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BWR PIRT AND ASSESSMENT MATRICES FOR

BWR LOCA AND NON-LOCA EVENTS

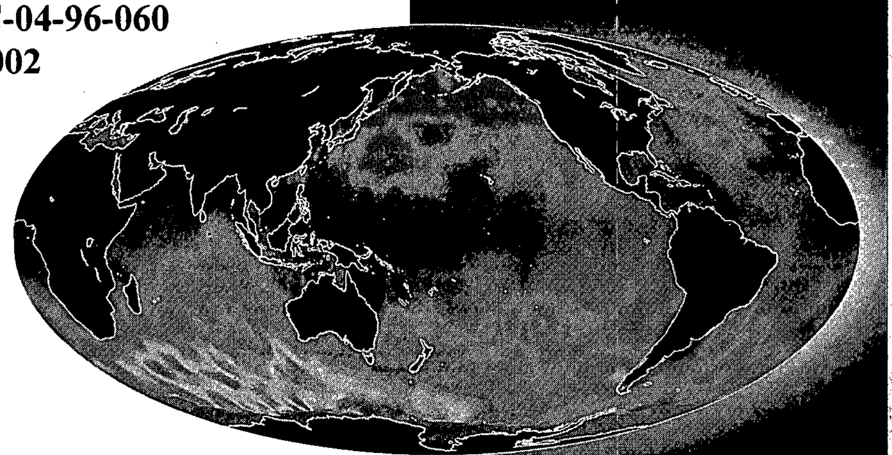
by

M. Straka and L. W. Ward

Prepared for

U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Contract NRC-04-96-060
Task 002



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ABSTRACT

This document presents the Phenomena Identification and Ranking Tables (PIRTs) for Loss-of-coolant Accidents (LOCAs) and Transients in domestic boiling water reactors. PIRTs were first introduced as part of the code Scaling, Applicability and Uncertainty evaluation methodology and were used as a guide to quantify uncertainty. PIRTs can also serve as useful tools to guide the development of research plans, support needed code development activities, and plan experiments. PIRTs are used in this document to identify the highly ranked phenomena characterizing large and small break LOCAs and transients in BWRs. The information from the PIRTS is used to identify key separate effects experiments, integral tests, and plant data to support the assessment and improvement of the TRAC-M code for application to BWR thermal hydraulic accidents. An assessment matrix is also presented. The key parameter ranges are also noted for the separate effects and integral tests identified to support assessment of the code for the PIRT highly ranked large break LOCA phenomena.

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1.0 INTRODUCTION

This document presents the information to support an assessment of thermal hydraulic system codes used to simulate domestic boiling water reactor (BWRs) behavior following loss-of-coolant accidents (LOCA) and transients. The information in this document includes: Phenomena Identification and Ranking Tables (PIRTs), code assessment matricies, and ranging of those physical parameters which are associated with the BWR transient phenomena ranked as "high" in the PIRTs. It should be noted that the key parameter ranges are presented for the large break LOCA (LB-LOCA) event, only. Parameter ranges for small break LOCAs and the non-LOCA events will be developed at a later date and are therefore excluded from this document. In summary, this section of the report contains the following information:

1. Development of PIRTs for domestic BWRs, for LOCA and non-LOCA events.

2. Identification of facilities and test data applicable for BWR thermal-hydraulic code validation.

3. Development of assessment matricies for BWR thermal-hydraulic code validation using information identified in Item 2.

4. Ranges of plant and experimental data of the key physical parameters identified in the PIRT that are ranked "high" for BWR LB-LOCA phenomena.

In general, a tabular format was chosen to present results of this work. It is important to note that each table was designed in such a fashion that it stands on its own merits. Thus, in general, no supporting information is required to use the tables presenting the information in this section of the report.

Lastly, since the parameter ranging was developed for only the LB LOCA event at this time, a brief description of the phenomenological behavior characterizing a typical large break LOCA in a BWR/4 is also given below, in Section 4.0, as background information.

2.0 PIRTs AND ASSESSMENT MATRICES

This section discusses the Phenomena Identification and Ranking Tables (PIRTs) that have been developed for domestic boiling water reactors (BWRs). Because of the many phenomena occurring during BWR abnormal events and accidents, and in view of the (five) different BWR types currently in commercial use, the BWRs were grouped in accordance with the particular type of in-vessel coolant recirculation and ECCS designs. Thus, three groups of BWRs were identified as follows:

1. BWR/2,
2. BWR/3 and /4,
3. BWR/5 and /6.

This grouping assures that relevant design differences are taken into account and that the extent of the BWR PIRTs still remain reasonable and manageable.

During the development of the PIRTs, it was noted that at least two PIRTs would be required: one for the LOCA events and a second for the non-LOCA events. Given these event categories the PIRTs then focus on BWR system components and thermal-hydraulic phenomena that occur for the whole spectrum of BWR transient events, including instability sequences. Most importantly, the applicable phenomena are assigned to each component and ranked in a systematic fashion within each specific event or category of events.

Where applicable, the course of the analyzed event was divided into its distinct phases. For example, the LB-LOCA PIRT consists of three phases: blowdown, refill/reflood, and long-term cooling.

Table I lists the main BWR system components. Typically, this (or similar) BWR system components would be used in the course of simulating BWR behaviour using one of the transient thermal-hydraulic system codes such as TRAC or RELAP5. From experience, it appears that no further advantage would be gained with a more detailed component categorization. Phenomena known to occur in BWRs are summarily compiled in Table II. They are listed alphabetically within each system component. In order to avoid repeating certain phenomena since they occur in several components, the components have been reduced to the core component and the rest; the lower, plenum, downcomer, etc. are identified as "other" in Table II. A few phenomena that are, in general, rather cumbersome to quantify have been omitted. Their impact on phenomenological behavior, however, has been included where appropriate. This includes, for example, control rod pattern and its impact on the axial and radial power distributions, or flow resistance and its effect on the pressure drop across various system components. Table II contains many general thermal-hydraulic phenomena, such as film boiling, for example, but also many reactor specific phenomena such as spatial neutron flux distribution, neutronic feedback, etc.

Table III presents the PIRT for the LOCA events which were subdivided into large-break and small-break events. Intermediate breaks are also covered by this division. Furthermore, for each LOCA event, its characteristic phases were observed as noted above. Also note that the LOCA PIRT was constructed using peak clad temperature as the "figure of merit." With the exception of the BWR/2, for the current generation of BWRs, peak clad temperature is not sensitive to containment phenomena which characterize the design basis LOCA. Because there are very few BWR/2 plant types, the LOCA containment phenomena were not included in PIRT Table III. Table IV shows the PIRT for the non-LOCA (transient) events. Because of the large number of possible plant events, it was necessary to divide them into categories with each category being characterized by a certain specific transient event. This approach lead to the selection of six categories. Subsequently, a surrogate transient event was chosen for each category which was then used during phenomena identification and their ranking. Because of their importance and somewhat different considerations, anticipated transients without scram (ATWS) and instability events were assigned their own categories. Table 2.1 below identifies the categories and their respective surrogate events.

Table 2.1: Transient Event Categories and Their Surrogate Events

TRANSIENT EVENT CATEGORY	SURROGATE EVENT
Pressurization	Turbine trip w/o bypass
Depressurization	Stuck open safety relief valve
Rapid reactivity increase	Control rod drop/bank withdrawal
Coolant temperature decrease	Failed feedwater heater
Instability	Power-flow oscillations*
ATWS	Turbine trip w/o bypas and w/o scram

* A specific initiating event has not been selected yet. .

Although for the Instability category no specific initiating event has been selected at this time, based on the literature survey (Refs. 1 and 2) and the known generic issues which affect BWR stability, a phenomena ranking was performed and presented in Table IV.

Table V lists the PIRT highly ranked phenomena and a brief justification for their ranking. There are 28 phenomena for LOCAs (large and small breaks) and 27 for transient events. However, many of these phenomena are common to both LOCA and non-LOCA events. Taking this into account, there are a total of 43 phenomena that have been ranked as "high." This number is necessitated, to some extent, by the need to include instability. Also, note that some of the phenomena ranked "high" occur only in this category. Also, some phenomena occur only in a certain BWR types, but not in others.

Tables VI and VII list tests available for BWR code validation. Table VI, based mainly on Ref. 3, includes separate effects tests (SET) and component tests proposed to validate the mathematical code models and correlations. Table VII lists integral (system) effects tests (IET) and their main features. It also presents transient events (including tests) in certain selected BWR plants. These data originate either from anticipated operational events or planned tests such as neutronic/thermal-hydraulic stability tests performed at Leibstadt and Ringhals-1, for example. The relative importance of the data for the code validation effort is also shown in each table (see the fourth column). In addition, information such as whether or not a TRAC input deck exists and is readily available is indicated in the respective table. This information is based on our best available knowledge.

From Tables III (LOCA PIRT), IV (non-LOCA PIRT) and VI (SET data) an Assessment Matrix (Table VIII) was constructed. In this matrix, highly ranked phenomena (ranked "H" in these two PIRTs) were compared against SETs and component tests to determine whether a particular phenomenon/process occurred in these tests. If no match was found, a reference to an IET and/or plant data was made since certain phenomena/processes such as fuel temperature feedback, for example, do not have a suitable SET counterpart.

Table IX was constructed using Table III (LOCA PIRT) and Table VII (IET data). This assessment matrix was constructed in a manner similar to Ref. 4, but it is much more comprehensive. More importantly, this assessment matrix exhibits in much greater detail phenomena known to affect BWR LOCA behavior. It contains highly ranked LOCA phenomena, LOCA tests (IETs) and respective test facilities. Thus, a quasi-three dimensional assignment is possible which shows: i) whether or not a particular phenomenon occurs during a certain LOCA test, ii) whether or not a particular facility is suitable to capture a certain phenomenon/process, and iii) whether or not a particular LOCA test was performed in a certain facility. Generally, a "blank" in a matrix cell means "not occurring," or "not suitable," or "not performed."

Finally, Table X was built using Table IV (non-LOCA PIRT) and Table VII (IET and plant data). Again, highly ranked phenomena are compared against the known transient tests/events and facilities/plants, respectively. In addition, tests/events versus facility/plant information are also shown in this table.

3.0 PARAMETER RANGES FOR LB LOCA HIGHLY RANKED PHENOMENA

It is noted that each thermal-hydraulic (or neutronic) phenomenon is affected by certain physical parameters. For example, the course of film boiling is affected by: the type of geometry and its characteristic dimensions, direction of coolant flow, local pressure, mass flux, local vapor quality, and local heat flux. Thus, at least seven parameters are needed to describe the process of film boiling. Since only typical BWR (or like) geometry and flow conditions are considered in this work, the number of physical parameters can be reduced to four key parameters: pressure, mass flux, vapor quality, and heat flux. To simplify the task of identifying the range of each physical parameter even further, often the system conditions can be substituted for the local ones. This is a significant relaxation since the local conditions, for example the local pressure, many times are not known or are very difficult to extract when analyzing experimental and/or plant data.

Following the approach described above, the key parameters were determined for each of highly ranked phenomena. Subsequently, for every phenomenon, the range of each associated key parameter was determined for a BWR plant and those experiments which capture this phenomenon. The results of this ranging process are shown in Appendix A. One table, spreading typically across one page, was constructed for each "high" ranked PIRT phenomenon. In general, these tables include all information including pertinent references. Therefore, each table can be used as a "stand-alone" document summarily characterizing the phenomenon in question. A summary of the key BWR plant parameter ranges is presented in Table XI, for additional information. It is noted that presently the parameter ranging was undertaken for the LB LOCA, only.

Based on the information compiled in Tables A-1 through A-25, it appears that the parameter ranges from phenomena which are expected to occur in BWR systems are well covered by the selected experiments. One notable exception (Table A-7) is the pressure drop (including its two-phase contribution) for which the only experimental data available in the pressure range between ~0.2 and 6.9 MPa are integral test data. This is less than desirable because benchmarking of a particular phenomenon with integral test data can often be obscured with other, difficult to separate, effects. In view of the importance of the pressure drop effect, a search for additional separate effects test data in the desired pressure range should be undertaken.

4.0 LARGE BREAK LOCA PHENOMENOLOGICAL BEHAVIOR

This section provides a description of the key emergency core cooling (ECC) system phenomenological behavior governing a large break LOCA in a BWR. A BWR/4 was chosen to illustrate the thermal hydraulic behavior following a large break LOCA.

The ECC system will be described first followed by a brief description of the LOCA phenomenological behavior. The TRAC-B code was used to simulate the large break LOCA in a BWR/4.

BWR/4 System Description

Fig. 1 shows a simplified diagram of the BWR/4 system configuration. The principal components of a BWR/4 system include:

- Reactor Vessel and Internals: Reactor pressure vessel, jet pumps, steam separators and dryers, core, and core support structures.
- Reactor Water Recirculation System: Pumps, valves, and piping used in providing and controlling flow.
- Main Steam Lines: Main steam valves, piping and pipe supports from reactor pressure vessel up to and including the isolation valves outside of the primary containment barrier.
- Control Rod Drive System: Control rods, control rod drive mechanisms and hydraulic system for insertion and withdrawal of the control rods.
- Nuclear Fuel and Instruments: The nuclear fuel(7x7) is located inside the core shroud.
- Engineering Safety Features: Pumps, valves, piping and water storage used to provide cooling and system inventory replacement during accident conditions. High Pressure Coolant Injection (HPCI), Low Pressure Core Spray (LPCS), Low Pressure Core Injection (LPCI), Automatic Depressurization System (ADS), and Residual Heat Removal (RHR).

The Reactor Vessel is divided into five regions: Lower Plenum, Core, Upper Plenum, Dome, and Downcomer region.

There are two external recirculation pumps and 20 internal jet pumps. Each recirculation line feeds five pairs of jet pumps, which are located outside the core shroud throughout the perimeter of the reactor vessel. The jet pumps provide approximately two-thirds of the recirculation flow within the reactor vessel. Approximately one-third of the core flow is taken is from the vessel through the two external recirculation loops. The external loop flow is pumped at a higher pressure, distributed through a manifold to which a number of riser pipes are connected, and returned to the vessel inlet nozzles. This flow is discharged from the jet pump throat where, due to a momentum exchange process, it induces the surrounding water in the downcomer region to be drawn into the jet pump throat where these two flows mix and then diffuse in the diffuser to be finally discharged into the lower plenum.

The BWR/4 power level is 3359 MWt with a core consisting of 764 fuel assemblies.

The steam separator and dryers are located above the core. This equipment is utilized to separate the steam from the liquid in order to avoid excessive rates of liquid in the steam supply system.

The control rods are utilized to effectively and rapidly reduce the power by absorption of neutrons. They are inserted from the bottom of the reactor vessel. There is one control rod for every four fuel assemblies in the core.

Description of the ECC system

The ECCS for a BWR/4 consists of high pressure coolant injection (HPCI), a low pressure core spray system (LPCS), a low pressure coolant injection system (LPCI), and an automatic depressurization system (ADS). Fig. 2 shows a simplified ECC system flow diagram for a BWR/4.

The HPCI consists of a single motor driven pump and is designed to inject water into the vessel over the full range of operating pressures. The HPCI uses the condensate storage tank as the initial water supply and upon exhaustion of this source, the suppression pool provides water to this spray system. The injected coolant is injected into the vessel downcomer through the feedwater line.

The LPCS is a low pressure core spray system. This low pressure spray system is designed to provide injection for the larger breaks that result in rapid depressurizations of the vessel. The LPCS is also injected into the upper plenum through a circular sparger around the periphery of the core. The function of the LPCS is to limit the peak clad temperatures for intermediate and large breaks, while HPCI along with ADS is intended for core cooling following small breaks. The LPCS draws water from the suppression pool. The LPCI is capable of delivering large amounts of coolant to refill the vessel once the system depressurizes. The LPCI consists of three residual heat removal pumps, each of which injects coolant through separate piping into the re-circulation loops.

The ADS activates about 1/3 of the safety relief valves in a BWR/4. These valves are opened in order to reduce the vessel pressure to mitigate the consequences of small breaks where depressurization is required to actuate the LPCI and LPCS.

Description of a Large Break LOCA

A LOCA in a BWR is defined as an instantaneous break in the system with break sizes up to and including a double-ended severance of the re-circulation loop piping. Re-circulation line breaks produce the highest peak cladding temperatures in BWRs. As such, a double-ended guillotine break in the recirculation line for a BWR/4 with the unavailability of off-site power is chosen for the discussion below. LPCS, HPCI and LPCI are credited in the simulation. The TRAC-B model of the BWR/4 is given in Fig. 3.

Off site power is assumed to be lost at the time of the break opening. Following reactor trip the core power decreases to the fission product decay heat values shown in Fig. 4.

Following opening of the break, the vessel pressure and core flow initially decrease. Since the energy expelled out the break and through the steam lines exceed the energy deposited into the coolant from the core, the system depressurizes over the first few seconds as illustrated in Fig. 5. Very little mass is assumed to enter the system during this period since the feedwater flow is assumed to coast to a zero value in one second. At about five seconds, the main steam isolation valves are assumed to be completely closed preventing steam from exiting the vessel. The closure of the main steam isolation valves causes the partial re-pressurization and the elevated system pressures during the first ten seconds of the event shown in Fig. 5.

The initial rapid loss in core flow, shown in Fig. 6 is due to the opening of the break in the re-circulation loop. The intact loop pump does however coast down during the event and influences the core flow behavior during the early portion of the transient. When the suction to the jet pumps uncover, the core flow rapidly decreases as shown in Fig. 7. And, upon uncovery of the suction nozzle to the re-circulation line, the volumetric flow rate through the break in this location increases significantly, causing an increase in the system depressurization rate. This increased depressurization after about 10 seconds in Fig. 5 causes the subcooled liquid in the lower plenum to eventually saturate and flash. Fig. 8 presents the lower plenum liquid mass and the decrease in inventory upon flashing at about 11 seconds into the transient. The flashing of the fluid in the lower plenum causes an associated increase in the core flow at about 11 seconds as noted in Fig 6. The jet pump discharge mass flow rates, presented in Fig. 7, display the early flow reversal on the broken loop side after the break opens. Fig. 9 presents the downcomer liquid level displaying the initial rapid loss in level due to the opening of the break and the effect of lower plenum flashing at 11 seconds.

The break mass flow rate is given in Fig.10 and illustrates the decrease in mass flow rate as the suction line uncovers early in the event.

The clad temperature responses for the low, average and high power rods are given in Fig. 11. The clad temperature is governed by the core flow early in the event as nucleate boiling governs the heat removal from the fuel rods during the initial portion of the event. As the core flow achieves a low flow condition, boiling transition develops as the core flow degrades and is a direct result of the uncovery of the jet pump discussed above. The heat transfer reaches film boiling and with uncovery of the hot spot at about 25 seconds in Fig. 11, the clad temperature for the high powered rod begins to increase due to the low heat transfer coefficients characteristic of steam cooling. The cladding temperature continues to increase at a rapid rate until the ECCS initiates injection into the reactor vessel initiating refill at about 46 seconds as noted in Fig.8. Coolant enters the core peripheral bundles from the low pressure core spray that condenses steam and pools in the upper plenum as shown in Fig. 12. The downflow of ECC injection (countercurrent flow) through the outer lower power bundles initiates refill of the lower plenum as shown in Fig.13. Because of the high steaming rates in the hotter fuel bundles, downflow of liquid is precluded in the central core region. That is, counter-current flow through the upper tie plate and the channel inlet orifices is precluded by the high steam velocities in these regions. Once the lower plenum refills and flashing in this region subsides, reflood of the core central bundles begins at about 80 seconds in Fig. 13 as liquid begins to accumulate in the average and high powered regions of the core. However, until sufficient coolant enters the core, heat removal from the bundles in the interior of the core is controlled by forced convection to steam and thermal radiation. As sufficient coolant enters the core interior hot bundles, the droplets entrained in the steam eventually provide sufficient cooling to terminate the cladding heat-up as dispersed flow film boiling governs the heat removal from the upper portion of the fuel rods. As the coolant injection into the core continues during this reflood period, the core eventually quenches and the heat transfer returns to nucleate boiling, where the clad temperatures remain within several degrees of the coolant saturation temperature during the long term. Fig. 14 presents the axial void distribution in the high powered channel. Once sufficient coolant have entered the core high power region, the peak clad temperature is terminated and quench occurs at 107 seconds as noted in Fig. 13.

The void fractions in the core are presented in Fig. 14. Early in the event, the two-phase level in the vessel remains at elevated values due to the early depressurization and attendant flashing of the liquid in the core. Following uncovery of the jet pump and the later lower plenum flashing, the fluid lost through the break along with the flashing and boiling in the core region causes the upper portions of the fuel bundles to uncover as shown in Fig. 14. Following lower plenum flashing and the continued depressurization of the system, the ECC is activated and coolant begins to enter and refill the vessel. Refill is initiated by the liquid downflow through the low powered peripheral bundles as noted by the increase in liquid inventory in this region shown in Fig. 13. Fig. 15 presents the bypass flow in the high powered region. The negative flow signifies the downflow of liquid through the bypass region which contributes to the refill of the lower plenum. Please note that the low and average powered core region bypass regions display this similar downward flow behavior and are not shown here. Reflood of the core begins after refill of the lower plenum and the clad temperature excursion is finally terminated at about 85 seconds into the event. Once sufficient coolant has entered the fuel bundles, fuel rod quenching is initiated. The heat transfer returns to nucleate boiling which maintains the core in a cooled condition for the long term.

