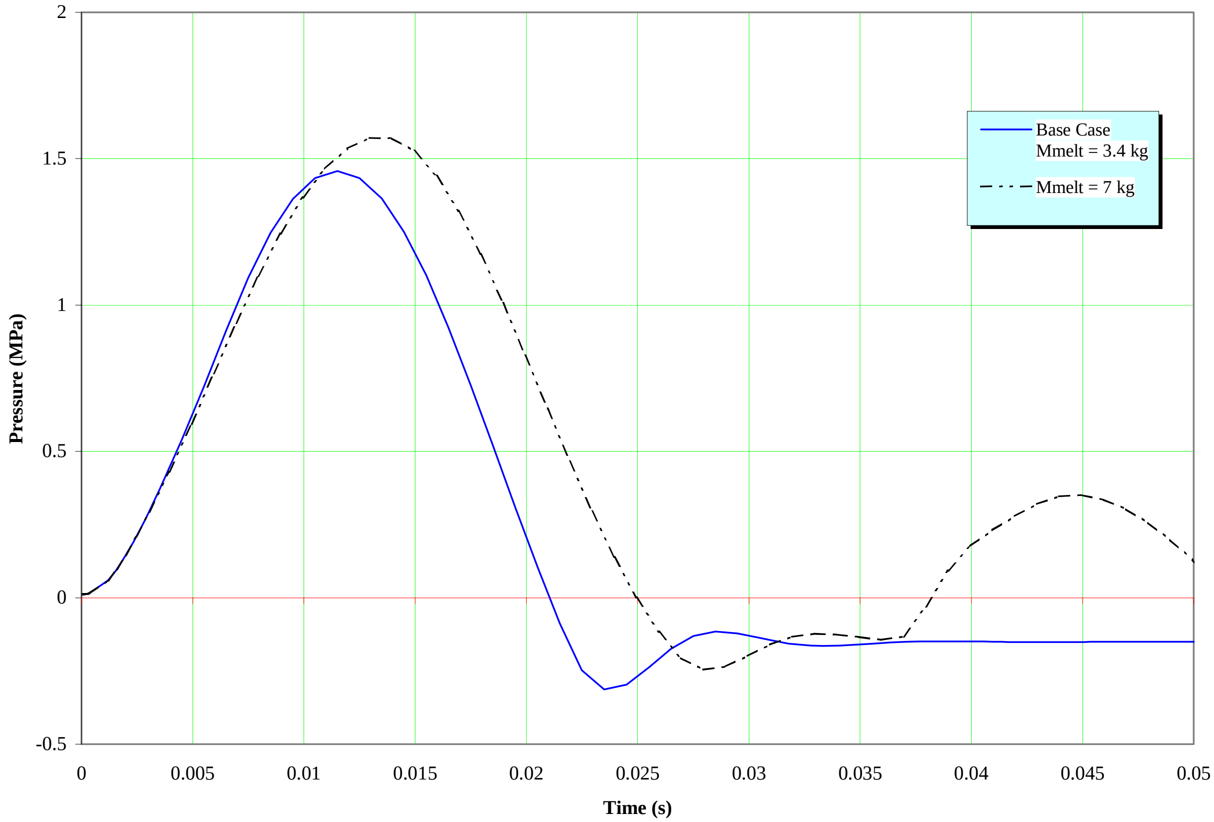

Figure 20 Pressure Across the Calandria Vessel Wall Following Fuel Channel Rupture