The injection rates for LPCI, LPCS, and HPCI are given in Fig. 16.

A summary of the key phenomenological events is given in Table 4.1. Table 4.2 presents the initial conditions for the TRAC-B large break LOCA for the BWR/4. Please see Ref 5. for more detailed information regarding this simulation.

5.0 SUMMARY

Key phenomena characterizing the small and large break LOCAs , and transient events in BWR systems are identified through the development of PIRTs. Assessment matrices are then identified to identify the separate effect tests, integral experiments and plant transient data to systematically benchmark thermal hydraulic codes for application to accidents and transients in BWRs.

In summary, this document contains the following information:

1. Development of PIRTs for domestic BWRs, for LOCA and non-LOCA events.

2. Identification of facilities and test data applicable for BWR thermal-hydraulic code validation.

3. Development of assessment matricies for BWR thermal-hydraulic code validation using information identified in Item 2.

4. Ranges of plant and experimental data of the key physical parameters identified in the PIRT that are ranked "high" for BWR LB-LOCA phenomena.

Results of the BWR large break LOCA PIRTs identified 25 highly ranked phenomena. A review of the parameter ranges for these highly ranked phenomena that are expected to occur for a BWR large break LOCA demonstrated that the parameter ranges are generally well covered by the selected tests and experiments.

6.0 REFERENCES

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2. OECD/CSNI Workshop on BWR Stability, Brookhaven, New York, September 1994.
3. Separate Effects Test Matrix for Thermal-Hydraulic Code validation, OECD/CSNI, September 1993.
4. CSNI Integral Test Facility Validation Matrix for the Assessment of Thermal-Hydraulic Codes for LWR LOCA, OECD/CSNI.
5. Mun, K.K., "TRAC-BF1/MOD1 Analysis of BWR/4 Large Break LOCA," UMCP-TRAC-12, May 1998.

Table 4.1: Major Event Summary for BWR/4 Double-Ended Recirculation Line Break.

Time After Break (seconds)	Event
0.0	Break opens (offsite power is lost)
0.5	Broken jet pump drive reverses
1.0	Feedwater flow is terminated
3.0	Uncovery of jet pump
5	Recirculation pumps trip on low downcomer level
5	LPCS and LPCI actuate on low downcomer level
6	Core Inlet flow reverses
7.3	Re-circulation suction line uncovery
9.8	MSIV Closure
11	Lower plenum flashing
22	Intact recirculation line jet pump drive flow reaches zero
23.3	HPCI begins
25	Fuel rod hot spot uncovers
36	LPCS and LPCI activated
46	Lower plenum refill begins
85	Peak clad temperature rise terminated
107	High power bundle quenches

Table 4.2: Initial Conditions

Parameter	Value
Power	3359 Mwt
Hot Bundle LHGR	11.2 kw/ft
Steam Dome Pressure	7.124 MPa
Core Inlet Mass Flow Rate	15794 kg/s
Feedwater Mass Flow Rate	1712 kg/s
Steam Line Mass Flow Rate	1712 kg/s
Jet Pump Mass Flow Rate	5561 kg/s
Recirculation Loop Mass Flow Rate	5352 kg/s
Core Inlet Subcooling	11 K
Core Average Exit Void Fraction	0.691
Hot Assembly Exit Void Fraction	0.787

Table I: BWR Components Used for Phenomena Identification

Label	Component
A	Core
B	Bypass
C	Lower plenum
D	Downcomer
E	Guide tubes
F	Upper plenum
G	Separators
H	Dryers
I	Steam dome
J	Jet pumps
K	Steam line
L	Recirculation pumps
M	Recirculation line

Table II: Phenomena Identification (by Component) for BWR LOCA and non LOCA Events

Component/ Label	Phenomenon	Comment
Core/A		
	Boiling: film	
	Boiling: nucleate	
	Boiling: subcooled	
	Counter-current flow limit: • SEO • UTP	 SEO=Side-Entry-Orifice UTP=Upper-Tie-Plate
	Channel-bypass leakage	
	Clad oxidation	
	Condensation: ECC water	steam-ECC water interaction
	Control rod pattern/movement	
	Cooling: • Steam • dispersed flow	fuel rod cooling by steam and droplets
	Dry-out	
	Entrainment/de-entrainment	
	Feedback: fuel temperature	neutronic feedback
	Feedback: moderator temperature	same
	Feedback: void	same
	Flashing	caused by depressurization
	Flow: coastdown	
	Flow:lower plenum distribution	
	Flow: multi-channel T/H effect	parallel boiling channels
	Flow: natural circulation	
	Fuel: burnup	
	Fuel: design/type	
	Heat: decay	
	Heat: prompt radiation	neutron and gamma heating
	Heat stored: fuel	
	Heat stored: metal	
	Heat conductance: channel box-bypass	through channel walls
	Heat conductance: fuel-clad gap	
	Heat conductance: pellet	
	Heat transfer: radiation	
	Interphase shear	
	Non-condensables	presence of air or fission gas
	Power distribution: axial	
	Power distribution: radial	core-wide
	Pressure drop	
	Quench front: fuel	
	Quench front: channel box	
	Reactivity: scram	
	Rewet: blowdown	fuel rewet during blowdown
	Rewet: bottom/reflood	
	Rewet: top/spray	
	Stability: neutronic/thermal-hydraulic	neutronic feedback incl.
	Subcooling: coolant	

Table II continued: Phenomena Identification (by Component) for BWR LOCA and non LOCA Events

Component/ Label	Phenomenon	Comment
Core/A		
	Void: collapse	
	Void: distribution	
	Void: subcooled liquid	void formation in subcooled liquid
	Water rod	
	2-phase level	
	3-D kinetics effect	
Other/B-M		
	Carry-over	
	Carry-under	
	Counter-current flow limit: • TOB • JPI • TOG	 TOB=Top of Bypass JPI =Jet Pump Inlet TOG=Top of Guide tube
	Condensation: ECC water	steam-ECC water interaction
	Condensation: structure	
	Entrainment/de-entrainment	
	Feedwater: flow decrease	
	Feedwater: temperature decrease	
	Flashing	caused by depressurization
	Flow: critical	
	Flow: lower plenum distribution	during blowdown
	Flow: stratification	
	Heat stored: metal	
	Interphase shear	
	Jet pump: forward flow	
	Jet pump: reverse flow	
	Motor-generator response	control of recirculation flow
	Pressure drop	
	Pressure wave propagation	rapid compression, e.g.
	Recirculation pump: coastdown	
	Recirculation pump: single-phase data	
	Recirculation pump: 2-phase data	
	Spray distribution	
	Void: collapse	
	Void: distribution	
	2-phase level	
	3-D thermal-hydraulic effect	

Table III: Phenomena Identification and Ranking Table (PIRT) for BWR LOCA Events

Figure of Ranking Merit: peak cladding temperature, core mixture level

	Large-break LOCA									Small-break LOCA											
Phase	Blowdown			Refill/Reflood			LT Cooling			Blowdown: Before ADS Actuation			Blowdown: After ADS Actuation			Refill/Reflood			LT Cooling		
BWR Type	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6
Component/Phenomena																					
Core/																					
Boiling: film	H	H	H	H	H	H	L	L	L	L	L	L	H	H	H	H	H	H	L	L	L
Boiling: nucleate	L	L	L	L	L	L	H	H	H	H	H	H	L	L	L	L	L	L	H	H	H
Boiling: subcooled	L	L	L	L	L	L	L	L	L	M	M	M	L	L	L	L	L	L	L	L	L
CCFL (UTP)	L	L	M	H	H	H	L	L	L	0	0	M	L	L	M	H	H	H	L	L	L
CCFL (SEO)	L	L	H	L	L	H	0	0	0	0	0	0	L	L	H	L	L	H	0	0	0
Channel-bypass leakage	H	H	H	H	H	H	L	L	L	M	M	M	H	H	H	H	H	H	L	L	L
Clad oxidation	L	L	L	M	M	L	L	L	L	L	L	L	L	L	L	M	M	L	L	L	L
Condensation: ECC water	L	L	L	L	L	L	L	L	L	0	0	L	L	L	L	L	L	L	L	L	L
Cooling: steam/dispersed flow	M	M	L	H	H	M	0	0	0	L	L	L	M	M	L	H	H	L	0	0	0
Dry-out	H	H	H	H	H	H	L	L	L	L	L	L	H	H	H	H	H	H	L	L	L
Entrainment/de-entrainment	M	M	M	M	M	M	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L
Feedback: fuel temperature	L	L	L	0	0	0	0	0	0	L	L	L	L	L	L	0	0	0	0	0	0
Feedback: moderator temperature	L	L	L	0	0	0	0	0	0	L	L	L	L	L	L	0	0	0	0	0	0
Feedback: void	L	L	L	0	0	0	0	0	0	M	M	M	L	L	L	0	0	0	0	0	0
Flashing	M	M	M	L	L	M	L	L	L	L	L	L	M	M	M	L	L	M	L	L	L
Flow: coastdown	H	H	H	0	0	0	0	0	0	L	L	L	L	L	L	0	0	0	0	0	0
Flow: natural circulation	L	L	L	H	H	H	H	H	H	L	L	L	L	L	H	H	H	H	H	H	H
Flow: multi-channel T/H effect	L	L	M	M	M	M	L	L	L	L	L	M	L	L	M	M	M	M	L	L	L
Heat: decay	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Heat: prompt radiation	L	L	L	0	0	0	0	0	0	L	L	L	0	0	0	0	0	0	0	0	0
Heat stored: fuel	H	H	H	L	L	L	L	L	L	M	M	M	H	H	H	L	L	L	L	L	L
Heat stored: metal	L	L	L	H	H	H	L	L	L	L	L	L	L	L	L	H	H	H	L	L	L
Heat conductance: channel box	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Heat conductance: fuel-clad gap	H	H	H	M	M	M	L	L	L	M	M	M	H	H	H	M	M	M	L	L	L
Heat conductance: pellet	M	M	M	M	M	M	L	L	L	M	M	M	M	M	M	M	M	M	L	L	L
Heat transfer: radiation	L	L	L	H	M	M	0	0	0	L	L	L	L	L	L	M	M	M	0	0	0
Interphase shear	H	H	H	H	H	H	L	L	L	H	H	H	H	H	H	H	H	H	L	L	L
Non-condensables	L	L	L	L	L	L	M	M	M	L	L	L	L	L	L	L	L	L	M	M	M
Power distribution: axial	M	M	M	M	M	M	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L
Power distribution: radial	M	M	M	H	H	H	L	L	L	L	L	L	M	M	M	H	H	H	L	L	L
Pressure drop	H	H	H	M	M	M	L	L	L	H	H	H	H	H	H	M	M	M	L	L	L

Table III continued: Phenomena Identification and Ranking Table (PIRT) for BWR LOCA Events

Figure of Ranking Merit: peak cladding temperature, core mixture level

	Large-break LOCA									Small-break LOCA											
Phase..	Blowdown			Refill/Reflood			LT Cooling			Blowdown						Refill/Reflood			LT Cooling		
										Before ADS Actuation			After ADS Actuation								
BWR Type..	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6
Component/Phenomena																					
Quench front: fuel	0	0	0	M	M	M	L	L	L	0	0	0	0	0	0	M	M	M	L	L	L
Quench front: channel box	0	0	0	M	M	M	L	L	L	0	0	0	0	0	0	M	M	M	L	L	L
Reactivity: scram	L	L	L	0	0	0	0	0	0	H	H	H	L	L	L	0	0	0	0	0	0
Rewet: blowdown	H	H	H	0	0	0	0	0	0	0	0	0	H	H	H	0	0	0	0	0	0
Rewet: bottom/reflood	L	L	L	H	H	H	L	L	L	0	0	0	0	0	0	H	H	H	L	L	L
Rewet: top/spray	L	L	M	H	H	H	H	H	H	0	0	M	L	L	M	H	H	H	H	H	H
Void distribution	H	H	H	H	H	H	M	M	M	H	H	H	H	H	H	H	H	H	M	M	M
Water rod	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
2-phase level	L	L	L	H	H	H	H	H	H	L	L	L	L	L	L	H	H	H	H	H	H
3-D kinetics effect	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Bypass/																					
CCFL (top)	M	M	H	H	H	H	0	0	0	L	L	L	M	M	H	H	H	H	0	0	0
Condensation: ECC water	L	L	L	L	L	H	L	L	L	L	L	L	L	L	L	L	L	H	L	L	L
Flashing	M	M	H	M	M	M	L	L	L	L	L	L	M	M	H	M	M	M	L	L	L
Heat stored: metal	M	M	M	H	H	M	L	L	L	L	L	L	M	M	M	H	H	M	L	L	L
Pressure drop	H	H	H	M	M	M	M	M	M	H	H	H	H	H	H	M	M	M	M	M	M
2-phase level	L	L	L	H	H	H	H	H	H	L	L	L	L	L	L	M	M	M	H	H	H
3-D T/H effect (LPCI)	0	0	L	0	0	M	0	0	L	0	0	L	0	0	L	0	0	M	0	0	L
Lower plenum/																					
Condensation: ECC water	L	L	L	M	H	M	L	L	L	L	L	L	L	L	L	M	H	M	L	L	L
Flashing	H	H	H	M	M	M	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L
Flow: distribution	0	H	H	0	M	M	0	L	L	0	L	H	0	H	H	0	M	M	0	L	L
Heat stored: metal	L	L	L	H	H	H	L	L	L	L	L	L	L	L	L	H	H	H	L	L	L
Interphase shear	H	H	H	M	H	M	L	L	L	L	L	L	M	M	M	M	H	M	L	L	L
Pressure drop	M	M	M	M	M	M	L	L	L	M	M	M	M	M	M	M	M	M	L	L	L
Void distribution	H	H	H	M	H	M	L	L	L	L	L	L	M	M	M	M	H	M	L	L	L
2-phase level																					
• Jet pump exit uncovery	0	H	H	0	M	M	0	L	L	0	L	L	0	M	M	0	M	M	0	L	L
• SEO uncovery	L	H	H	L	H	H	L	L	L	L	L	L	L	M	M	L	H	H	L	L	L

Table III continued: Phenomena Identification and Ranking Table (PIRT) for BWR LOCA Events

Figure of Ranking Merit: peak cladding temperature, core mixture level

	Large-break LOCA									Small-break LOCA											
Phase	Blowdown			Refill/Reflood			LT Cooling			Blowdown						Refill/Reflood			LT Cooling		
										Before ADS Actuation			After ADS Actuation								
BWR Type	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6
Component/Phenomena																					
Downcomer/																					
Condensation: ECC water (HPCI)	H	H	L	M	M	M	L	L	L	L	L	L	H	H	L	M	M	M	L	L	L
Flashing	H	H	H	L	L	L	L	L	L	L	L	L	H	H	H	L	L	L	L	L	L
Interphase shear	H	H	H	H	H	H	L	L	L	L	L	L	H	H	H	H	H	H	L	L	L
Void distribution	H	H	H	H	H	L	L	L	L	L	L	L	H	H	L	H	H	L	L	L	L
2-phase level																					
• HPCI sparger uncovery	H	H	0	H	H	0	H	H	0	L	L	L	H	H	0	H	H	0	H	H	0
• jet pump inlet uncovery	0	H	H	0	L	L	0	L	L	0	L	L	0	H	H	0	L	L	0	L	L
• RCL suction uncovery	H	H	H	L	L	L	L	L	L	L	L	L	H	H	H	L	L	L	L	L	L
3-D T/H effect	M	M	M	L	L	L	L	L	L	L	L	L	M	M	M	L	L	L	L	L	L
Guide Tubes/																					
CCFL (top)	0	0	0	M	M	M	0	0	0	0	0	0	0	0	0	L	L	L	0	0	0
Condensation: ECC water	L	L	L	L	L	H	L	L	L	L	L	L	L	L	L	L	L	M	L	L	L
Flashing	L	L	M	L	L	M	L	L	L	L	L	L	L	L	M	L	L	M	L	L	L
Upper plenum/																					
Condensation: ECC water (CS)	L	L	H	H	H	H	H	H	H	L	L	L	L	L	H	H	H	H	H	H	H
Pressure drop	H	H	H	M	M	M	M	M	M	H	H	H	H	H	H	M	M	M	M	M	M
Spray distribution	L	L	H	M	M	H	M	M	H	L	L	L	L	L	H	M	M	H	M	M	H
Void distribution	L	L	H	H	H	H	H	H	H	L	L	L	L	L	H	H	H	H	H	H	H
2-phase level	L	L	H	H	H	H	H	H	H	L	L	L	L	L	H	H	H	H	H	H	H
3-D T/H effect	L	L	H	H	H	H	H	H	H	L	L	L	L	L	H	H	H	H	H	H	H
Separators/																					
Carry-under	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Carry-over	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Pressure drop	H	H	H	L	L	L	L	L	L	H	H	H	H	H	H	L	L	L	L	L	L

Table III continued: Phenomena Identification and Ranking Table (PIRT) for BWR LOCA Events

Figure of Ranking Merit: peak cladding temperature, core mixture level

	Large-break LOCA									Small-break LOCA											
Phase	Blowdown			Refill/Reflood			LT Cooling			Blowdown						Refill/Reflood			LT Cooling		
										Before ADS Actuation			After ADS Actuation								
BWR Type	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6
Component/Phenomena																					
Dryers/																					
Carry-over	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Pressure drop	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Steam dome/																					
Condensation: structures	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Pressure drop	M	M	M	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L	L	L	L
Jet pumps/																					
CCFL (top)	0	L	L	0	L	L	0	0	0	0	0	0	0	H	H	0	L	L	0	0	0
Condensation: ECC water (LPCI)	0	L	0	0	H	0	0	H	0	0	0	0	0	L	0	0	H	0	0	H	0
Flashing	0	M	M	0	L	L	0	L	L	0	L	L	0	M	M	0	L	L	0	L	L
Flow: critical	0	H	H	0	L	L	0	L	L	0	L	L	0	H	H	0	L	L	0	L	L
Flow: forward	0	H	H	0	L	L	0	L	L	0	H	H	0	H	H	0	L	L	0	L	L
Flow: reverse	0	H	H	0	L	L	0	L	L	0	L	M	0	H	H	0	L	L	0	L	L
Pressure drop	0	H	H	0	L	L	0	L	L	0	H	H	0	H	H	0	L	L	0	L	L
Steam line/																					
Entrainment/de-entrainment	M	M	M	L	L	L	L	L	L	L	L	L	M	M	M	L	L	L	L	L	L
Pressure drop	M	M	M	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L	L	L	L
Recirculation pumps/																					
Coastdown	H	H	H	0	0	0	0	0	0	H	H	H	0	0	0	0	0	0	0	0	0
Flashing	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Single-phase data	M	M	M	0	0	0	0	0	0	M	M	M	0	0	0	0	0	0	0	0	0
2-phase data	M	M	M	0	0	0	0	0	0	M	M	M	0	0	0	0	0	0	0	0	0
Recirculation line/																					
Flow: critical (break)	H	H	H	M	M	M	L	L	L	H	H	H	H	H	H	M	M	M	L	L	L
Flow: stratification	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	L	L	L	L	L	L

Table III continued: Phenomena Identification and Ranking Table (PIRT) for BWR LOCA Events

Figure of Ranking Merit: peak cladding temperature, core mixture level

	Large-break LOCA									**Small-break LOCA**											
Phase	Blowdown			Refill/Reflood			LT Cooling			Blowdown						Refill/Reflood			LT Cooling		
										Before ADS Actuation			After ADS Actuation								
BWR Type	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6	/2	/3 /4	/5 /6
Component/Phenomena																					
Flashing	H	H	H	L	L	L	L	L	L	L	L	L	M	M	M	L	L	L	L	L	L
Pressure drop	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

Ranking:
0 = Not applicable
L = Low
M = Medium
H = High

Acronyms (less known):
ADS=Automatic Depressurization System
CCFL=Counter-Current Flow Limit
CS=Core Spray
HPCI=High-pressure Coolant Injection
LPCI= Low-pressure Coolant Injection
LT=Long-Term
RCL=Recirculation Line
SEO=Side-Entry-Orifice
UTP=Upper Tie-Plate

Table IV: Phenomena Identification and Ranking Table (PIRT) for BWR non-LOCA Events

Figure of Ranking Merit: Minimum critical power ratio, energy in fuel, power stability

	TRANSIENT CATEGORIES					
Category	Pressurization	Depressurization	Rapid reactivity increase	Coolant temp. decrease	Instability (power osc.)	ATWS
Component/Phenomena						
Core/						
Boiling: film	L	L	H	H	H	L
Boiling: nucleate	M	M	M	M	M	M
Boiling: subcooled	M	M	M	M	H	M
Channel-bypass leakage	M	M	M	M	M	M
Control rod pattern/movement	L	L	M	L	H	L
Dry-out	L	L	H	H	H	L
Feedback: fuel temperature	H	M	H	H	H	H
Feedback: moderator temperature	L	L	L	L	L	L
Feedback: void	H	H	H	H	H	H
Flashing	L	M	L	L	0	L
Flow: coastdown	L	L	L	L	H	H
Flow: natural circulation	L	L	L	L	H	L
Flow: multi-channel T/H effect	H	H	H	H	H	H
Fuel: burnup	L	L	M	L	H	M
Fuel: design/type	L	L	M	L	H	M
Heat: decay	M	M	M	M	M	M
Heat: prompt radiation	L	L	L	L	L	L
Heat stored: fuel	M	M	M	M	M	M
Heat stored: metal	L	M	L	M	L	L
Heat conductance: channel box	L	L	L	L	L	L
Heat conductance: fuel-clad gap	H	M	H	M	H	H
Heat conductance: pellet	M	M	M	M	M	M
Interphase shear	H	H	H	H	H	H
Power distribution: axial	M	L	H	L	H	L
Power distribution: radial	M	L	H	L	H	L
Pressure drop	H	H	H	H	H	H
Reactivity: scram	H	L	L	M	H	H
Stability: neutronic/thermal-hydr.	L	L	L	L	H	L
Subcooling: coolant	M	M	M	L	H	M
Void: collapse	H	L	H	H	M	H
Void: distribution	H	H	H	H	H	H
Void: subcooled liquid	H	H	H	H	H	H

Table IV continued: Phenomena Identification and Ranking Table (PIRT) for BWR non-LOCA Events

Figure of Ranking Merit: Minimum critical power ratio, energy in fuel, power stability

	TRANSIENT CATEGORIES					
Category	Pressurization	Depressurization	Rapid reactivity increase	Coolant temp. decrease	Instability (power osc.)	ATWS
Component/Phenomena						
Water rod	L	L	L	L	L	L
3-D kinetics effect	H	M	H	H	H	H
Bypass/						
Flashing	0	M	0	0	0	0
Heat stored: metal	L	M	L	L	L	L
Pressure drop	H	H	H	H	H	H
2-phase level	L	M	0	0	0	L
Lower plenum/						
Flashing	L	M	0	0	0	L
Flow: distribution	L	M	0	0	0	L
Heat stored: metal	L	M	0	M	M	L
Interphase shear	0	M	0	0	0	L
Pressure drop	H	H	H	H	H	H
Void: distribution	0	M	0	0	0	0
3-D T/H effect	L	L	L	H	H	L
Downcomer/						
Flashing	L	M	0	0	0	L
Interphase shear	H	H	L	H	H	H
Void: collapse	H	0	0	M	0	H
Void: distribution	H	H	L	H	H	H
2-phase level	H	H	L	H	H	H
Guide Tubes/						
Flashing	L	M	0	0	0	L
Upper plenum/						
Condensation: ECC water	0	0	0	H	0	0
Pressure drop	H	H	H	H	H	H
Spray distribution	0	0	0	M	0	0
Void: collapse	H	0	0	M	0	H

Table IV continued: Phenomena Identification and Ranking Table (PIRT) for BWR non-LOCA Events

Figure of Ranking Merit: Minimum critical power ratio, energy in fuel, power stability

	TRANSIENT CATEGORIES					
Category..	Pressurization	Depressurization	Rapid reactivity increase	Coolant temp. decrease	Instability (power osc.)	ATWS
Component/Phenomena						
Void: distribution	0	0	0	M	0	0
2-phase level	0	0	0	H	0	0
3-D T/H effect	0	0	0	M	0	0
Separators/						
Carry-under	H	H	L	H	H	H
Carry-over	L	L	L	L	L	L
Pressure drop	H	H	H	H	H	H
Void: collapse	H	0	0	M	0	H
Dryers/						
Carry-over	L	L	L	L	L	L
Pressure drop	L	L	L	L	H	L
Steam dome/						
Pressure drop	L	L	L	L	L	L
Jet pumps/						
Flashing	0	M	0	0	0	0
Flow: forward	H	H	L	H	H	H
Flow: reverse	L	L	L	L	L	L
Pressure drop	H	H	L	H	H	H
Steam line/						
Pressure wave propagation	H	H	L	L	L	H
Entrainment/de-entrainment	L	L	L	L	L	L
Flow: critical	H	H	L	L	L	H
Pressure drop	H	M	L	M	M	H
Recirculation pumps/						
Coastdown	H	H	L	L	H	H
Single-phase data	M	M	L	L	M	M
2-phase data	0	L	0	0	0	0
Motor-gen. Response (BWR/2/3/4)	M	M	L	M	M	M

Table IV continued: Phenomena Identification and Ranking Table (PIRT) for BWR non-LOCA Events

Figure of Ranking Merit: Minimum critical power ratio, energy in fuel, power stability

	TRANSIENT CATEGORIES					
Category..	Pressurization	Depressurization	Rapid reactivity increase	Coolant temp. decrease	Instability (power osc.)	ATWS
Component/Phenomena						
Recirculation line/						
Flashing	L	M	0	L	0	L
Pressure drop	M	M	L	L	L	M
Feedwater/						
Flow decrease	L	L	L	M	L	M
Temperature decrease	L	L	L	M	H	L

Ranking:
0 = Not applicable
L = Low
M= Medium
H = High

Table V: Justification of Phenomena Ranked High in BWR LOCA (L) and non-LOCA (NL) PIRTs

Phenomenon	Event	Justification
Boiling: film	L NL	Heat transfer in this mode governs the maximum peak clad temperature (PCT). Same.
Boiling: nucleate	L	Heat transfer in this mode governs the fuel temperature during the long-term cooling phase.
Boiling: subcooled	NL	Affects the axial power shape via the subcooled void profile and its neutronic feedback effect.
Carry-under	NL	Affects subcooling at the core inlet.
Condensation: ECC water	L NL	Effects pressure decrease and reduces flow of steam through limiting openings - such as the upper tie-plate (UTP). Affects thermal-hydraulic processes in the upper plenum (in the case of an inadvertent ECCS actuation).
Counter-current flow limit (CCFL)	L	• CCFL at SEO retards gravitational channel drainage especially during blowdown. • CCFL at UTP limits ECC water delivery into the core after a core spray actuation. • CCFL at the top of bypass limits ECC water delivery after a core spray actuation. • CCFL at the jet pump inlet limits ECC water delivery into the lower plenum after an LPCI actuation (BWR/3 and /4).
Channel-bypass leakage	L	Reverse flow via the channel-bypass leakage path aids in channel cooling during blowdown and refill.
Cooling: steam/dispersed flow	L	Steam cooling including dispersed flow (steam and droplets) are prevailing cooling modes in the refill/reflood phase before rewetting. (Steam-to-droplet interfacial heat transfer and droplet size are some of the parameters affecting heat transfer in dispersed flow, e.g.).
Dry-out	L NL	Prediction of dry-out is important for cladding failure analysis. Same.
Feedback: fuel temperature	NL	• Represents the feedback effect of fuel temperature applied to reactivity (usually expressed as a temperature coefficient of reactivity). • Affects the core stability and its margin.
Feedback: void	NL	• Represents the feedback effect of coolant void in terms of reactivity (usually expressed as a void coefficient of reactivity). • Affects strongly the core stability.
Flashing	L	Affects depressurization, core cooling via liquid entrainment, and break flow.
Flow: critical	L NL	Determines break flow thus affecting depressurization of the system and its mass inventory, i.e. uncovery of the core. Determines safety relief valve flow, e.g. during a stuck-open relief valve transient.
Flow: lower plenum distribution	L	Affects core cooling in the early phase of blowdown.

Table V continued: Justification of Phenomena Ranked High in BWR LOCA (L) and non-LOCA (NL) PIRTs

Phenomenon	Event	Justification
Flow: multi-channel T/H effect	NL	Parallel boiling channels may incur dynamic instability (density-wave oscillations) amplified by a nuclear feedback.
Flow: natural circulation	L NL	Internal natural circulation pattern may develop during refill/reflood (core shroud-downcomer) persisting into the long-term cooling phase. Natural circulation flow (following trip of recirculation pumps) may decrease the stability margin.
Heat: decay	L	Affects peak clad temperature and dry-out occurrence.
Heat stored: fuel	L	Important heat input during the blowdown phase.
Heat stored: metal	L	Affects refill of the lower plenum and bypass (less in BWR/5 and /6).
Heat conductance: fuel-clad gap	NL	Affects the core stability margin.
Heat conductance: pellet	NL	Determines the temperature distribution in fuel - affects fuel temperature feedback.
Heat transfer: radiation	L	Affects the PCT during the heat-up phase (BWR/2).
Interphase shear	L NL	• Affects the fluid behavior under two-phase conditions - determines the two-phase level (level swell). • Governs phase separation and entrainment in the lower plenum and determines the two-phase level in the upper plenum, e.g. Affects entrainment carry-over, carry-under, and two-phase pressure drop.
Jet pump: forward flow	L NL	Governs flow coast-down in the early blowdown stage. Determines the initial core flow during loss-of-flow (forced) transients (recirculation pump trip, e.g.) .
Jet pump: reverse flow	L	Affects significantly break flow during the blowdown phase.
Neutron flux distribution: axial	NL	Axial power shape affects stability.
Neutron flux distribution: radial	L NL	Determines the radial power distribution (channel grouping). Affects stability.
Pressure drop	L NL	• Governs behavior of an individual channel (or a group of similar channels) due to the BWR parallel channel (incl. bypass) configuration. • Affects the in-shroud and downcomer flow path towards the break location in a recirculation line during the blowdown phase. Determines boundary condition for parallel boiling channels.
Pressure wave propagation	NL	Rapid decompression or compression (turbine stop valve closure, e.g.) affects void in the core.
Reactivity: scram	L/NL	Necessary to scram a reactor.
Recirculation pump: coastdown/flow coastdown	L NL	Governs the core flow in the early blowdown stage. Determines the initial core flow during loss-of-flow (forced) transients (recirculation pump trip, e.g.) .
Rewet: blowdown	L	Temporary fuel dry-out followed by rewet before ECCS actuation (observed during blowdown in some LOCA experiments).

Table V continued: **Justification of Phenomena Ranked High in BWR LOCA (L) and non-LOCA (NL) PIRTs**

Phenomenon	Event	Justification
Rewet: bottom/reflood	L	ECC water entering the core from bottom gradually rewetting fuel while progressing upwards.
Rewet: top/spray	L	Falling liquid film due to core spray rewetting the core from above while progressing downwards.
Spray distribution	L	Affects CCFL and its breakdown at the upper tie-plate.
Stability: thermal-hydraulic	NL	Thermal-hydraulic feedback via the density-wave mechanism affects the stability margin of a core.
Stability: neutronic/thermal-hydraulic	NL	Neutronic feedback significantly affects the stability margin of a core.
Subcooling: coolant	NL	Affects density-wave travel time and two-phase pressure drop via boiling boundary change - may be destabilizing.
Void: collapse	NL	Affects power production via the void coefficient.
Void: distribution/2-phase level	L	• Determines flow regime in both the blowdown and reflood phases. • Affects cooling of the core in the blowdown phase, determines timing of jet pump exit uncovery in the lower plenum, uncovery of the jet pump inlet, break flow composition (steam contribution). • Affects the amount of condensation in the upper plenum after a core spray actuation. • Location of the mixture (2-phase) level is crucial for fuel-coolant heat transfer below and above the 2-phase level. • Determines timing of SEO uncovery and uncovery of the recirculation line suction and HPCI sparger in owncomer.
	NL	• Affects power distribution via the void coefficient. • Determines dynamic effect of downcomer during some transients such as turbine trip or inadvertent depressurization.
Void: subcooled liquid	NL	Void formation in subcooled liquid affects power distribution via the void coefficient.
3-D kinetics effect	NL	Necessary to determine the radial and axial power distributions for stability.
3-D thermal-hydraulic effect	L	Occurs in the upper plenum after a spray actuation.
	NL	Feedwater-induced subcooling asymmetry can develop in the lower plenum.

Acronyms:
L =LOCA Event Category
NL =Non-LOCA Event Category
ECC=emergency core cooling
HPCI=High-Pressure Coolant Injection
LPCI= Low-Pressure Coolant Injection
SEO = Side-Entry-Orifice

Table VI: Separate Effects, Component, and Analytical Tests Applicable to BWR

NO.	TEST	FACILITY/ORIGINATOR	TEST FEATURE	ASSESS. NEED	TRAC INPUT	DATA	REF/OECD/CSNI
	Separate Effects/						
S1	boiling: film	THTF	Test 3.06.6B and Test 3.08.6C	++	1	1	11.38
S2	boiling (incl. CHF)	Harwell/Bennett	3 tests (mass flux: 380 to 3,800 kg/sq.m-sec)	++	1	1	10.7
S3	boiling: subcooled	ANL/Christensen	steady-state experiment (ANL-6385)	++	1	1	11.47
S4	boron tracking	UC-Santa Barbara	boron mixing in the BWR lower plenum	+		1	11.2
S5	bundle uncovery	TLTA Test 6441	gradual boil-off	++		1	Ref. 6.1
S6	CCFL: steam-water	Dartmouth/Wallis	saturated flooding test (EPRI-NP-1336)	+	2	1	11.16
S7	"	8x8 bundle CCFL	saturated and subcooled CCFL at a BWR tie-plate	++	2	1	Ref. 6.2
S8	"	8x8 bundle	saturated CCFL at a BWR side-entry orifice	++	2		
S9	cooling: spray	GOETA Test 42	top reflood (STUDSVIK/RL-78/24)	++	2		8.1
S10	steam	ANL/Heinemann	superheated steam (ANL-6213)	+	2	1	Ref. 6.3
S11	steam cooling/dispersed flow	THTF	Tests 3.09.10I-N	++		1	
S12	critical flow	CFR/critical flow rig	used for R5/M3 assessment (AEA-RS 1093)	++			11.54
S13	"	EPRI-Wyle pipe rupture		+			Ref. 6.4
S14	"	Marviken	Test 15 and 24	++	1	1	8.2
S15	flashing: blowdown	Edwards pipe	rapid blowdown	++	1	1	Ref. 6.5
S16	level swell	GE vessel Test 1004-3	small vessel test w/ void fraction<0.5	++	1	1	11.44
S17	"	GE vessel Test 5801-13	large vessel test	++	1	1	
S18	heat radiation	GOETA Test 27	steady-state experiment in 8x8 bundle	+	2	1	8.1
S19	interphase friction	CISE adiabatic pipe	void fraction>0.5 (CISE-R-291)	++	2	1	Ref. 6.6
S20	"	Dartmouth/Wallis	air-water flow	+	2	1	11.17
S21	"	Pericles	boil-off in a bundle w/ void fraction <0.9	++	2	1	
S22	natural circulation	FRIGG Run 301047		++	1	1	8.3
S23	post-CHF heat transfer	Lehigh/Chen	post-CHF non-equilibrium boiling	++	2	1	11.42
S24	two-phase pressure drop	Sher&Greer	boiling pressure drop in thin rect. channel	++		1	
S25	"	Muscettola	AEEW-R-284	++			
S26	reflood/rewet	BWR-FLECHT	bottom reflood	+	1	1	11.23
S27	"	FLECHT-SEASET	bottom reflood	++	1	1	11.41
S28	"	GOETA Test 42	bottom and top reflood	++	2	1	8.1
S29	"	NEPTUN	bottom reflood	+	1		9.2
S30	thermal-hydraulic stability	FRIGG-3	uniform (axially) perturbed power (f-domain)	++	1		8.3
S31	"	FRIGG-4	cosine perturbed power (f-domain)	++	1		"
S32	void distribution (axial)	ANL/Marchaterre	subcooled and saturated void (ANL-5735)	++	1	1	Ref. 6.7
S33	"	FRIGG-2	boiling in a 6x6 bundle	+			
	Component/						
C1	centrifugal pump	Semiscale pump	single- and two-phase pump performance	+	1		11.39
C2	jet pump	INEL 1/6 jet pump	forward and reverse flow performance	++	1	1	11.1

Table VI continued: Separate Effects, Component, and Analytical Tests Applicable to BWR

NO.	TEST	FACILITY/ORIGINATOR	TEST FEATURE	ASSESS. NEED	TRAC INPUT	DATA	REF/OECD/CSNI
C3	mixing: lower plenum	SSTF SET	steam-water	++		1	11.28
C4	3-D T/H in the upper plenum	SSTF SET	refill/reflood behaviour of parallel channels	++			11.28
C5	multi-channel T/H effects	SSTF SET	parallel channel dynamics	++			11.28
	Analytical/						
A1	mass & momentum eqs.	U-tube manometer	wall friction assessed	+		1	
A2	interphase friction	Bubble rise		+			

ASSESSMENT NEED:
++ = vital
+ = desirable

TRAC INPUT:
1 = exists/available at Scientech
2 = exists

DATA:
1 = available at Scientech

Table VII: Integral Facility Tests and Plant Data Applicable to BWR

NO.	TEST/EVENT	FACILITY/PLANT	TEST/EVENT FEATURES	ASSESS. NEED	TRAC INPUT	DATA	REF/OECD/CSNI
	LOCA	**Integral/**					
I1	large recirc break (BWR/6)	FIST 6DBA1B	avg power/normal ECC	++	1	1	Ref. 7.1
I2	" (BWR/4)	FIST 4DBA1	avg power/one LPCI failed	++		1	132/6
I3	"	FIX-II Test 3061	blowdown only (100% break)				"
I4	"	ROSA-III Run 901	avg+peak power/normal ECC	++		1	Ref. 7.2
I5	"	ROSA-III Run 905	avg+peak power/no ECC			1	"
I6	"	ROSA-III Run 902	avg+peak power/LPCI (2) failed			1	"
I7	"	ROSA-III Run 924	avg+peak power/LPCS+LPCI(1) failed			1	"
I8	"	ROSA-III Run 926	avg+peak power/HPCS failed	++		1	132/6
I9	"	TBL Test 108					"
I10	"	TLTA 6422 Run 3	avg power/normal ECC			1	Ref. 7.3
I11	"	TLTA 6424 Run 1	peak power/normal ECC	++		1	"
I12	"	TLTA 6423 Run 3	peak power/low flow/high temperature ECC	++	1	1	"
I13	"	TLTA 6426 Run 1	avg power/no ECC	++		1	"
I14	intermediate recirc break	FIST 6IB1	RC suction break/no LPCS			1	132/6
I15	"	FIST 6LB1A	LPCI line break/no HPCS			1	Ref. 7.4
I16	"	ROSA-III Run 962	RC discharge break/no HPCS				Ref. 7.2
I17	refill/reflood	Piper-ONE PO-LB-1	multiple ECCS failures				132/6
I18	"	SSTF	system test in large-scale BWR mock-up	+		1	Ref. 7.5
I19	small recirc break	FIST 6SB1	"stuck" open SRV/no HPCS	++	2	1	132/6
I20	"	Piper-ONE PO-SB-7	ISP No. 21				"
I21	"	ROSA-III Run 912	ISP No. 12	++		1	"
I22	"	ROSA-III Run 984	avg+peak power/no HPCS (counterpart to FIST 6SB2C)	+		1	"
I23	"	TBL Test 311					"
I24	"	TLTA 6432 Run 1	avg power /no HPCS (counterpart to FIST 6SB2C)			1	"
I25	steam line break	FIST 6MSB1	break location upstream of flow limiter	++		1	"
I26	"	ROSA-III Run 953	no HPCS and ADS	+		1	"
I27	"	TBL Test 314					"
	TRANSIENT	**Integral/**					
I28	**ATWS**: MSIV closure	FIST 6PMC2A	ECCS and ADS not available	++	1	1	Ref. 7.1
I29	water level drop	FIST T23C	FW fails, HPCS/RCIC fail during ADS actuation, bundle uncovery	+		1	132/6
I30	controlled depress.	FIST 6PMC3	HPCS maint. level, SRV depressurized, low pressure natural circ.	++		1	"
I31	natural circulation	FIST 6PNC1	high pressure: make-up by FW	+	2	1	Ref. 7.1
I32	"	FIST 6PNC3	high pressure: make-up by HPCS			1	Ref. 7.4
I33	"	ROSA-III NC-1 …NC-5	high and low pressure: level varied	++		1	Ref. 7.2
I34	water level drop	FIST T1QUV	FW/ECCS/RCIC/ADS fail, high pressure bundle uncovery			1	132/6
I35	turbine trip	FIST 4PTT1	simulation of Peach Bottom turbine trip test	++	2	1	"

Table VII continued: **Integral Facility Tests and Plant Data Applicable to BWR**