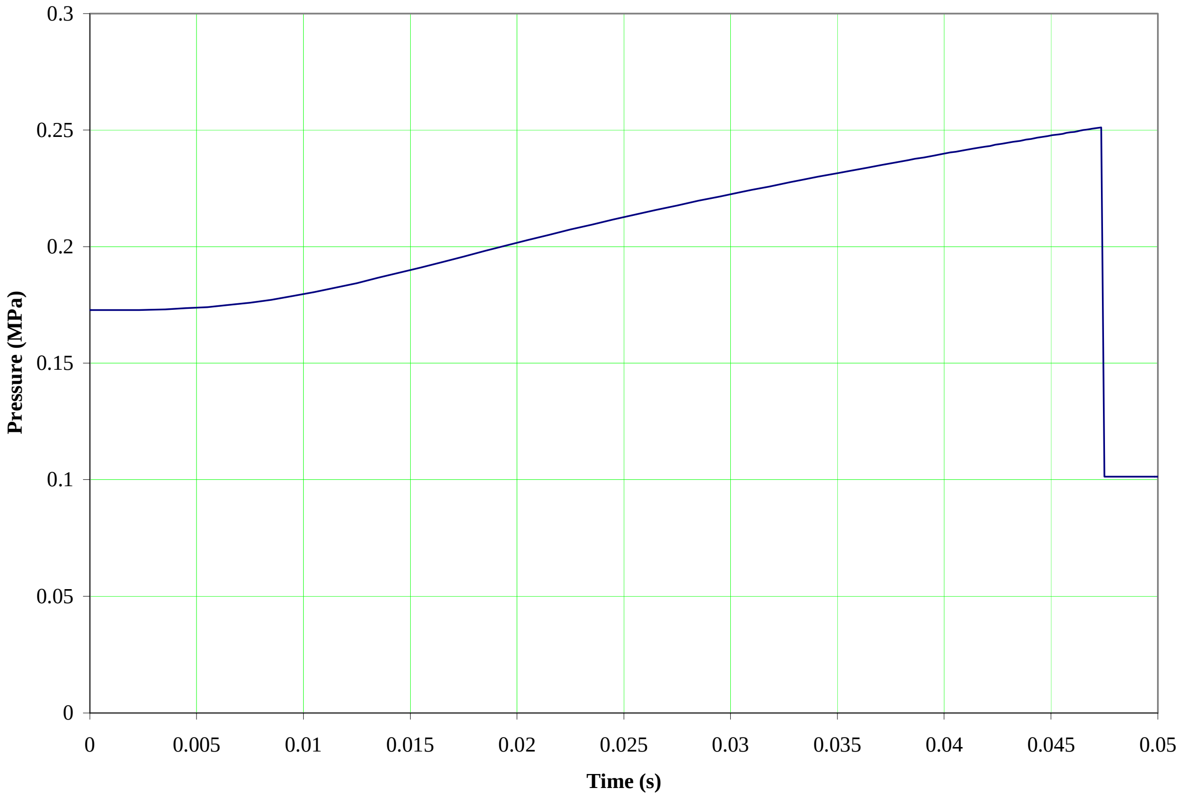

Figure 21 Moderator Cover Gas Pressure Following Fuel Channel Failure

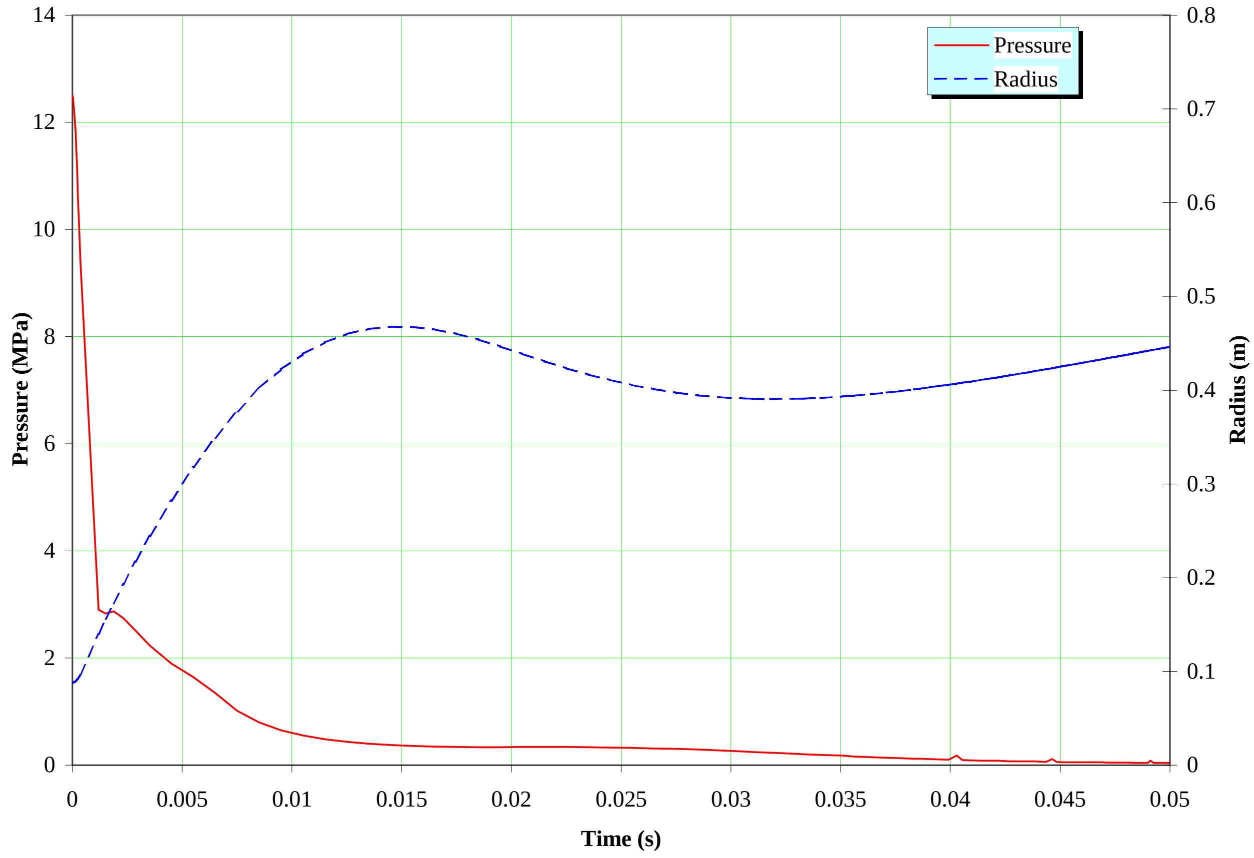

Figure 22 Steam Bubble Conditions Following Channel Failure

Appendix A

Phenomenon Definitions

The phenomenon definitions used in this Phenomena Identification and Ranking Table (PIRT) activity are shown in the following table.

PIRT Term	Definition
Ablation/erosion	Erosion of a component by molten material.
Availability	The component functions as per design.
Axial power distribution	Variation in nuclear power generation along the length of a fuel channel.
Boiling – film	A boiling regime in which vapor blankets all or an appreciable portion of the heating surface.
Boiling – nucleate	A boiling regime in which bubble formation is at the liquid-solid interface that results in slow surface temperature increases for a relatively large increase in surface heat flux.
Boiling – subcooled	A boiling regime beginning with the onset of nucleate boiling and continuing to the onset of saturated boiling. The boundary between the latter two regimes occurring when the bulk liquid temperature approaches saturation at the given pressure.
Boiling – transition	A boiling regime that spans the boiling surface between critical heat flux and minimum film boiling (i.e., Liedenfrost point).
Break characteristics	The size, location and shape of a break in a component.
Break orientation	The azimuthal orientation of the break.
Bundle slumping	Deformation of CANDU fuel bundles due to gravitational forces.
Change in path/state (open/close)	The flow path within the component is opened or closed during the phase.
Coastdown/rundown	The reduction in time of pressure driven flow following pump trip.
Condensation – fluid-to-surface	The process whereby steam is cooled due to contact with a colder surface, resulting in a change of phase from vapor to liquid at the surface.
Condensation – inter-phase	The process whereby steam is cooled due to contact with a colder liquid, resulting in a change of phase from vapor to liquid at the interface between the two phases.
Conduction	Heat conduction is the process by which heat flows from a region of higher temperature to a region of lower temperature within a medium or between different mediums in direct physical contact.