NO.	TEST/EVENT	FACILITY/PLANT	TEST/EVENT FEATURES	ASSESS. NEED	TRAC INPUT	DATA	REF/OECD/CSNI
		Plant/					
P1	**AOT**: FW trip	Browns Ferry	AOT (Anticipated Operational Transient)	+	1	1	
P2	load rejection	"	"	+	1	1	
P3	RC pump trip	"	"	+	1	1	
P4	MSIV closure	Leibstadt	start-up test	+	2		132/6
P5	FW loss	Leibstadt	start-up test	+	2		"
P6	turbine trip	Peach Bottom-2	plant test	++	2	1	"
	STABILITY	**Plant/**					
P7	"	Dodeward	plant test (damped oscillations)		1	1	SOAR
P8	"	LaSalle-2	global power oscillations during an AOT	++	1		"
P9	"	Leibstadt	plant test (global and regional oscillations)	+	2		"
P10	"	Ringhals-1	OECD/NEA stability benchmark tests & start-up event	++	2		"
P11	"	WNP-2	global power oscillations during a startup	+			"

ASSESSMENT NEED:
++ = vital
+ = desirable

TRAC INPUT:
1 = exists/available at Scientech
2 = exists

DATA:
1 = available at Scientech

Facility Acronyms:
FIST=Full Integral Scale Test (USA)
ROSA=Rig Of Safety Assessment (Japan)
SSTF=Steam Sector Test Facility (USA)
TLTA=Two-Loop Test Apparatus (USA)
TBL = Two Bundle Loop (Japan)

Table VIII: BWR LOCA Assessment Matrix Using Separate Effects, Component, and Analytical Test Data

	TEST No./TEST NAME																																			
	S1 / THTF	S2 / Bennett	S5 / Bundle uncovery	S6 / Wallis	S7 / Upper tie-plate CCFL	S8 /Side-entry orifice CCFL	S9 / GOETA	S10 / Heinemann	S11 /THTF	S12 / CFR	S13 / EPRI-Wyle	S14 / Marviken	S15 / Edwards pipe	S16 / GE 1 ft vessel	S17 /GE 3 ft vessel	S18 / GOETA 27	S19 / CISE pipe	S20 / Wallis	S21 /Pericles	S22/ FRIGG natural circ.	S23 / Lehigh	S24 /Sheer & Greer	S25 /Muscettola	S26 / BWR-FLECHT	S27 /FLECHT-SEASET	S28 / GOETA 42	S29 / NEPTUN	S32 / Marchaterre	S33 /FRIGG-2	A1 / U-tube	A2 / Bubble rise	C1 / Semiscale pump	C2 / INEL jet pump	C3 /SSTF lower plenum	C4 /SSTF upper plenum	**Integr. Facility/ Plant**
Highly Ranked PHENOMENA																																				
Boiling: film	+	+	+																		+															
Boiling: nucleate		+	+																																	
Counter-current flow limit (bypass)				+																																
Counter-current flow limit (jet pump)																																				+
Counter-current flow limit (SEO)						+																												+		
Counter-current flow limit (UTP)				+	+																														+	
Channel-bypass leakage																																				+
Condensation: ECC water							+																											+	+	
Cooling: steam/dispersed flow			+					+	+																											
Dry-out	+	+	+																		+															
Flashing													+	+	+																					
Flow: core flow coastdown																																				+
Flow: critical										+	+	+	0	0	0																					
Flow: lower plenum distribution																																				+
Flow: natural circulation																				+																
Heat: decay																																				+
Heat stored: fuel	0																							0	0	0	0									
Heat stored: metal																																				+
Heat conductance: fuel-clad gap																																				+
Heat transfer: radiation																+																				
Interphase shear			+											+	+		+	+	+									0	0		+					
Jet pump: forward flow																																	+			
Jet pump: reverse flow																																	+			
Power distribution: radial																																				+
Pressure drop																				0		+	+							0						

Table VIII continued: **BWR LOCA Assessment Matrix Using Separate Effects, Component, and Analytical Test Data**

	TEST No./TEST NAME																																		
	S1 / THTF	S2 / Bennett	S5 / Bundle uncovery	S6 / Wallis	S7 / Upper tie-plate CCFL	S8 /Side-entry orifice CCFL	S9 / GOETA	S10 / Heinemann	S11 /THTF	S12 / CFR	S13 / EPRI-Wyle	S14 / Marviken	S15 / Edwards pipe	S16 / GE 1 ft vessel	S17 /GE 3 ft vessel	S18 / GOETA 27	S19 / CISE pipe	S20 / Wallis	S21 /Pericles	S22/ FRIGG natural circ.	S23 / Lehigh	S24 /Sheer & Greer	S25 /Muscettola	S26 / BWR-FLECHT	S27 /FLECHT-SEASET	S28 / GOETA 42	S29 / NEPTUN	S32 / Marchaterre	S33 /FRIGG-2	A1 / U-tube	A2 / Bubble rise	C1 / Semiscale pump	C2 / INEL jet pump	C3 / SSTF lower plenum	C4 /SSTF upper plenum	**Integr. Facility/ Plant**
Highly Ranked PHENOMENA																																			
Recirculation pump: coastdown																																+				
Rewet: blowdown																																				+
Rewet: bottom/reflood																			+					+	+	+	+									
Rewet: top/spray							+																			+										
Spray (ECC) distribution																																			+	
Void: distribution			0											+	+				0	0				0	0		0	+	+							
2-phase level			+						+					+	+																				+	
3-D thermal-hydraulic effect																																		+	+	

Table IX: BWR LOCA Assessment Matrix Using Integral Facility Test Data

	LOCA TEST															FACILITY						
	Large-break in recirc. suction line:	Avg power/ECC normal	/ECC none	Peak power/ECC normal	Peak power/ECC: low flow/high temp.	/ECC: various failures	**Intermediate break:**	RC discharge line break/no HPCS	RC suction break/no LPCS	LPCI line break/no HPCS	**Small-break in recirc. suction line:**	Avg power/no HPCS	/no HPCS/stuck SRV	Peak power/no HPCS	**Steam line break**	FIST	FIX-II	Piper-ONE	ROSA-III	SSTF	TBL	TLTA-5A
Highly Ranked PHENOMENA/																						
Boiling: film		+	+	+	+	+		+		+		+	+	+		+	+	+	+		+	+
Boiling: nucleate		+	+	+	+	+		+	+	+		+	+	+	+	+	+	+	+		+	+
Counter-current flow limit (bypass)		+		+	+	+						+	+	+		0	0	0	0	+	0	0
Counter-current flow limit (SEO)		+	0	+	+	+		+	+	+		+	+	+	+	+	0	0	0	0	0	0
Counter-current flow limit (UTP)		+		+	+	+		+		+		+	+	+	+	+	0	0	+	+	+	+
Counter-current flow limit (jet pump)									+	+		+	+	+	+	+	0	0			+	+
Channel-bypass leakage		+		+	+	+		+	+	+		+	+	+		+			+		0	0
Condensation (ECC water):																						
bypass		+		+	+	+		+	+	+		+	+	+	+	0	0	0	0	+	0	0
downcomer		+		+	+	+		+	0	+		+	+	+	+	0	0	0	0		0	0
guide tubes		0		0	0	0		0	0	0		0	0	0	0	0	0	0	0		0	0
jet pumps		+		+	+	+		+	+	+		+	+	+	+	+	0	+	0		0	0
lower plenum		+		+	+	+		+	+	+		0	0	0	+	0	0	0	0	0	0	0
upper plenum		+		+	+	+		+	+	+		+	+	+	+	0	0	0	0	+	0	0
Cooling: steam		+	+	+	+	+		0		0		+	+	+		+	0	0	0		0	+
Dry-out		+	+	+	+	+		+		+		+	+	+		+	+	+	+		+	+
Flashing																						
bypass		+	+	+	+	+		+	+	+		+	+	+	+	0	0	0	0		0	0
downcomer		+	+	+	+	+		+	0	+		+	+	+	+	0	0	0	0		0	0
lower plenum		+	+	+	+	+		+	+	+		0	0	0	+	0	0	0	0		0	0
Flow: critical																						
jet pumps		+	+	+	+	+		0	0							0					0	0
break location		+	+	+	+	+		+	+	+		+	+	+	+	0	0	0	0		0	0
Flow: natural circulation		+	0	+	+	+		+	+	+		+	+		+	+	+	+	0		+	0
Flow: core flow coastdown		+	+	+	+	+		+	+	+		+	+	+	+	+	+		+		+	+
Flow: lower plenum distribution		+	+	+	+	+			+	+					+	0	0	0	0		0	0
Heat: decay		+	+	+	+	+		+	+	+		+	+	+	+	+	+	+	+	+	+	+
Heat stored: fuel		+	+	+	+	+		+	+	+		+	+	+	+	0	0	0	0		0	0
Heat stored: metal		+	+	+	+	+		+	+	+		+	+	+	+	0	0	0	0		0	0
Heat conductance: fuel-clad gap																						
Heat transfer: radiation		0	+	+	+	+		0		0		+	+	+		+	+	0	+		+	+
Interphase shear		+	+	+	+	+		+	+	+		+	+	+	+	+	+	+	+		+	+
Jet pump: forward flow		+	+	+	+	+		+	+	+		+	+	+		+	+		+		+	+
Jet pump: reverse flow		+	+	+	+	+						+	+	+	+	+	0		0		+	0

Table IX continued: BWR LOCA Assessment Matrix Using Integral Facility Test Data

	LOCA TEST															FACILITY						
	Large-break in recirc. suction line:	Avg power/ECC normal	/ECC none	Peak power/ECC normal	Peak power/ECC: low flow/high temp.	/ECC: various failures	**Intermediate break:**	RC discharge line break/no HPCS	RC suction break/no LPCS	LPCI line break/no HPCS	**Small-break in recirc. suction line:**	Avg power/no HPCS	/no HPCS/stuck SRV	Peak power/no HPCS	**Steam line break**	FIST	FIX-II	Piper-ONE	ROSA-III	SSTF	TBL	TLTA-5A
Highly Ranked PHENOMENA/																						
Power distribution: radial		+	+	+	+	+								+					0	0		
Pressure drop		+	+	+	+	+		+	+	+		+	+	+	+	+	+	+	+	+	+	+
Recirculation pump: coastdown		+	+	+	+	+		+	+	+		+	+	+	+	+	+	0	+		+	+
Rewet: blowdown				+	+											+						+
Rewet: bottom/reflood		+		+	+	+		+		+		+	+	+		+	+	+	+		+	+
Rewet: top/spray		+		+	+	+		+		+		+	+	+		0	0	0	0		0	0
Spray (ECC) distribution		+		+	+														0	+		
Void: distribution		+	+	+	+	+		+	+	+		+	+	+	+	+	+	+	0	+	+	+
2-phase level:																						
bypass		+	+	+	+	+		+		+		+	+	+		+	0	+	0		0	0
core		+	+	+	+	+		+		+		+	+	+		+	0	+	0		0	0
downcomer						+										+						
lower plenum		+	+	+	+	+		+	+	+		+	+	+	+	+	0	0	0		+	+
upper plenum		+		+															0	+		
3-D T/H effect (upper plenum)		+		+																+		
FACILITY/																						
FIST		+							+	+		+	+		+							
FIX-II		+																				
Piper-ONE		+										+										
ROSA-III		+	+	+		+		+	+			+	+	+	+							
SSTF																						
TBL		+										+			+							
TLTA-5A		+	+	+	+							+										

Phenomena vs. LOCA Test
+ = occurring
0 = partially occurring

Phenomena vs. Facility
+ = suitable
0 = partially suitable

LOCA Test vs. Facility
+ = performed

~~Facility Acronyms:~~

FIST=Full Integral Scale Test (USA)
TLTA=Two-Loop Test Apparatus (USA)
ROSA=Rig Of Safety Assessment (Japan)
TBL = Two Bundle Loop (Japan)
SSTF=Sector Steam Test Facility (USA)

Acronyms (less known):

Table X: BWR non-LOCA Assessment Matrix Using Separate Effects and Component Test Data

	TEST No./NAME							
	S3 / Christensen	S4 / UCSB	S22 / FRIGG natural circ.	S30 / FRIGG-3 [1)]	S31 / FRIGG-4 [1)]	S32 / Marchaterre	C5 / SSTF multiple chnls	**Integr. Facility/ Plant**
Highly Ranked PHENOMENA								
Boiling: subcooled	+							
Carry-under								+
Control rod pattern/movement								+
Feedback: fuel temperature								+
Feedback: void								+
Feedwater: temperature decrease								+
Flow: multi-channel T/H effect							+	
Fuel: burnup								+
Fuel: design/type								+
Power distribution: axial								+
Pressure wave propagation								+
Reactivity: scram								+
Stability: neutronic/thermal-hydraulic				+	+			+
Subcooling: coolant	+					+		
Void: collapse						0		+
Void: subcooled liquid	0					+		
3-D kinetics effect								+
3-D thermal-hydraulic effect (mixing)		+						

[1)] thermal-hydraulic stability

Phenomena vs. Test

+ = captured

0 = partially captured

Table XI: BWR non-LOCA Assessment Matrix Using Integral Facility Test and Plant Data

	FACILITY TEST/PLANT EVENT															FACILITY/PLANT								
	AOT:	Feedwater trip	Load rejection trip	MSIV closure	Natural circulation	RC pump trip	Turbine trip	Loss of water supply	ATWS:	Controlled depressurization	Loss of water supply	MSIV closure	Stability:	global oscillations	regional oscillations	FIST	ROSA-III	Browns Ferry	Dodeward	LaSalle-2	Leibstadt	Peach Bottom-2	Ringhals-1	WNP-2
Highly Ranked PHENOMENA/																								
Boiling: subcooled		+	+	+	+	+	+	+		+	+	+		+	+	0	0							
Carry-under		+	+	+	0	+	+	0		0	0	0		+	+	0	0	+	+	+	+	+	+	+
Control rod pattern/movement														+	+				0	0	+	0	+	+
Feedback: fuel temperature		+	+	+		+	+							+	+			+	+	+	+	+	+	+
Feedback: void		+	+	+		+	+							+	+			+	+	+	+	+	+	+
Feedwater: temperature decrease														+	+						+		+	
Flow: multi-channel T/H effect		+	+	+	+	+	+							+	+		+	+	+	+	+	+	+	+
Fuel: burnup														+	+				0	+	+	0	+	+
Fuel: design/type														+	+				0	+	+	0	+	+
Power distribution: axial														+	+				0	+	+	0	+	+
Pressure wave propagation							+											+	+	+	+	+	+	+
Reactivity: scram			+	+			+							+	+			+	+	+	+	+	+	+
Stability: neutronic/thermal-hydraulic														+	+			+	+	+	+	+	+	+
Subcooling: coolant														+	+				0	+	+	0	+	+
Void: collapse			+	+			+					+				+	+	+	+	+	+	+	+	+
Void: subcooled liquid		+	+	+		+	+							+	+	+	+	+	+	+	+	+	+	+
3-D kinetics effect															+			+	+	+	+	+	+	+
3-D T/H effect (mixing)																		+	+	+	+	+	+	+
FACILITY/PLANT/																								
FIST					+		+	+		+	+	+												
ROSA-III					+																			
Browns Ferry		+	+			+																		
Dodeward														+										
LaSalle-2														+										
Leibstadt		+		+										+	+									
Peach Bottom-2							+																	
Ringhals-1														+	+									
WNP-2														+										

Phenomena vs. Facility Test/Plant Event
+ = occurring
0 = partially occurring

Phenomena vs. Facility/Plant
+ = suitable
0 = partially suitable

Test/Event vs. Facility/Plant
+ = performed/occurred

Table XII: Phenomena Ranked High in BWR LB-LOCA PIRT: Justification and Key Physical Parameters

Phenomenon	Phase	Justification	Key Physical Parameters: Parameter	Key Physical Parameters: Range
Boiling: film		Heat transfer in this mode governs the maximum peak clad temperature (PCT). It includes cooling such as dispersed flow in the refill/reflood phase before rewetting.	Pressure Wall temperature Local quality (Void)	15-1200 psia >min. film boil. temperature >critical quality >0.7 but <0.999
Boiling: nucleate		Heat transfer in this mode governs the fuel temperature during the long-term cooling phase.	Pressure Wall temperature (Void)	15-1200 psia <critical heat temperature <0.999
Condensation: ECC water		Effects pressure decrease by condensation in lower plenum, downcomer, bypass, and reduces flow of steam through limiting openings - such as the upper tie-plate (UTP).	Pressure ECC temperature $\text{Quality}_{\text{equilibrium}}$	15-150 psia <saturation temperature ~0-1.1
Counter-current flow limit (CCFL)	BL, RR BL, RR RR RR	• CCFL at side-entry orifice (SEO) retards gravitational channel drainage especially during blowdown. • CCFL at UTP limits ECC water delivery into the core after a core spray actuation. • CCFL at the top of bypass limits ECC water delivery after a core spray actuation. • CCFL at the jet pump inlet limits ECC water delivery into the lower plenum after an LPCI actuation (BWR/3 and /4).	Pressure Mass $\text{velocity}_{\text{vapor}}$ • UTP • SEO Mass $\text{velocity}_{\text{liquid}}$ • UTP • SEO Subcooling	15-750 psia 0.1-3.0 lb/ft^2-s 0.1-1.5 lb/ft^2-s 1-20.0 lb/ft^2-s 1-10.0 lb/ft^2-s 0-100 deg F
Channel-bypass leakage		Reverse flow via the channel-bypass leakage path aids in channel cooling during blowdown and refill.	Reverse flow	~1 lb/sec
Cooling: steam		Steam cooling may occur in the refill/reflood phase before rewetting. It governs the PCT.	Pressure Heat flux $\text{Quality}_{\text{equilibrium}}$ (Void)	15-150 psia ~5000 Btu/ft^2-hr ≥1.0 >0.999
Dry-out (critical heat flux)		Prediction of dry-out (temperature excursion) is important for cladding failure analysis.	Pressure Mass velocity Void	15-1200 psia ~0-260 lb/ft^2-s ~0.7-1.0
Flashing	BL	Affects depressurization, break flow, and core cooling via liquid entrainment.	Pressure Geometry	300-1000 psia Plenum, pipes, annulus
Flow: core flow coastdown		Determines fuel cooling during the early stage of blowdown.	RC pump torque/inertia	see RC pump: coastdown
Flow: critical		Determines break flow thus affecting depressurization of the system and its mass inventory, i.e. uncovery of the core.	Pressure Subcooling L/D	40-1200 psia 0-30 deg F >1
Flow: lower plenum distribution		Affects core cooling in the early phase of blowdown.	Core/plenum flow area Hydraulic resistance	~ ~

Table XII continued: Phenomena Ranked High in BWR LB-LOCA PIRT: Justification and Key Physical Parameters

Phenomenon	Phase	Justification	Key Physical Parameters: Parameter	Key Physical Parameters: Range
Flow: natural circulation		Internal natural circulation pattern may develop during refill/reflood (core shroud-downcomer) persisting into the long-term cooling phase.	Power Downcomer level Hydraulic resistance	
Heat: decay		Affects peak clad temperature and dry-out occurrence.	Burnup	
Heat stored: fuel		Important heat input during the blowdown phase.	UO_2 temperature UO_2 heat capacity	
Heat stored: metal		Affects refill of the lower plenum and bypass (less in BWR/5 and /6).	Coolant volume/structure mass Coolant volume/structure area	
Heat conductance: fuel-clad gap		Governs removal of stored heat in the fuel.	Burnup (Fuel-clad interaction)	
Heat transfer: radiation		Affects the PCT during the heat-up phase (BWR/2).	Temperature gradient Emissivity Geometry	
Interphase shear		• Affects the fluid behavior under two-phase conditions - determines the two-phase level (level swell). • Governs phase separation and entrainment in the lower plenum and determines the two-phase level in the upper plenum, e.g.	Pressure Mass velocity Geometry ($diameter_{hydraulic}$)	
Jet pump: forward flow		Governs flow coast-down in the early blowdown stage.	Mass velocity	
Jet pump: reverse flow		Affects significantly break flow during the blowdown phase.	Mass velocity	
Power distribution: radial		Determines the radial power distribution (channel grouping).	Neutron leakage Burnup	0.5 – 1.2 of avg power (see above)
Pressure drop		• Governs behavior of an individual channel (or a group of similar channels) due to the BWR parallel channel (incl. bypass) configuration. • Affects the flow distribution during the blowdown phase along the in-shroud and downcomer flow path towards the break location in a recirculation line.	Geometry Hydraulic resistance	
RC pump: coast-down		Governs the core flow in the early blowdown stage.	RC pump torque/inertia	1.2-1.8
Rewet: blowdown		Temporary fuel dry-out followed by rewet before ECCS actuation (observed during blowdown in some LOCA experiments).	Wall temperature	
Rewet: bottom/reflood		ECC water entering the core from bottom gradually rewetting dry fuel while progressing upwards.	Wall temperature	

Table XII continued: Phenomena Ranked High in BWR LB-LOCA PIRT: Justification and Key Physical Parameters

Phenomenon	Phase	Justification	Key Physical Parameters Parameter	Range
Rewet: top/spray		Falling liquid film due to core spray rewetting the core from above while progressing downwards.	Wall temperature	
Spray distribution		Affects CCFL and its breakdown at the upper tie-plate.	Sparger geometry	
Void: distribution		• Determines flow regime in both the blowdown and reflood phases. • Affects cooling of the core in the blowdown phase, determines timing of jet pump exit uncovery in the lower plenum, uncovery of the jet pump inlet, break flow composition (steam contribution). • Affects the amount of condensation in the upper plenum after a core spray actuation.	Pressure Mass velocity	
2-phase level		• Location of the mixture (2-phase) level is crucial for fuel-coolant heat transfer below and above the 2-phase level. • Determines timing of jet pump exit and SEO uncovery in the lower plenum in the blowdown phase, and uncovery of the jet pump inlet, recirculation line suction and HPCI sparger in downcomer. • Also affects the amount of condensation in the upper plenum after core spray actuation.	Pressure Pressure gradient (dP/dt) Mass velocity	
3-D thermal-hydraulic effect		In the upper plenum after spray actuation.	Subcooling	

Acronyms:
ECC=emergency core cooling
HPCI=high-pressure coolant injection
LPCI=low-pressure coolant injection
SEO =side-entry-orifice
RC=main recirculation

Notes:
1) The key phenomena has been ranged in terms of physical, i.e. measurable, parameters whenever possible.

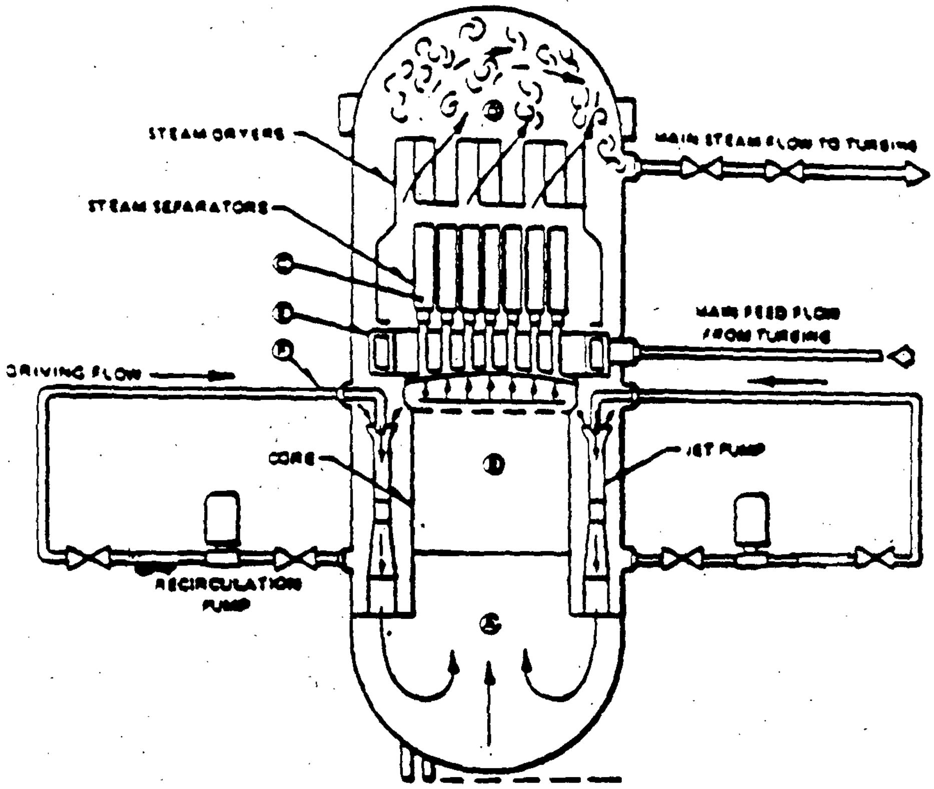


Fig. 1: Simplified BWR/4 system Illustration

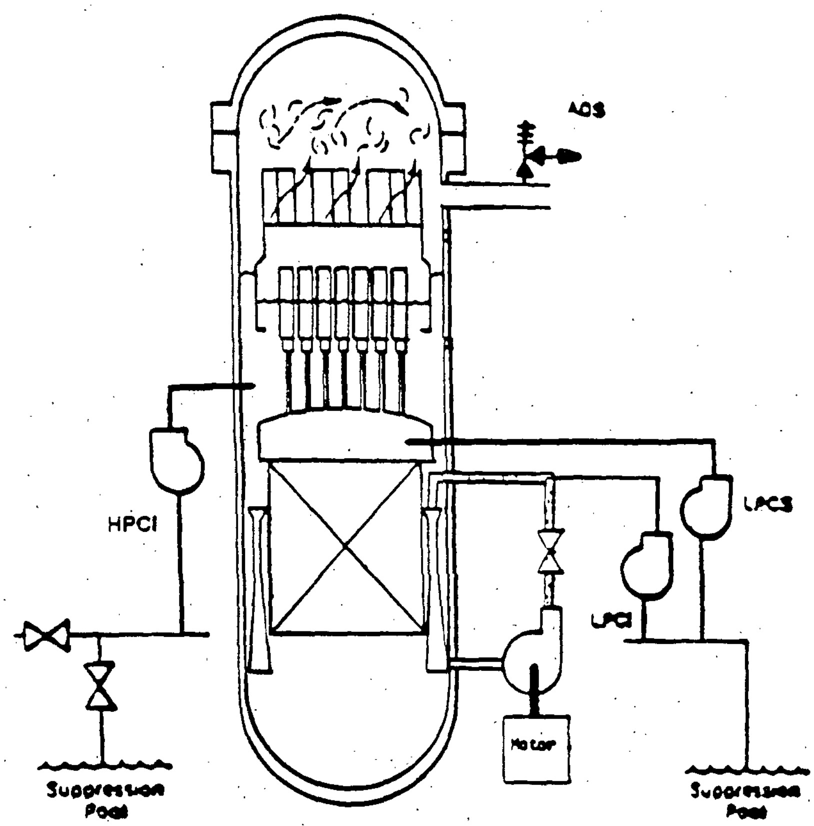


Fig. 2: Simplified BWR/4 Emergency Core Cooling system

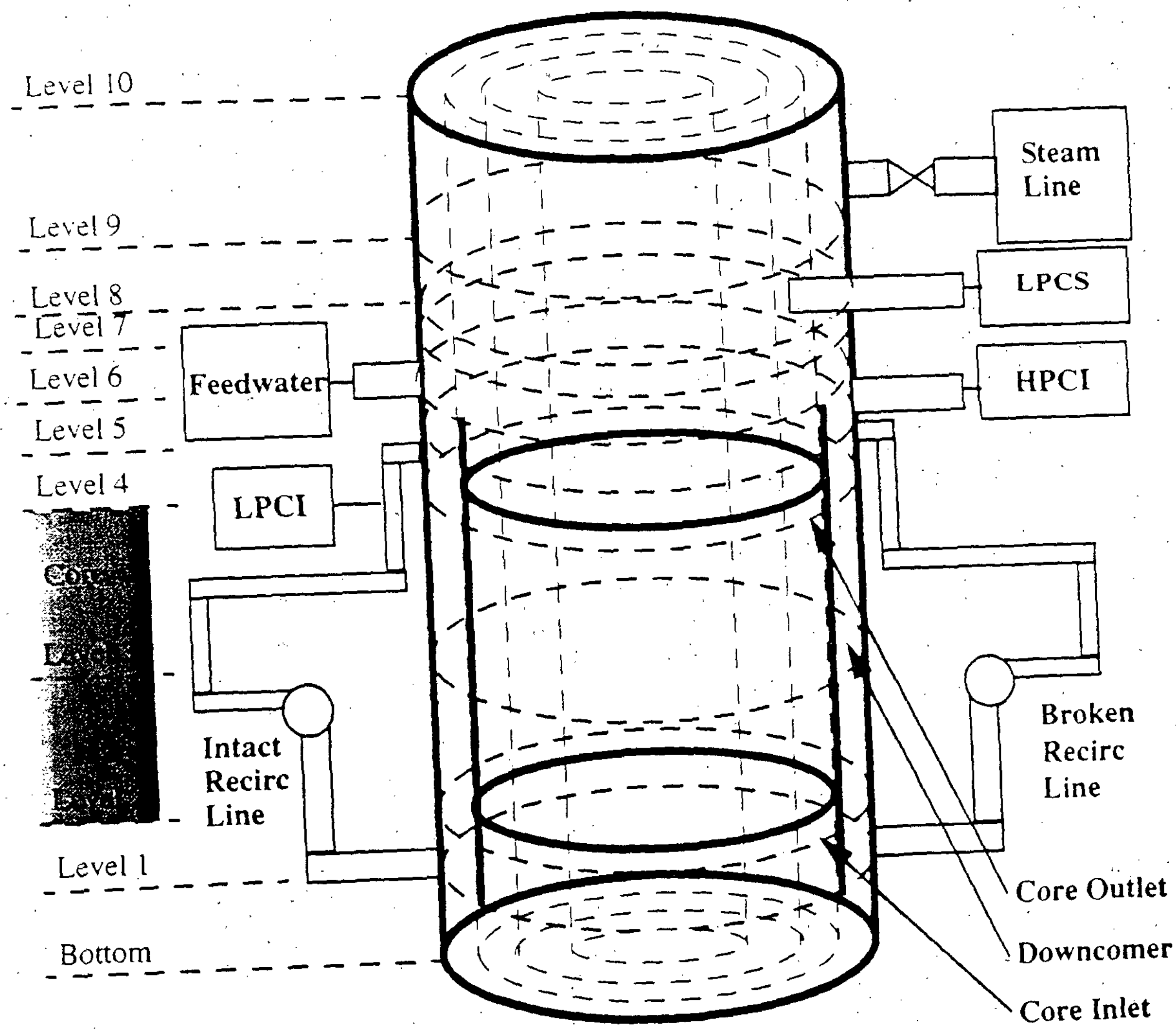
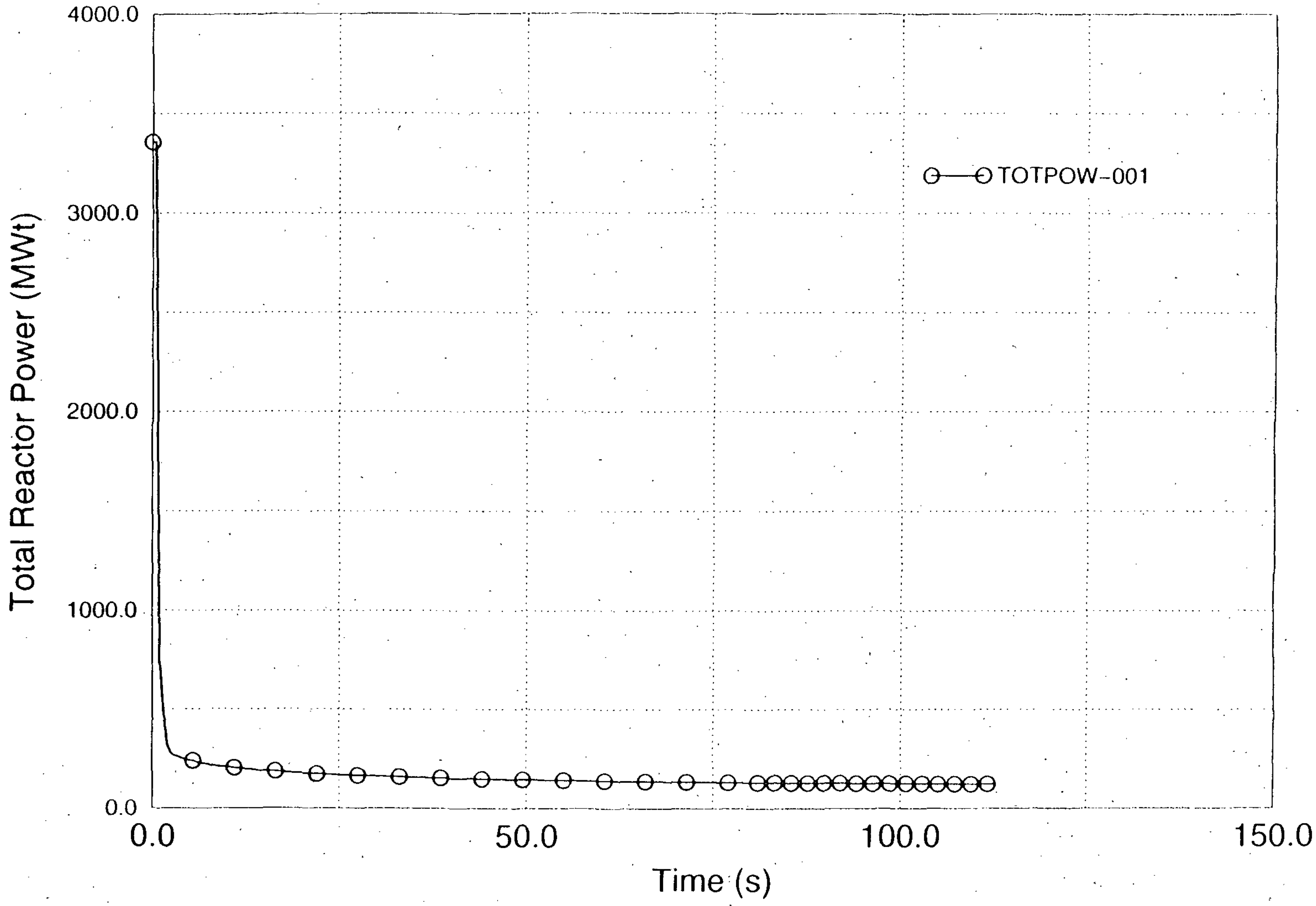


FIGURE 3: BWR/4 Nodalization Diagram

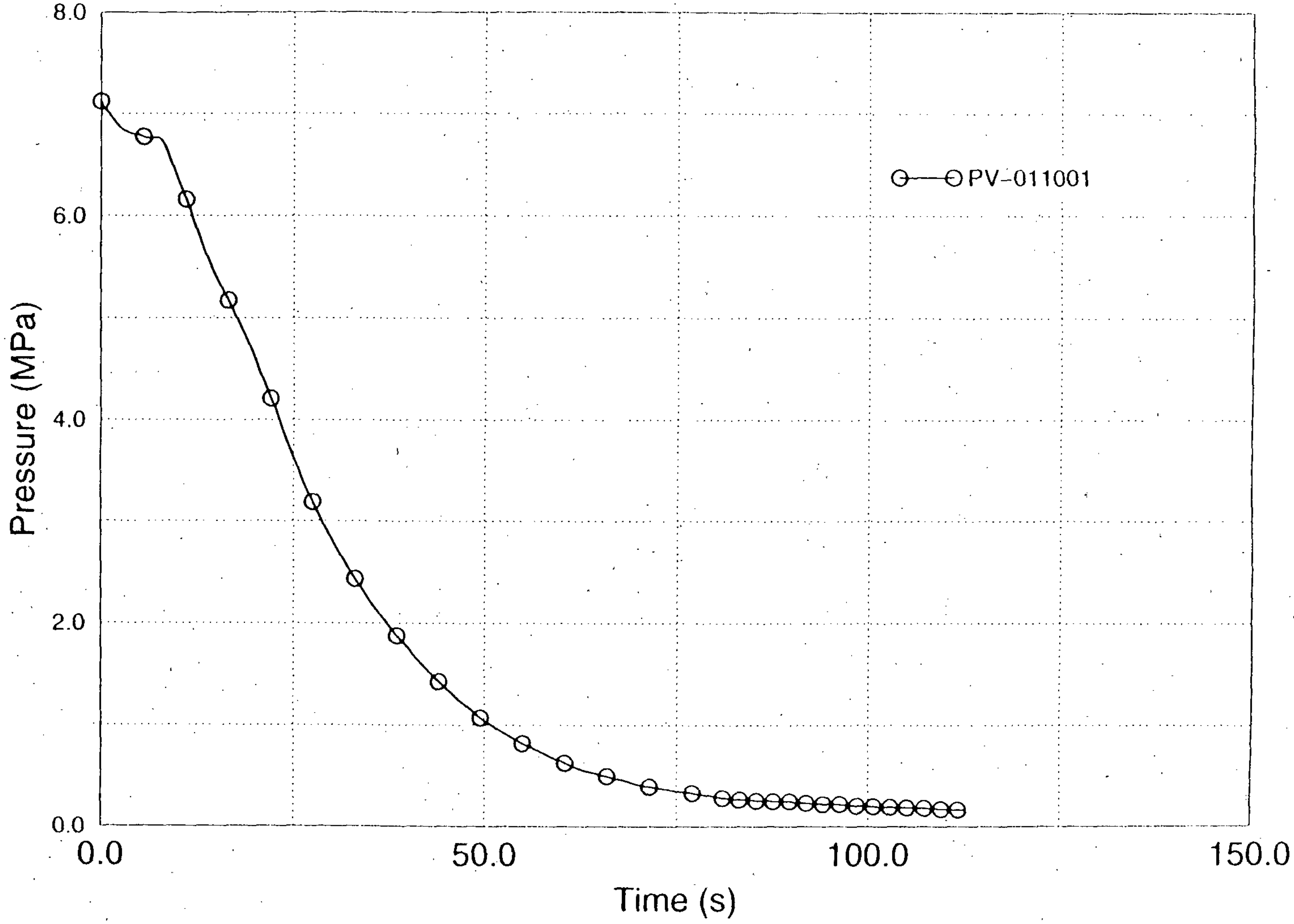
BWR/4 Large Break LOCA

(Figure 4: Reactor Power)



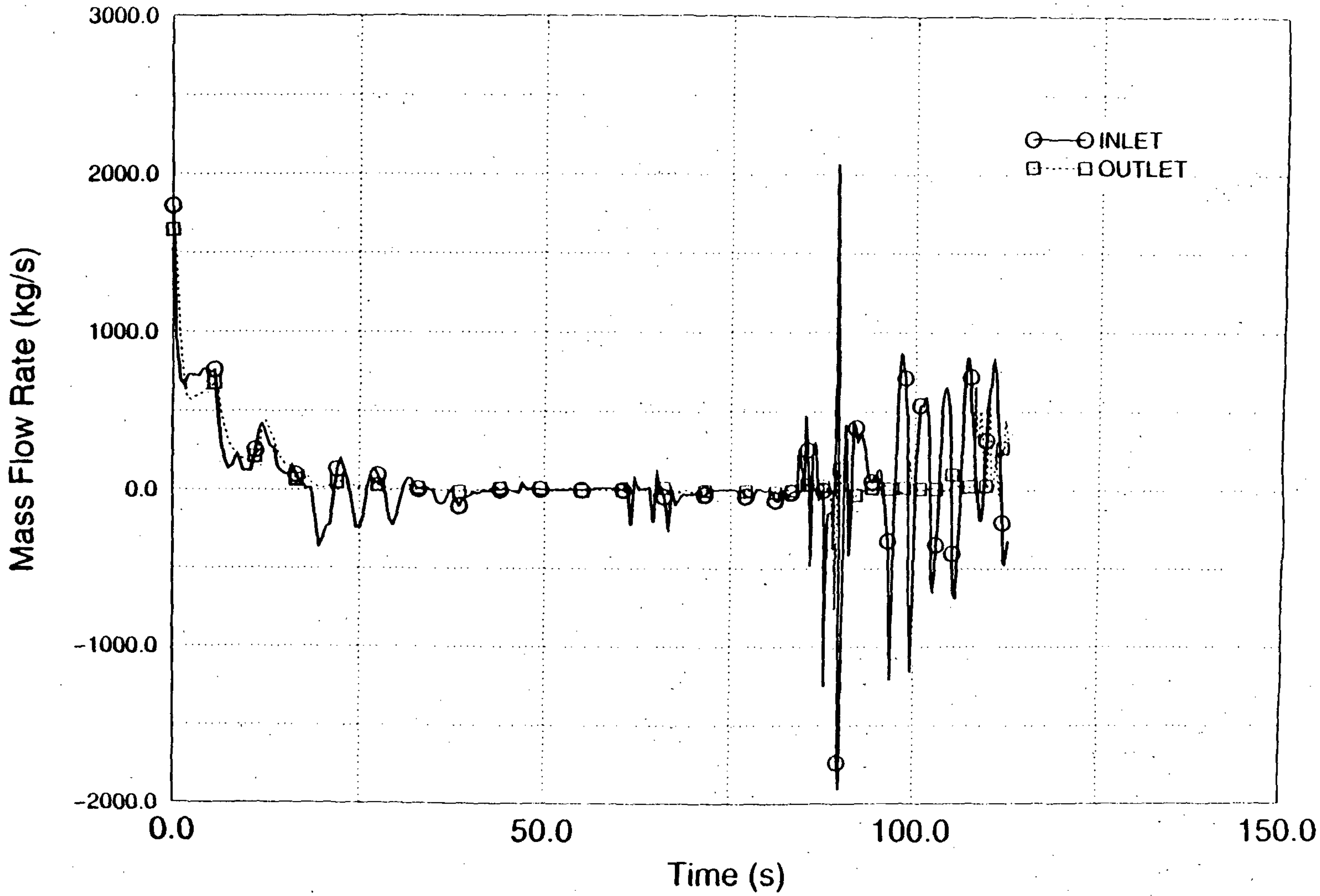
BWR/4 Large Break LOCA

(Figure 5: Reactor Dome Pressure)