PIRT Term	Definition
Constrained axial expansion	The axial compression of the fuel string when the fuel string axial deformation exceeds the sum of the axial thermal expansion of the pressure tube and the residual fuel string-to-shield plug axial gap.
Contact heat transfer – bearing pad-to-pressure tube	Heat transfer from a bearing pad to its pressure tube. It is a combination of conduction, convection and radiant heat transfer, all of which are lumped together for an effective heat transfer.
Contact heat transfer – fuel element-to-pressure tube	Heat transfer from a fuel element to its pressure tube. It is a combination of conduction, convection and radiant heat transfer, all of which are lumped together for an effective heat transfer.
Contact heat transfer – debris-to-calandria tube	Heat transfer from debris to a calandria tube. It is a combination of conduction, convection and radiant heat transfer, all of which are lumped together for an effective heat transfer.
Convective heat transfer	The process of energy transport to a fluid be the combined action of heat conduction, energy storage, and mixing motion.
Critical flow	The maximum possible flow through a flow-constricting item of hardware, usually a nozzle, orifice, or break in a pipe.
Critical Heat Flux (CHF)	The maximum heat flux that defines the boundary between nucleate and transition boiling regimes. It is also known as dryout, burnout or boiling crisis.
Criticality	The state of a nuclear chain reacting medium when the chain reaction is just self-sustaining (or critical), that is when the reactivity is zero.
Debris generation	The formation of debris by jet impingement on reactor structures and the sweeping of containment debris by water flow.
Debris transport	The movement of debris towards the reactor-building sump by water flows within containment.
Decay heating	The heat from delayed emission of beta and gamma rays.
De-entrainment	The process whereby liquid is mechanically removed by impingement (de-entrained) from a steam flow.
Deformation	A change in a component's geometry while under stress or the movement of one component towards another. For the current application it can apply to pressure-tube deformation, fuel-element deformation or calandria-tube deformation.
Deformation – fuel string relocation	A change in the fuel string/fuel bundle geometry owing to the axial movement and impact of a fuel string by hydraulic forces following a large break in the Heat Transport System.

PIRT Term	Definition
Deformation (includes failure)	Movement of one component towards another. For the current application it applies to pressure-tube deformation (both ballooning and sagging) and, if deformation is significant, failure.
Departure from Nucleate Boiling (DNB)	(see Boiling – transition).
Distribution – multiple channels	Multiple flow paths from the headers.
Embrittlement	A marked reduction in fuel sheath ductility due to oxygen or hydrogen uptake.
End power peaking	The enhanced power at the axial ends of fuel string of pellets in a fuel bundle, due to reduced neutron absorption beyond the fuel string.
Entrainment	The process whereby liquid is captured (entrained) by a high-velocity steam flow.
Failure	The breaching of the fuel sheath.
Fission heating	Heat promptly generated in the fuel by fissions.
Flashing	Void formation without heat addition.
Flow – counter current	The process whereby liquid flows opposite (counter) to the gas flow direction.
Flow – gravity driven	The downward flow of fluid under the influence of gravity.
Flow – gravity driven (draining)	The downward flow of fluid on a surface under the influence of gravity.
Flow – natural circulation	Flow driven by density differences.
Flow – pressure driven	Flow leaving a component under the influence of an upstream forcing function.
Flow – stalled (stagnation)	The stagnation of flow in a fuel channel caused by an inlet header break where the hydraulic losses out the break balance the hydraulic forces in a feeder / fuel channel arrangements, causing the flow to stagnate.
Flow blockage	A severe restriction of flow by debris relocation.
Flow regime	The distribution of phases (liquid/vapor) within a pipe, e.g., bubbly flow, slug, stratified, annular. Also the friction between phases caused by velocity differences at the liquid/liquid interface.
Flow reversal	Change in established flow direction to the reverse direction.

PIRT Term	Definition
Forced convection to liquid	The process of energy transport to a fluid by the combined action of heat conduction, energy storage, and mixing motion, where the fluid is single-phase liquid.
Forced convection to vapor	The process of energy transport to a fluid by the combined action of heat conduction, energy storage, and mixing motion, where the fluid is single-phase vapor.
Fragmentation	The breakup of a fuel element due to large internal or external forces.
Impact loading	The transfer of kinetic energy from a projectile onto a structure.
Gap conductance	The overall thermal resistance to the flow of heat between two opposing surfaces.
Jet impingement (debris generation)	The creation of debris from the impact of the discharge flow from the break on nearby structure.
Level	The vertical height of a column of single or two-phase fluid.
Level – swelling	The increase in the level of a lower (primarily) liquid region due to vapor generation.
Mechanical interaction	The physical interaction between two contacting surfaces.
Melting	The change in state of a material from a solid to a liquid.
Mixing – multiple fluid streams	The combining of two or more fluid streams into a single stream.
Molten Fuel Moderator Interaction	Energy transferred from molten material to the moderator. This includes the pressure pulses generated from the rapid generation of steam as the melt transfers its stored energy to the moderator water.
Multi-dimensional flow	Flow with two or more dominant velocity vectors.
Non-condensable gas generation	The impact of the presence of non-condensable gases upon heat transfer or any other phenomenon such as flow, condensation, flashing, and vapor volume expansion.
Oscillations	The periodic variation of any given hydraulic characteristic between two values.
Oxidation	A chemical reaction that increases the oxidation content of a material. Of specific interest is cladding oxidation, which occurs at elevated temperatures, which can occur only under accident conditions.
Post-dryout heat transfer	Wall-to-coolant heat transfer where the heated wall is no longer covered by liquid in a sustainable way when the heat flux through the wall exceeds CHF. Post-dryout (PDO) heat transfer includes transition boiling and film boiling. (see also Boiling – transition and Boiling –film)
Pipe thrust	The reaction force to the break discharge flow.