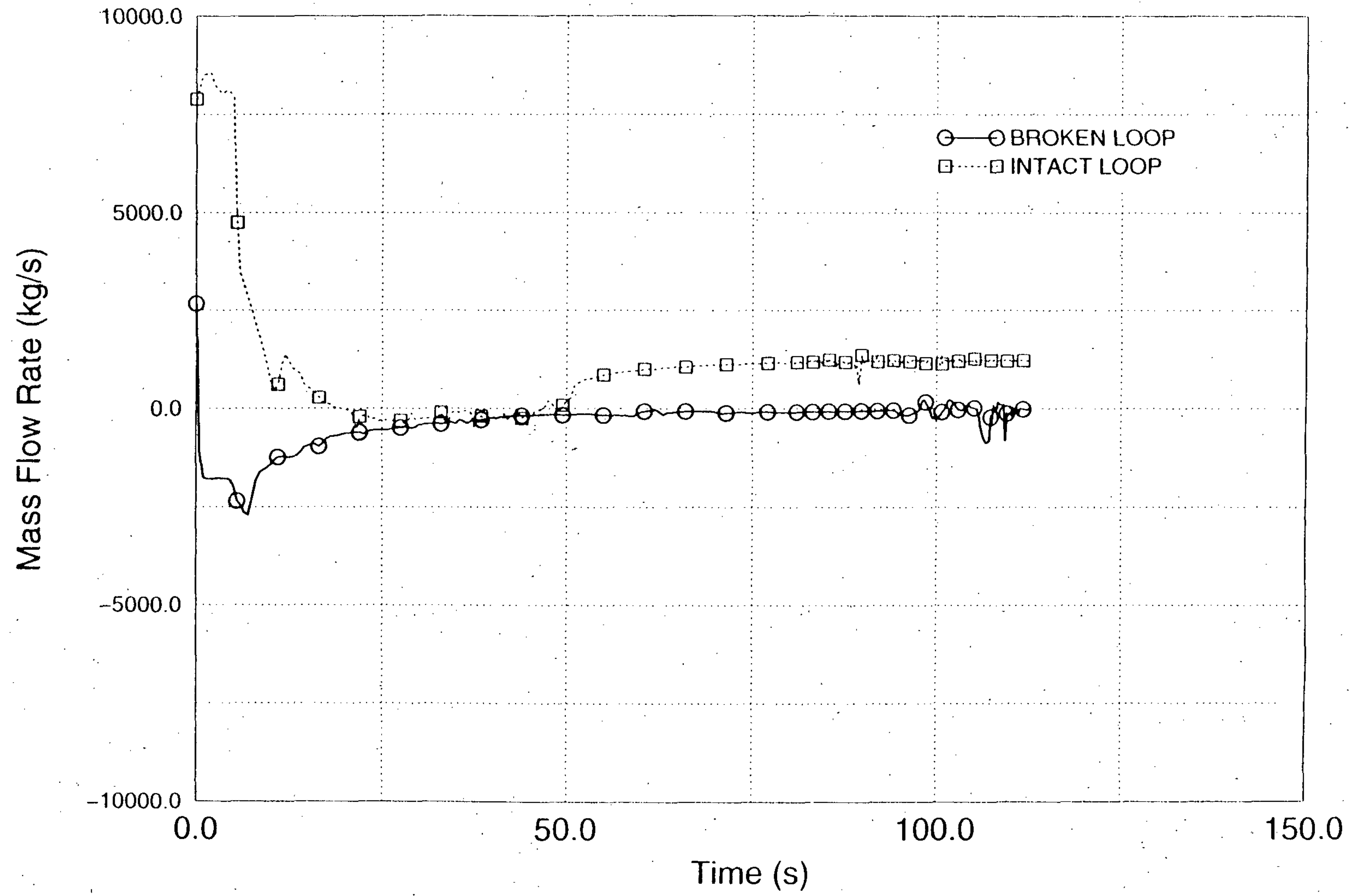
BWR/4 Large Break LOCA

(Figure 6: Channel Inlet and Outlet Flow Rate: High-Power)



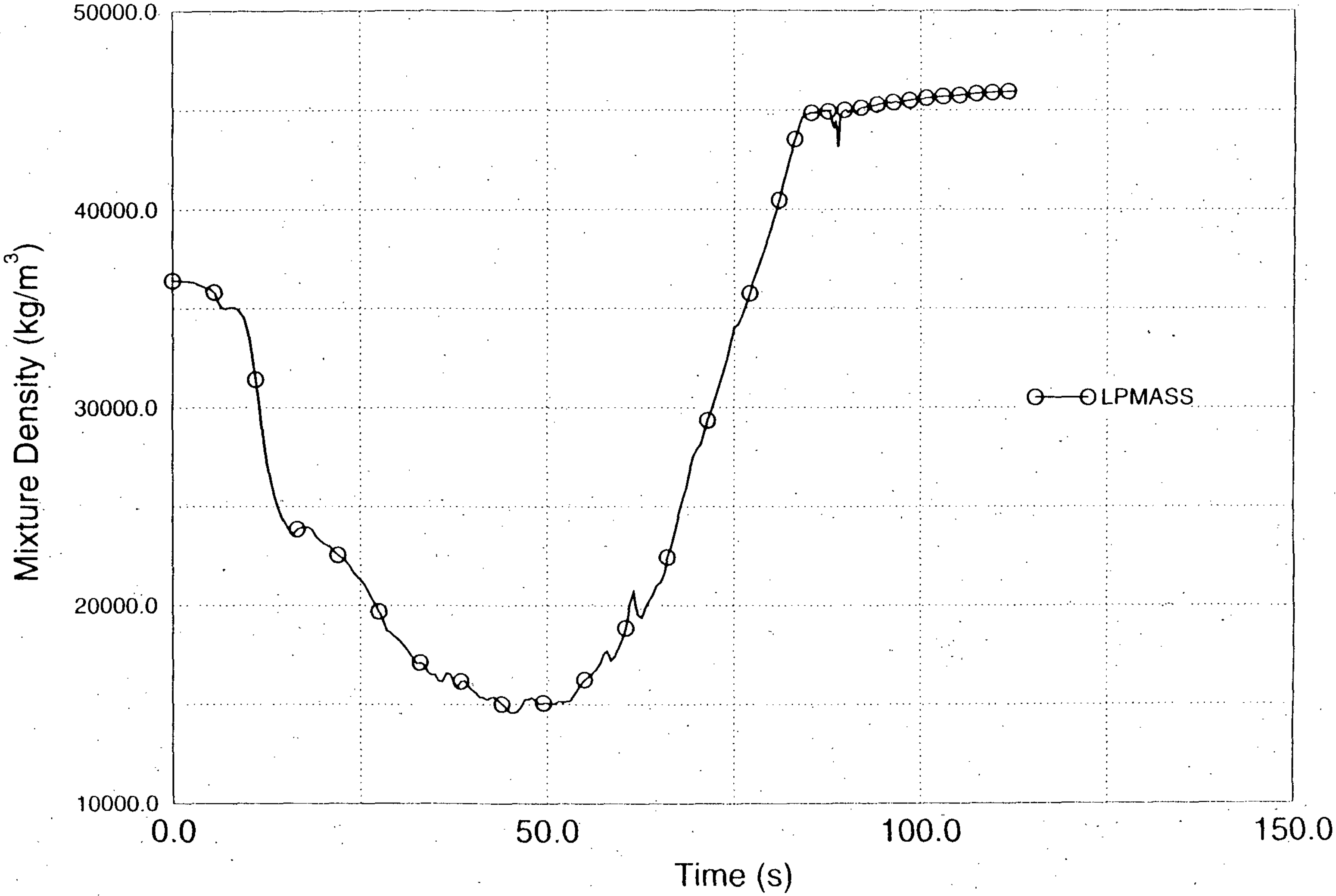
BWR/4 Large Break LOCA

(Figure 7: Flow Rate through Jet Pump Discharge)



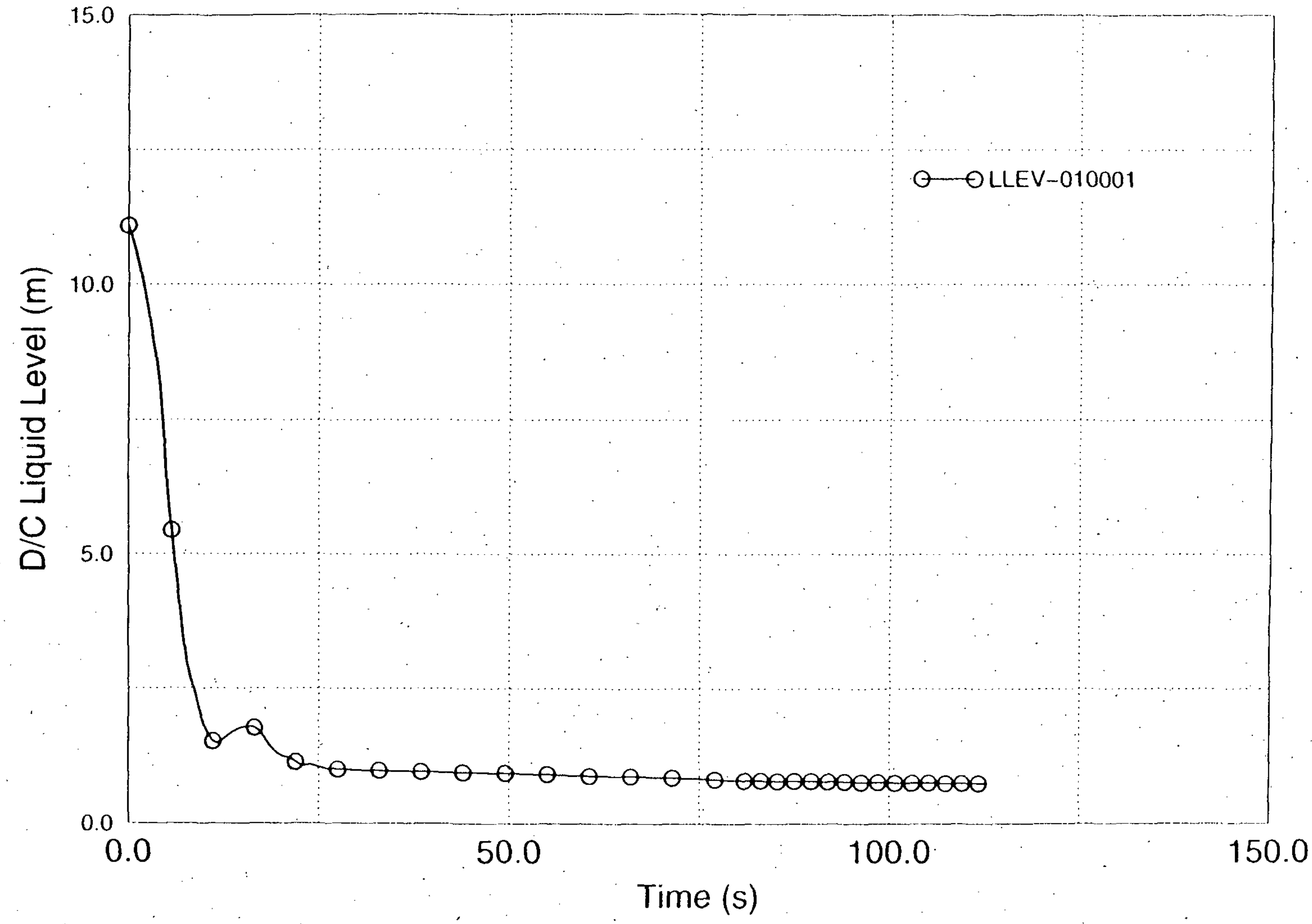
BWR/4 Large Break LOCA

(Figure 8: Lower Plenum Fluid Mass)



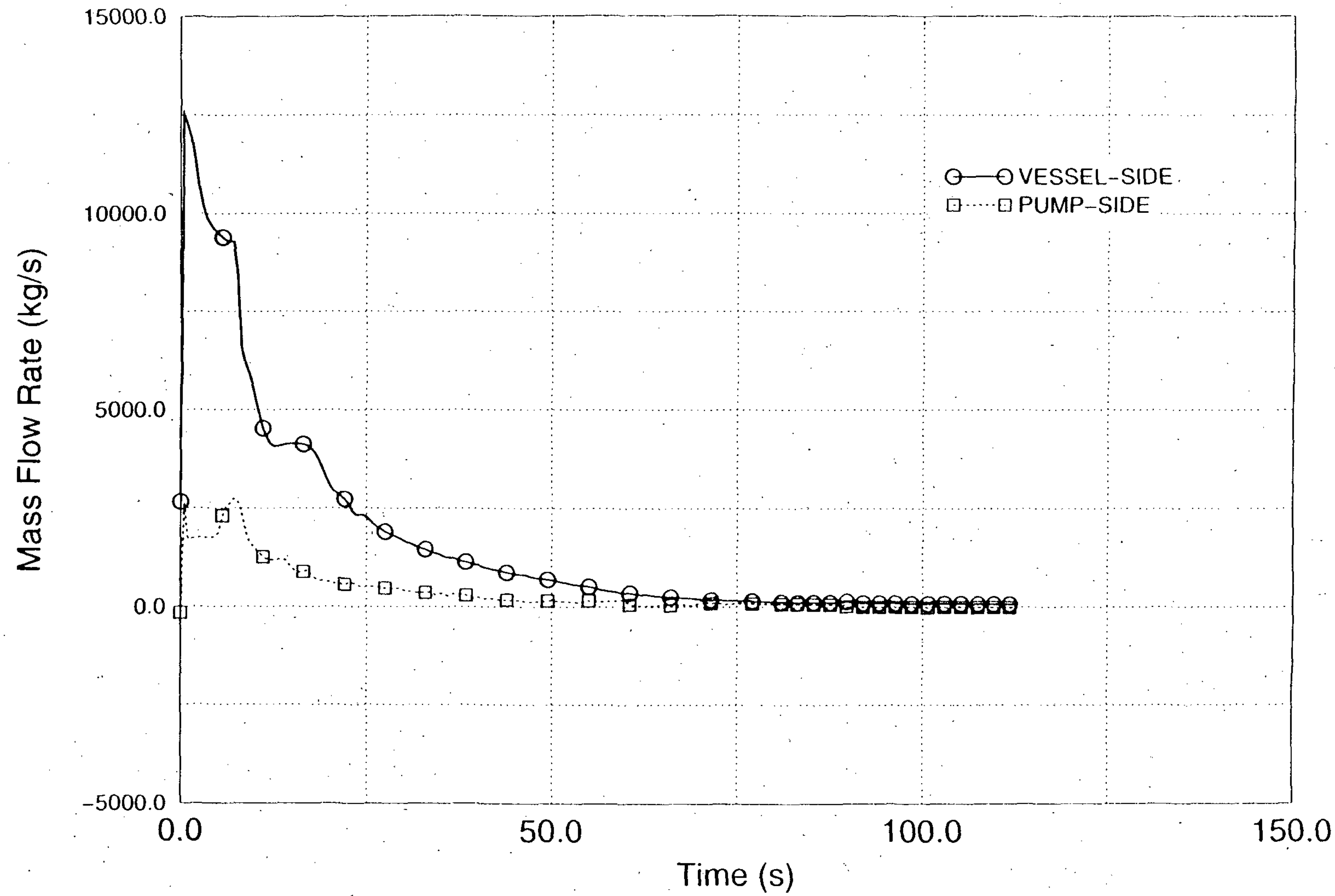
BWR/4 Large Break LOCA

(Figure 9: Downcomer Liquid Level)



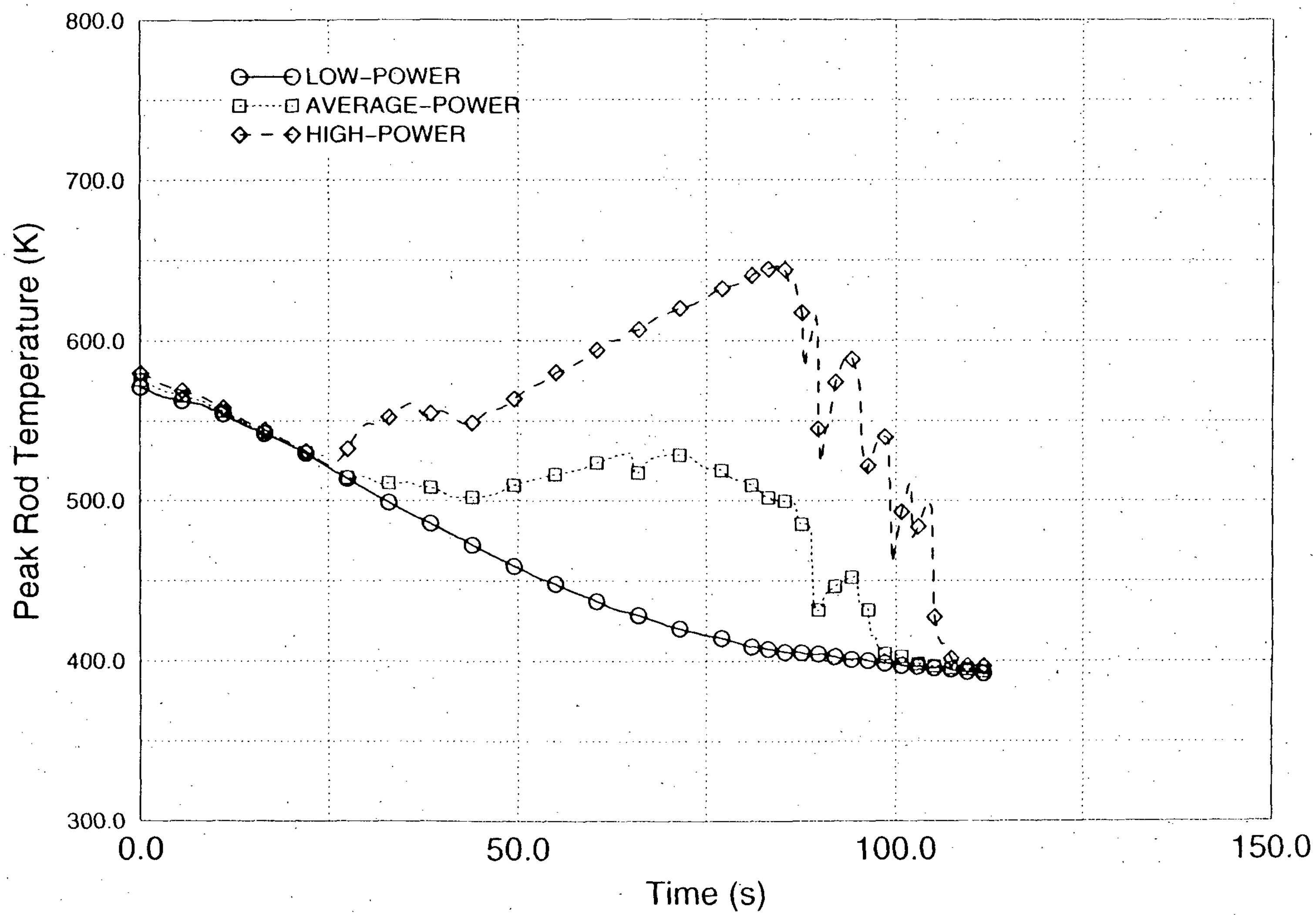
BWR/4 Large Break LOCA

(Figure 10: Break Mass Flow Rate)



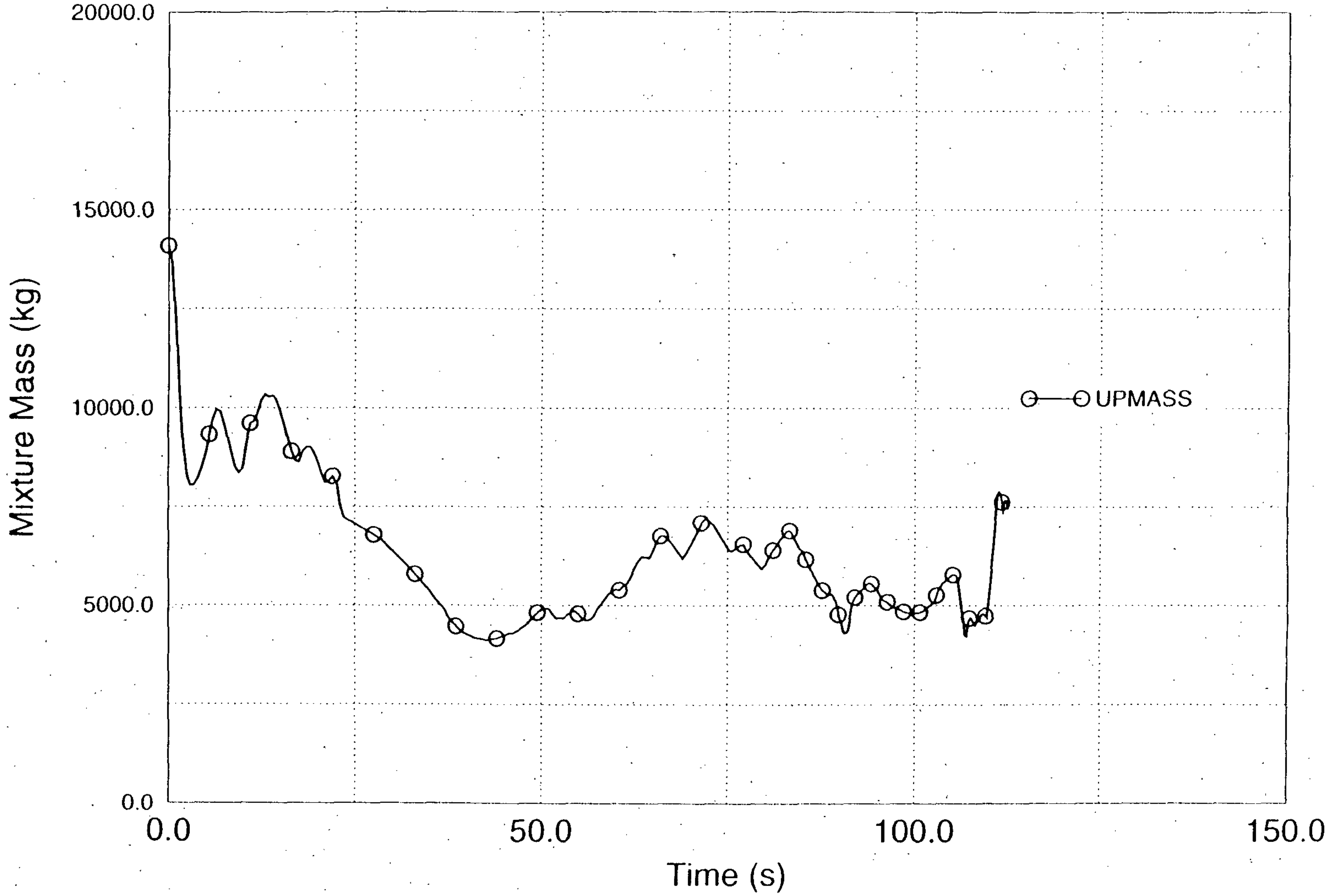
BWR/4 Large Break LOCA

(Figure 11: Peak Clad Temperatures)



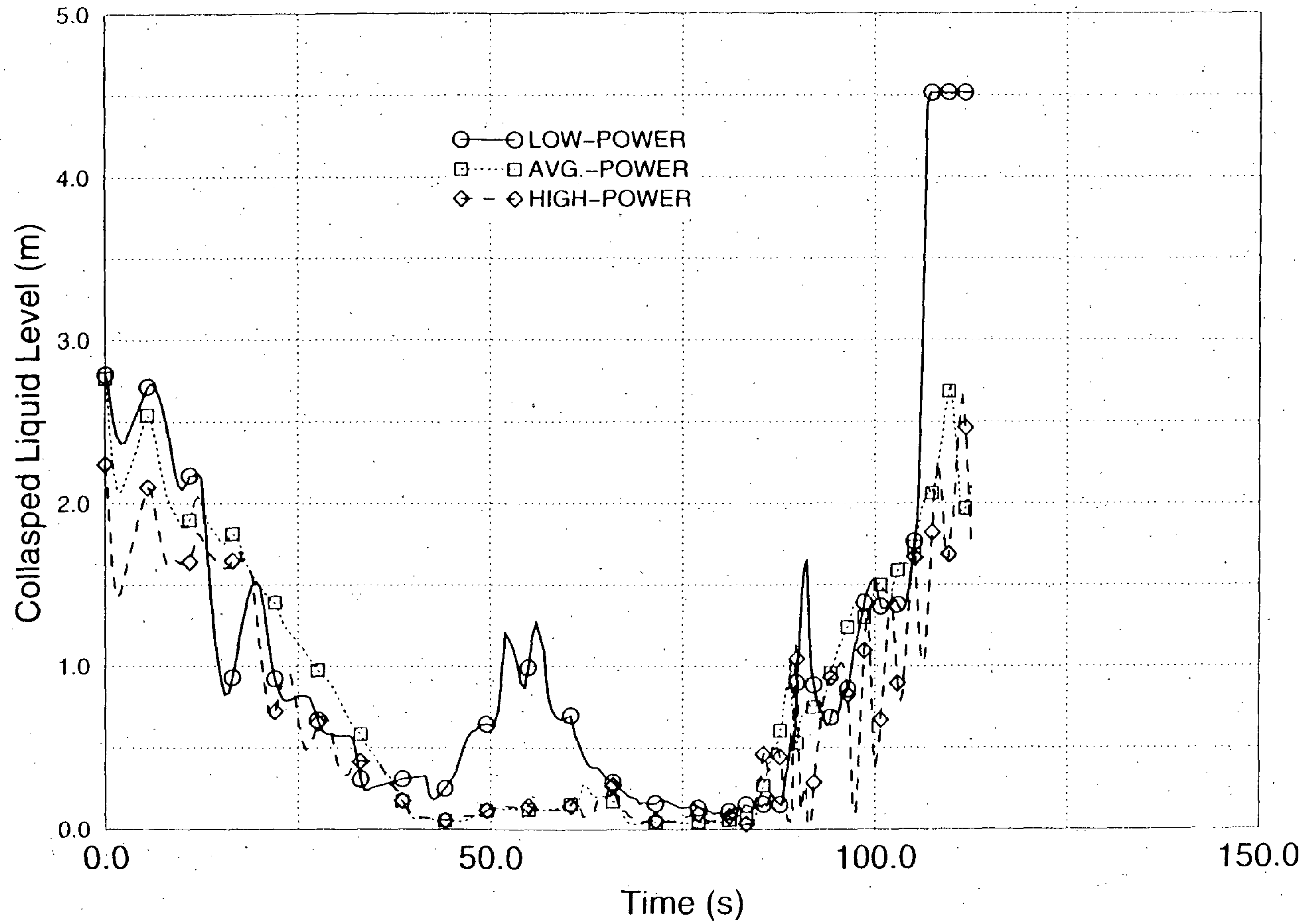
BWR/4 Large Break LOCA

(Figure 12: Upper Plenum Fluid Mass)



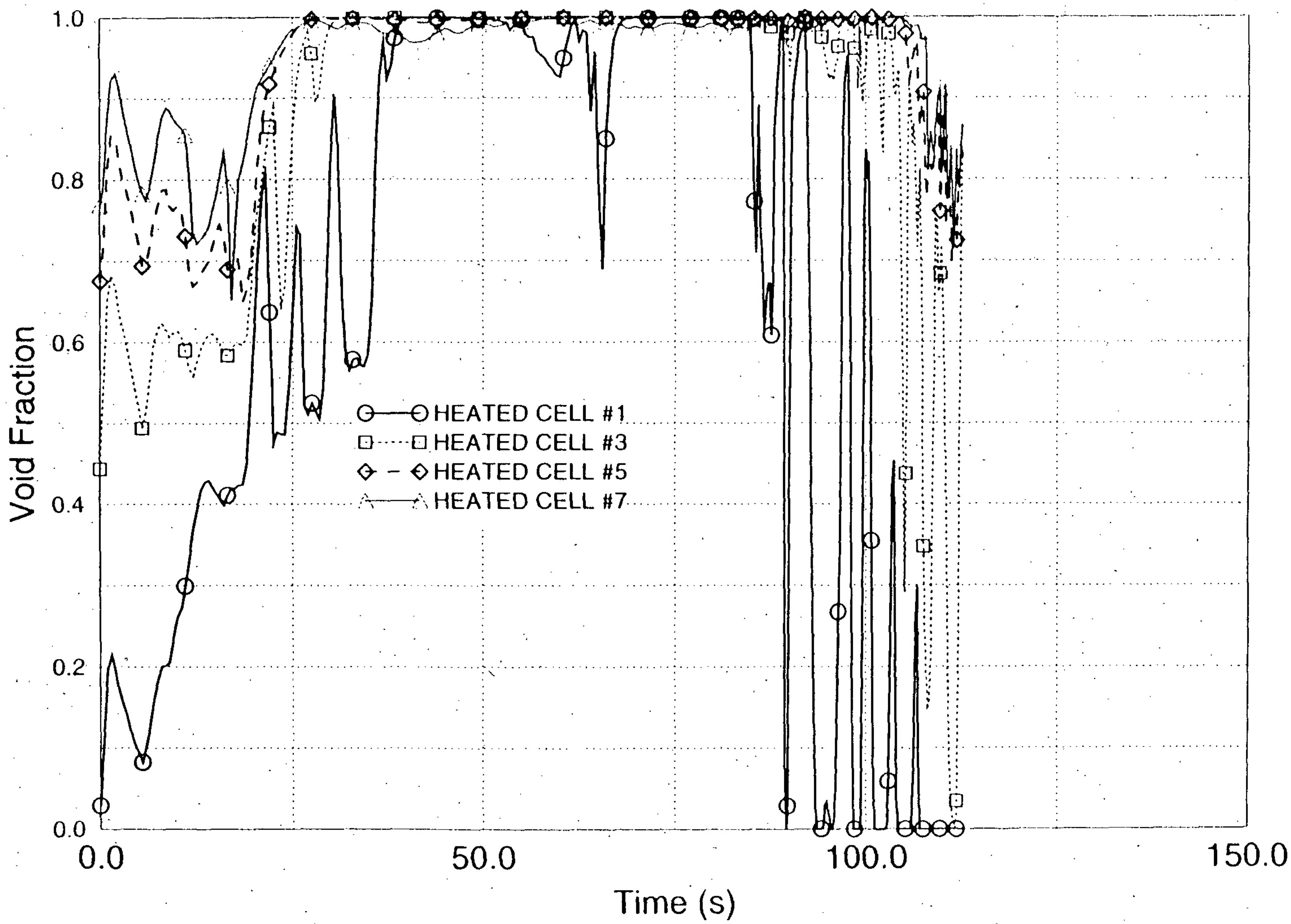
BWR/4 Large Break LOCA

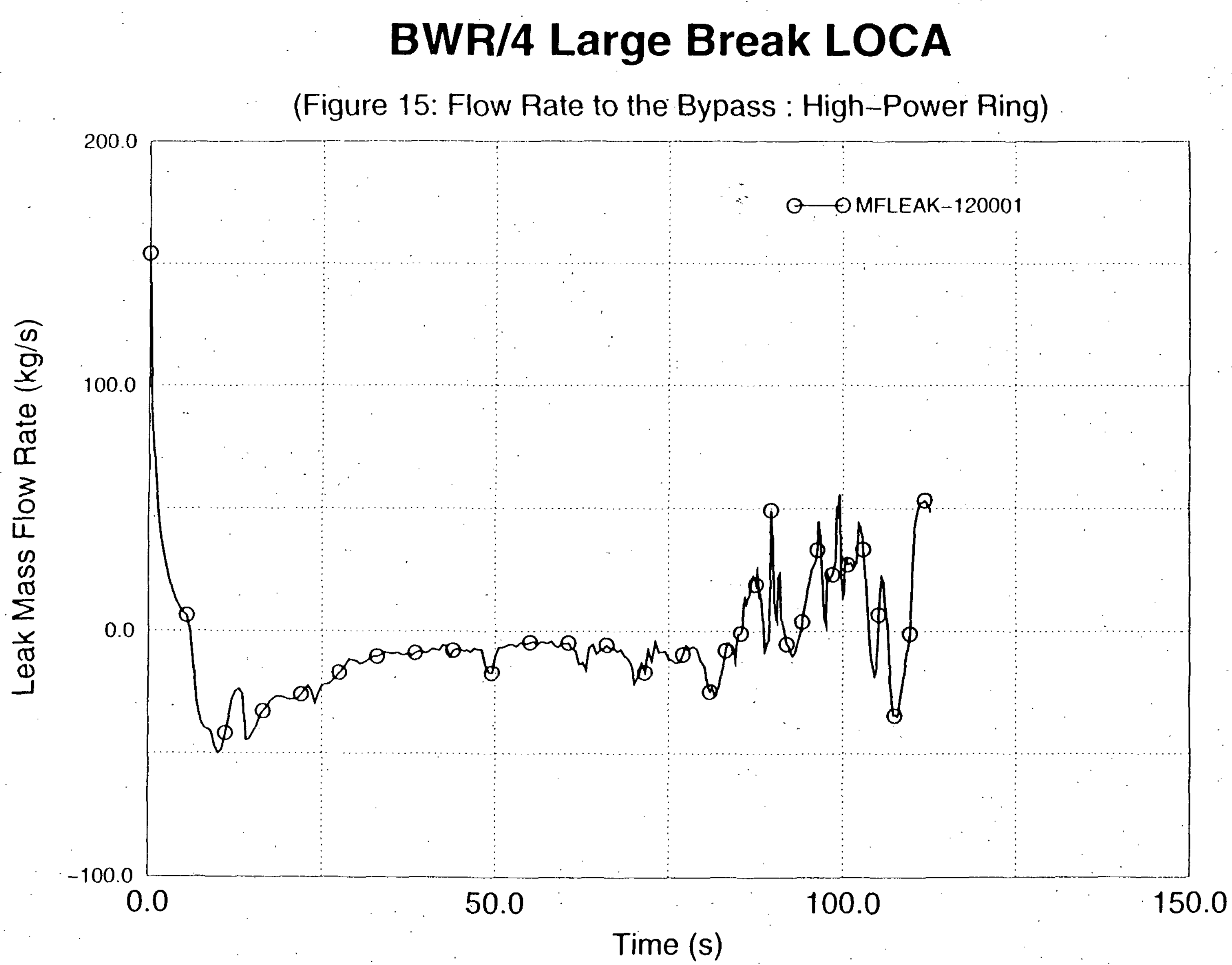
(Figure 13: Collapsed Liquid Level of the Channels)



BWR/4 Large Break LOCA

(Figure 14: Axial Void Distribution in High-Powered Channel)

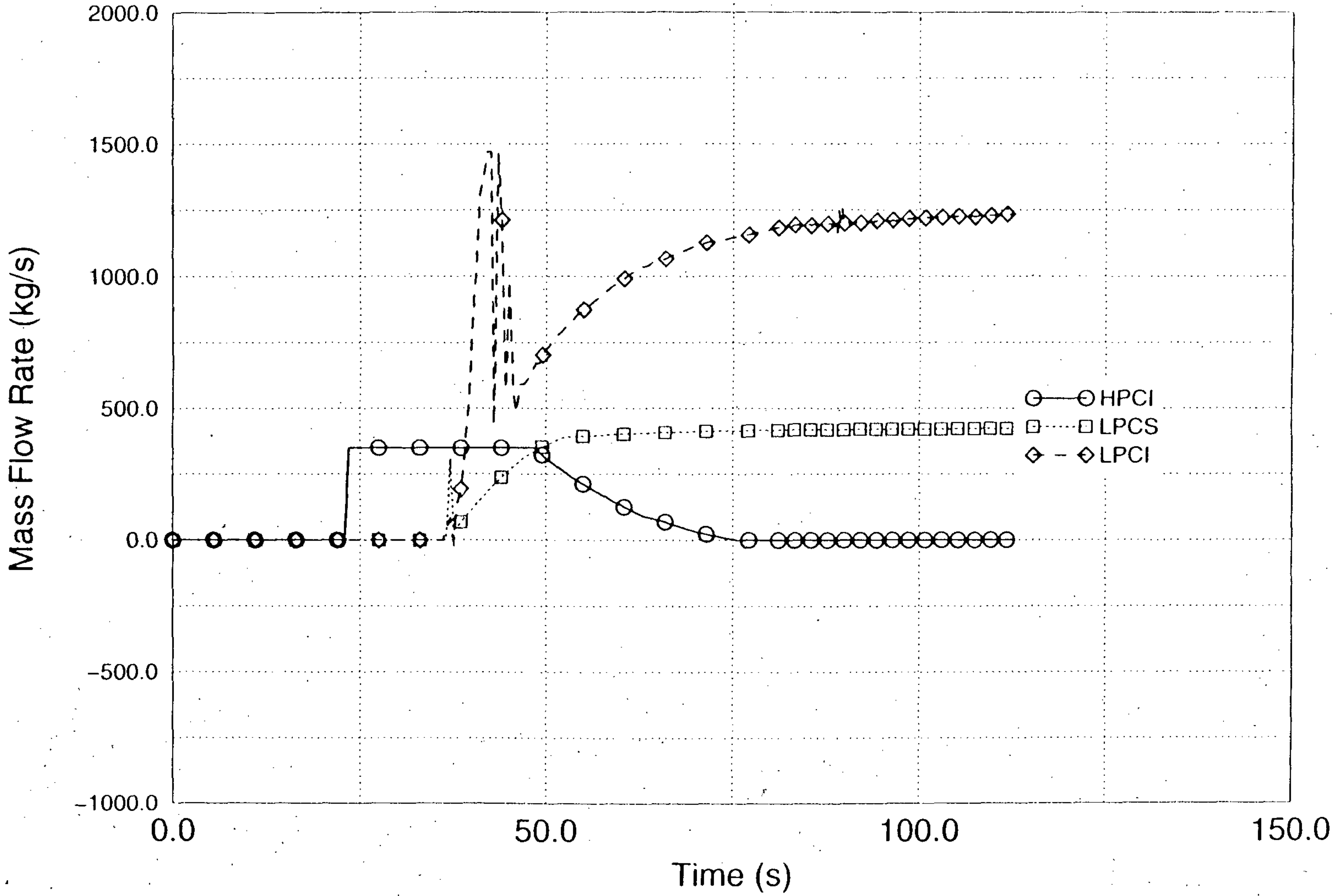




BWR/4 Large Break LOCA
(Figure 15: Flow Rate to the Bypass : High-Power Ring)
MFLEAK-120001
Leak Mass Flow Rate (kg/s)
200.0
100.0
0.0
-100.0
0.0
50.0
100.0
150.0
Time (s)

BWR/4 Large–Break LOCA

(Figure 16: Core Cooling Water Injection Rate)



APPENDIX A

This Appendix contains the parameter ranges for the highly ranked phenomena for the large break LOCA event as summarized in Table V. The parameter ranges are given for the plant, the separate effects tests, and integral experiments. Please also note that several of the highly ranked phenomena and associated parameter ranges for the BWR LOCA reference the parameter range tables developed for the PWR LB LOCA, since the test data are applicable to BWR behavior as well.

Please also note that references to Table D in the Appendix A Tables refers to the ranging tables developed for PWRs in Boyack, B. E. and Lime, J. F., "TRAC-P PWR Large Break LOCA Validation Matrix (DRAFT)," LANL, January 27, 1999, Rev. 0.0. The parameter ranges and experiments developed for the highly ranked phenomena for the PWR PIRTS, in some cases, are applicable to those developed for BWRs and are appropriately referenced in this Appendix.

Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill/reflood				
PIRT Parameter	**Counter-Current Flow (Upper Tie Plate)**				
	Plant Range	Test Facility			
Plant Parameter		Tobin BD/ECC	Jones BD/ECC(GE 8x8 bundle data)	Naitoh et. al.	GOTA BWR ECC Tests
P (MPa)	0.1 – 5.0	Near atmospheric	Near atmospheric	Near atmospheric	0.1- 2.0
Steam Flow (gm/s)	90 – 200	36 – 99	0 – 126	43 –83	
Liquid Flow (cm^3/s)	0 – 1000	549 –972	315 – 916	117 – 1033	0.045 – 2.20 Kg/s
$Kf^{1/2}$	0 – 2.1		0.0. – 0.8	0.0 – 0.7	
$Kg^{1/2}$	0 - 2.1		1.0 – 2.1	1.0 – 2.1	
Water Temp (°C)	40 – 80	Saturated	38 – 96	27 – 97	37 – 97
Comments	Note that the range for Kf and Kg include the range where CCFL exists. Data on a channel basis	Sat. steam/water	Sat. steam	Steam inlet from bundle bottom	Top spray, 64 rods(CCF in bundle pacers, not in tie plate)

References

1. D.D. Jones, "Test Report TLTA Components CCFL Tests," GE Nuclear Systems Products Division, BD/ECC Program, NEDG-NUREG-23732, (1977).
2. R. Tobin, CCFL Test Results, Phase 1 – TLTA 7x7 Bundle," GE Nuclear System Products Division, BD/ECC Program, GEAP-21304-5 (1977).
3. D.D. Jones, "Subcooled Countercurrent Flow Limiting characteristics of the upper Region of a PWR Fuel Bundle," GE Nuclear Systems Products Division, BD/ECC Program, NEDG-NUREG-23549, (1977).
4. M. Natitoh, et. al., "Restrictive Effect of Ascending Steam on Falling Water during Top spray Emergency core Cooling," J. of Nucl. Sci. and Tech.,Vol 15, 11, pp 806, (1978).
5. Sun, K. H. and Ferdandez, R. T.,"Countercurrent Flow Limitation Correlation for BWR Bundles during a LOCA, ANS Transactions, Vol. 27, pp. 605, (1977).
6. Sun, K. H., "Flooding Correlations for BWR Bundle Upper tie Plate and side Entry Orifices," Second Multi-Phase Flow and Heat Transfer Symposium Workshop, Miami Beach, Florida, April 16-19, 1979.