PIRT Term	Definition
Pressure	The force (per unit area) applied by a fluid on its surroundings.
Pressure drop (1-phase, 2-phase)	The reduction in pressure with distance
Pressure forming	The deformation of a component or material by an applied pressure.
Pressure loading	Hydrodynamic forces applied to a structure due to a pressure gradient through a fluid.
Pump performance / characteristics	The behavior of a pump under all normal and off-normal conditions.
Radial power distribution	Decrease in power density in the fuel due to decrease of neutron flux in the fuel bundle interior.
Radiant heat transfer	The transfer of energy from a higher temperature body to a lower temperature body without relying on the intervening medium, i.e., the transfer can take place in a vacuum.
Reactivity – coolant temperature change	The change in core reactivity due to the effect of change in coolant temperature on coolant density and neutron spectrum.
Reactivity – density / void	The change in core reactivity due to an increase or decrease in the amount of void in the cooling fluid.
Reactivity – device movement	The change in core reactivity due to the firing of either shutdown system, movement of mechanical control absorbers, or movement of zonal control rods.
Reactivity – fuel string relocation	A change in core reactivity due to fuel string relocation from flow reversal in the fuel channel.
Reactivity – fuel temperature change	The change in core reactivity due to the effect of a change in fuel temperature.
Reactivity – isotope change	The change in core reactivity due to an increase or decrease in isotopic concentration of materials in the nuclear lattice.
Reactivity – moderator poison	The change in core reactivity due to a change in moderator poison concentration.
Reactivity – moderator purity	A change in core reactivity due to a change in moderator purity.
Reactivity – moderator temperature	The change in neutron spectrum resulting from a change in moderator temperature (commonly called the moderator-temperature reactivity coefficient).
Reactivity effect of firing SDS1	Rapid core-reactivity reduction due to increased absorption of neutrons in inserted rods.
Reactivity effect of firing SDS2	Rapid core-reactivity reduction due to increased absorption of neutrons in injected poison.

PIRT Term	Definition
Refill	The point at which a pipe is completely filled with liquid. Refill is indicated experimentally by a decrease in surface temperature below the local saturation temperature.
Relocation	Movement of molten material under gravitational forces.
Reflux condensation	Condensation of upward-flowing steam in a vertical, cooled pipe, and interaction with the liquid condensate film, which may drain downwards, or be dragged upwards by the steam.
Rewet	The post-dryout process in which liquid once again resumes intimate contact with a heated surface.
Solid-to-solid (fuel element-to-pressure tube) contact heat transfer	Heat transfer from a fuel element to its pressure tube. It is a combination of conduction, convection and radiation heat transfer, all of which are lumped together for an effective heat transfer.
Stored energy release	The process by which the energy within a solid structure is released to a lower energy state through one or more heat transfer processes, e.g., conduction and convection.
Swelling – fission product	The increase in fuel volume due to the formation of pressurized, gas filled pores/bubbles and inclusion of solid fission products in the fuel matrix.
Temperature	A measure of the sensible heat energy content per unit volume.
UO_2/Zircaloy interaction (alloying)	Chemical interaction between UO_2 and Zircaloy that yields an alloy with a lower melting temperature than the two parent materials.
UO_2 dissolution by molten Zircaloy	Dissolution of the fuel matrix by molten Zircaloy.
Void generation from heat transfer	The generation of vapor (boiling) due to heat transfer with a wall or evaporation at the two-phase interface.
Waterhammer	Pressure pulse(s) created as a result of a rapid change in fluid velocity.
Waterhammer – condensation induced	Pressure pulse(s) created as a result of a rapid change in fluid velocity, where the acceleration of the fluid is driven by condensation of a trapped vapor volume.