Table A-1 (cont) Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)
Transient Phase	Blowdown, refill/reflood
PIRT Parameter	**Countercurrent flow (upper tie plate)**

	Plant Range	Test Facility			
Plant Parameter		UPTF			
P (MPa)	0.1 – 5.0	0.3 – 1.5			
Steam flow (Kg/s)	61 – 153	35 – 300			
Liquid flow (Kg/s)	300 – 460	30 – 1200			
$Kf^{1/2}$	0 – 2.1				
$Kg^{1/2}$	0 – 2.1				
Water Temp. (°C)	40 – 80	Sat – 30.0			
Flow cross section, (m2)	2.6	3.755(1:1 scale)			
Comments	Flow cross section is for BWR/4, hole dia. is also important. Data on a core basis.	Steady-state hot leg water injection			

<u>Nomenclature</u>

P, pressure

$Kf^{1/2}$, Kutateladze No. for liquid

$Kg^{1/2}$, Kutateladze No. for steam

References

1. Simon, U. et al, "UPTF Calibration Tests, Final Report on Research Project BMFT 1500664, Kraftwerk Union, Technischer Bericht R 54/85/14, December 1985.

Table A-2 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill/reflood				
PIRT Parameter	**Countercurrent flow (side entry orifice)**				
	Plant Range	Test Facility			
Plant Parameter		Jones BD/ECC (GE 8x8 bundle data)			
P (MPa)	0.1 – 2.0	Near atmospheric			
Steam flow (gm/s)	7 – 30	0 – 38			
Liquid flow (cm3/s)	0 – 500	0 – 505			
$Kf^{1/2}$	0 – 3.0	0.0 – 1.2			
$Kg^{1/2}$	0 – 1.8	0.9 – 2.0			
Water Temp. (°C)	40 – 80	Saturated steam/water			
Comments	Flow rates are for channel	Bundle bottom inlet, side entry orifices;five orifices sizes			

Nomenclature
P, pressure
q, heat flux
G, mass flux

References

1. D.D. Jones, "Test Report TLTA Components CCFL Tests," GE Nuclear Systems Products Division, BD/ECC Program, NEDG-NUREG-23732, (1977).

Table A-3 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill/reflood				
Phenomenon/Justification	**Heat transfer: radiation**			Affects the peak clad temperature (in BWR/2)	
	Plant Range	Facility range			
		Separate effect tests		Integral tests	
Key Parameter/Facility		GOETA[1)]	THTF[2)]	TLTA-5A[3)]	
$T_w - T_v$ (K)	~400	550 –850	<400	400 –600	
Emissivity (-)	0.6 – 1.0	0.7	0.4 – 0.6	~0.6	
Geometry	rod-to-rod and wall	rod-to-rod and wall	rod-to-rod and wall	rod-to-rod and wall	
Comments		stagnant steam	steady-state boiloff	LBLOCA/no ECC	

[1)] Test 27: Experimental investigations of cooling by top spray and bottom flooding for a BWR, Studsvik/RL-78/59, June 1978.
[2)] Test 3.09.10K: Experimental investigations of uncovered bundle heat transfer…, NUREG/CR-2456.
[3)] Test 6426/Run 1: BWR BD/ECC program, NUREG/CR-2229.

T_w=wall temperature
T_v=steam temperature

Table A-4 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown/refill/reflood				
Phenomenon/Justification	**Interphase shear** Affects two-phase separation (level), entrainment, and pressure drop				
	Plant Range	Facility range			
		Separate effect tests			
Key Parameter/Facility		CISE[1]	GE Level Swell[2]	TLTA-5A[3]	Pericles[4]
P (MPa)	0.1 – 7.2	5.0	0.1 – 7.0		0.2 – 0 .4
G_l (kg/m^2-s)		80 –380		~0 – 360	
G_v (kg/m^2-s)		4 –310		2.4 – 360	
Void (-)	~0 – 1.0	0.2 – 0.9	0 – 1.0	0.1 – 1.0	0.2 – 0.9
Geometry	bundle, plenum, pipe	round tube	vessel 1ft & 4ft OD	full scale bundle	bundle
Comments		steady-state flow	flashing/blowdown	steady-state boiloff	steady-state boiloff

1) Density measurements of steam/water mixture flowing in tube, CISE-R-291, December 1969.
2) Test 1004-3 and Test 5801-13: BWR refill-reflood program, NUREG/CR-1899, October 1981.
3) Test 6441: BWR BD/ECC program, NUREG/CR-2229.
4) Study of two-dimensional effects in core of LWR during the reflood phase, CEC, Final Report Contract No. SR))2F, 1984.

Note: Ref. 3 and 4 are applicable for assessment of interphase drag in bundles.

G_l =mass flux of liquid phase
G_v=mass flux of steam

Table A-5 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)
Transient Phase	Blowdown
Phenomenon/Justification	**Jet pump: forward flow** Affects coastdown of the core flow

	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		TLTA-5A[1]	FIST[2]		
N – Ratio (-)	0.15 – 0.22				
M – Ratio (-)	1.5 – 2.5	2 – 2.25			
Forward flow loss (-)		~4.0	~8.0		
Comments		LBLOCA	LBLOCA		

[1] Test 6426/Run 1: BWR BD/ECC program, NUREG/CR-2229.
[2] Test 6DBA1B: BWR FIST: Phase 1 results, NURG/CR-3711, March 1985.

Table A-5a Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
Phenomenon/Justification	**Jet pump: reverse flow**				Affects break flow
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		TLTA-5A[1)]	FIST[2)]		
Reverse flow loss (-)	~0.9	~1.2	~1.3		
Comments		LBLOCA	LBLOCA		

[1)] Test 6426/Run 1: BWR BD/ECC program, NUREG/CR-2229.
[2)] Test 6DBA1B: BWR FIST: Phase 1 results, NURG/CR-3711, March 1985.

Table A-6 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill/reflood				
Phenomenon/Justification	**Radial power distribution** Affects the peak clad temp. location and channel grouping				
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		ROSA-III[1)]			
P_{rad} (-)	0.5 –1.2	1 –1.4			
Geometry	channeled bundles	4 half-length bundles			
Comments		LBLOCA			

[1)] Test 926: ROSA-III experimental program, JAERI-1307, November 1987.

Table A-7 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
Phenomenon/Justification	**Pressure drop** Affects the flow distribution between the shroud and downcomer				
	Plant Range	Facility range			
		Separate effect tests			Integral tests
Key Parameter/Facility		Sher andGreer[1)]	Muscettola[2)]	EPRI[3)]	ROSA-III[4)]
P (MPa)	0.7 – 7.2	7.6 and 14	6.9	< 0.2	0.7 – 7.2
G (kg/m^2-s)	~30 – 2020	950 – 6780	1145 – 4370	1500 – 2100	~10 – 1100
x (-)		0 – 0.4	0.01– 0.7		
Geometry	bundle, plenum, pipe	rectangular tube	round tube	square tube	4 half-length bundles
Comments		steam-water	steam-water	air-water	LBLOCA

1) Boiling pressure drop in thin rectangular chennels, Chem. Symp.Series 23, 61-73, 1959.
2) Two-phase pressure drop – comparison with measurements, AEEW-R-284, 1963.
3) Experimental study of the diversion cross-flow, EPRI NP-3459, Vol. 1, April 1984.
4) Test 926: ROSA-III Experimental Program, JAERI-1307, November 1987.

Table A-8 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
Phenomenon/Justification	**Recirculation pump coastdown**	Determines the core flow			
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		ROSA-III[1]	FIST[2]		
Torque/Inertia (s^{-2})	38 – 58	~100			
Time (s)	5 – 8		5 –8		
Geometry	centrifugal pump	centrifugal pump	centrifugal pump		
Comments		LBLOCA	LBLOCA		

[1] Test 926: ROSA-III Experimental Program, JAERI-1307, November 1987.
[2] Test 4DBA1: BWR FIST Phase 2, NUREG/CR-4128, March 1986.

Table A-9 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
Phenomenon/Justification	**Rewet**	Determines the transition from film to nucleate boiling			
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		TLTA-5A[1)]			
T_{wall} (K)	650– 850	620– 850			
T_{sat} (K)	~550	~550			
P (MPa)	7.0 – 6.0	~6.5			
x (-)	~0.5	~0.5			
Geometry	channeled 8x8 bundle	full scale bundle			
Comments		LBLOCA/no ECC			

[1)] Test 6426/Run 1: BWR BD/ECC program, NUREG/CR-2229.

Table A-10 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Reflood				
Phenomenon/Justification	**Rewet**	Determines the transition from film to nucleate boiling			
	Plant Range	Facility range			
		Separate effect tests			
Key Parameter/Facility		GOETA[1]	NEPTUN[2]	BWR-FLECHT[3]	PWR-FLECHT[4]
P (MPa)	0.1 – 1.0	0.7	0.1 – 0.4	0.15 – 0.45	0.15 – 0.30
T_{wall} (K)	600 – 800	850 – 1100	1030 – 1140	1030– 1220	530 – 1140
$T_{sat} - T_{ECC}$ (K)	25 – 150	75	22 – 134	0 – 90	10 – 80
V_{flood} (cm/s)	2.5 – 10.0	–	1.5 – 15.0	8 – 14.0	1.6 – 3.8
W_{spray} (kg/s) *)	0.5 – 0.75	0.44	–	–	–
Geometry	channeled 8x8 bundle	channeled 8x8 bundle	half-length bundle	7x7 bundle	10x10 bundle
Comments	*) on channel basis	top reflood	bottom reflood	bottom reflood	bottom reflood

1) Test 42: Experimental investigations of cooling by top spray and bottom flooding for a BWR, Studsvik/RL-78/59, June 1978.
2) NEPTUN bundle reflooding experiments, EIR Report No. 386, 1981.
3) Effect of geometry and other parameters on bottom flooding heat transf. associated with nucl. fuel bundle simulators, ANCR-1049, April 1972.
4) FLECHT – low flooding rate cosine test series, WCAP-8651, December 1975.

Table A-10 (cont) Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Reflood				
Phenomenon/Justification	**Rewet**	Determines the transition from film to nucleate boiling			
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		TLTA-5A[5)]	FIST[6)]		
P (MPa)	0.1 – 1.0	0.1 – 1.0	0.3 – 0.5		
T_{wall} (K)	600 – 800	500 – 800	550 – 800		
$T_{sat} - T_{ECC}$ (K)	25 – 150	132	84 – 104		
V_{flod} (cm/s)	2.5 – 10.0	5.1			
W_{spray} (kg/s) [*)]	0.5 – 0.75	0.67	0.5		
Geometry	channeled 8x8 bundle	full scale bundle	full scale bundle		
Comments	[*)] on channel basis	LBLOCA	LBLOCA		

[5)] Test 6424/Run 1: BWR BD/ECC program, NUREG/CR-2229.
[6)] Test 4DBA1: BWR FIST Phase 2, NUREG/CR-4128, March 1986.

Table A-11 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill/reflood				
Phenomenon/Justification	**3-D thermal-hydraulics in upper plenum**	Affects CCFL in the upper plenum and top reflood			
	Plant Range	Facility range			
		Component tests			
Key Parameter/Facility		SSTF/UP[1]			
P (MPa)	0.1– 1.0	0.2 – 1.0			
W_{spray} (kg/s) *)	~0.5	0.4 – 0.54			
$T_{sat} - T_{ECC}$ (K)	25 – 150	54 – 145			
W_{steam} (kg/s) *)	0.05 – 0.2	0.09 – 0.16			
Geometry	upper plenum	full scale upper plenum			
Comments	*) on channel basis	spray into 2-phase mix.			

1) BWR refill-reflood program Task 4.4, NUREG/CR-2786, May 1983.

Table A-12 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown/reflood				
Phenomenon/Justification	**Void distribution/2-phase level**	Determines heat transfer in the core below and above the 2-phase level, timing of jet pump, inlet orifice, and recirc. suction uncovery			
	Plant Range	Facility range			
		Separate effect tests			
Key Parameter/Facility		Frigg[1]	TLTA-5A[2]	GE Level Swell[3]	SSTF/LP[4]
P (MPa)	0.1 – 7 .0	~5.0		0.1 – 7.0	0.2 – 1.0
G (kg/m^2-s)		690 – 1500	2.4 – 360		
Void (-)	0 – 1.0	0 – 0.8	0.1 – 1.0	0 – 1.0	0 – 1.0
Geometry	bundle, plenum, annulus	37 rod bundle	full scale bundle	vessel 1ft & 4ft OD	full scale lower plen.
Comments		steady-state boiling	steady-state boiloff	flashing/blowdown	flashing experiment

[1] Frigg-2, Hydrodynamic and heat transfer measurements on a full scale 36-rod Marviken fuel element, ASEA and ABB, 1968.
[2] Test 6441: BWR BD/ECC program, NUREG/CR-2229.
[3] Test 1004-3 and Test 5801-13: BWR refill-reflood program, NUREG/CR-1899, October 1981.
[4] BWR refill-reflood program Task 4.4, NUREG/CR-2786, May 1983.

Table A-12 (cont) Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown/reflood				
Phenomenon/Justification	**Void distribution/2-phase level**	Determines heat transfer in the core, uncovery timing of jet pump, inlet orifice, recirculation suction, and affects condensation			
	Plant Range	Facility range			
		Integral tests			
Key Parameter/Facility		TLTA-5A[5)]	FIST[6)]		
P (MPa)	0.1 – 7 .0	0.1 – 7.0	0.1 – 7.0		
G (kg/m^2-s)					
Void (-)	0 – 1.0	0 – 1.0	0 – 1.0		
Geometry	bundle, plenum, annulus	full scale bundle	full scale bundle		
Comments		LBLOCA	LBLOCA		

5) Test 6424/Run 1: BWR BD/ECC program, NUREG/CR-2229.
6) Test 4DBA1: BWR FIST Phase 2, NUREG/CR-4128, March 1986.

Table A-13 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill/reflood				
Phenomenon/Justification	**Spray distribution**	Affects CCFL and its breakdown at the upper tie-plate			
	Plant Range	Facility range			
		Component tests			
Key Parameter/Facility		SSTF[1)]			
Sparger height (m)	0.15 – 0.7	0.15 – 0.4			
2-phase level (m)	0 – 1.0	0 –0.4			
Geometry	upper plenum	full scale upper plenum			
Comments		different BWR sprays			

[1)] BWR refill-reflood program Task 4.4, NUREG/CR-2133, May 1982.

Table A-14 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill, reflood				
PIRT Parameter	**Channel Bypass Leakage**				
	Plant Range	Test Facility			
Plant Parameter		ROSA-III Tests 901, 902, 924, 926, 905	FIST Test 6DBA1B		
Pressure (MPa)	0.1 – 7.0	0.1 – 7.0	0.1 – 7.0		
Leakage Flow (kg/s)	0- 1.5		0 – 1.2		
Geometry	Channel bundle	Simulated leakage paths with drilled holes	Prototypical		
Comments		4 channels	one channel		

References

1.0 Tasaka et. al., ROSA-III Double-Ended Break Test series for a Loss-of-Coolant Accident in a BWR," Nucl. Tech. Vol. 68, Jan 1985, pp.77-93.

2.0 Kumamaru, H. et. al., "Similarity Study of ROSA-III and FIST Large Break Counterpart Tests to BWR Large Break LOCA," Nucl. Engr. And Design 103, pp223-238, June 1986.

Table A-15 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Long term cooling				
PIRT Parameter	**Nucleate Boiling**				
	Plant Range	Test Facility			
Plant Parameter		ORNL Test 3.07.9N			
P (MPa)	0.1 – 7.0	12.7			
Wall Superheat (K)	0 – 10	14 - 17			
Void Fraction	0 - 0.4	0.17 - 0.89			
Mass Flux (kg/m2-s)	0 – 1500	806			
Heat Flux (MW/m2)	0 - 0.555	0.94			
Subcooling (K)	10 – 60	14.29			
Comments					

G. L. Yoder et al., Dispersed Flow Film Boiling in Rod Bundle Geometry Steady State Heat Transfer Data and Correlation Comparisons, NUREG/CR-2456, ORNL-5848, March 1982.

Table A-16 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill, reflood				
PIRT Parameter	**Condensation:ECC Water**				
	Plant Range	Test Facility (See Table D-3a)			
Plant Parameter					
Pressure (MPa)	0.1- 5.0				
Void fraction	0.0 -1.0				
ECC Temp (F)	80 – 180				

Table A-17 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill, reflood				
PIRT Parameter	**Steam Cooling**				
	Plant Range	Test Facility (See also Table D-4)			
Plant Parameter		THTF Bundle Uncovery Tests 3.09.10 I,J, K, L, M, & N	G-2 336 Rod bundle Uncovery Tests 718, 722, 727, &731		
Pressure (MPa)	0.1 – 5.0	3.9 – 7.0	0.1 – 5.5		
Void fraction	1.0	1.0	1.0		
Clad Temp (F)	500- 2200	500 – 1500	500 – 1600		
Vapor Temp (F)	500 –1800	500 – 1200	500 -1300		
Vapor Re	100-2000	1100- 18,000	1000- 7000		
Comments		Tests contain level swell and thermal radiation to steam data also	Tests contain level swell data also.		

References

1.0 Anklam et.al., "Experimental Investigations of Uncovered-Bundle Heat Transfer and Two-Phase Mixture Level Swell Under High Pressure Low Heat Flux Conditions," NUREG/CR-2456, ORNL, March 1982.

2.0 Yeh, H. et. al., "Heat Transfer Above the Two-Phase Mixture Level Under Core Uncovery Conditions in a 336 Rod Bundle," EPRI NP -2161, December 1981.

Table A-18 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
PIRT Parameter	**Critical Flow**				
	Plant Range	Test Facility (See Table D-10a &10b)			
Plant Parameter					
Pressure (MPa)	0.7 – 7.0				
L/D	1 – >10				
Subcooling (K)	0 – 20				

Table A-19 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill, reflood, long term cooling				
PIRT Parameter	**Decay Heat**				
	Plant Range	Test Facility (See Table D-5)			
Plant Parameter					
Time (sec)	$0 - 10^{10}$				
Comments					

Table A-20 **Key Parameters and Their Ranges for High Ranked PIRT Phenomena**

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown , refill, reflood				
PIRT Parameter	**Film Boiling**				
	Plant Range	Test Facility (See Also Table D-1 for additional tests)			
Plant Parameter		THTF Film Boiling Tests 3.03.6AR 3.06.6B & 3.08.6C			
P (MPa)	0.3 – 5.0	5.17 - 12.4			
Heat Flux (kw/m2)		160 – 1100			
Equil.Quality (%)	0.1-90	0.15 – 100			
Clad Temps (K)	500 – 1400	600 – 1000			
Mass Flux kg/s-m2		129- 1090			
Comments					

References

Morris, D. G. et. al., "An Analysis of Transient Film Boiling of High Pressure Water in a Rod Bundle," NUREG/CR-2469, ORNL, March 1982.

Table A-21 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill, reflood				
PIRT Parameter	**Flashing in lower plenum, core, and downcomer**				
	Plant Range	Test Facility			
Plant Parameter		ROSA-III Tests 901, 902, 924, 926, 905	FIST Test 6DBA1B		
Pressure (MPa)	0.1 – 5.0	0.1 – 7.0	0.1 – 7.0		

References

3.0 Tasaka et. al., ROSA-III Double-Ended Break Test series for a Loss-of-Coolant Accident in a BWR," Nucl. Tech. Vol. 68, Jan 1985, pp.77-93.

4.0 Kumamaru, H. et. al., "Similarity Study of ROSA-III and FIST Large Break Counterpart Tests to BWR Large Break LOCA," Nucl. Engr. And Design 103, pp223-238, June 1986.

Table A-22 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
PIRT Parameter	**Flow: Lower Plenum Distribution**				
	Plant Range	Test Facility			
Plant Parameter		ROSA-III Tests 901, 902, 924, 926, 905	FIST Test 6DBA1B	TLTA Tests 6422 Run 3, 6424 Run 1, 6423 Run 3, & 6426 Run 1	SSTF Test EA2-2
Pressure (MPa)	0.1 – 5.0	0.1 – 7.0	0.1 – 7.0	7.1	0.507
					Low plen inj rate = 3.024 kg/s Core steam inj rate= 4.98 kg/s LPCI = 49.21 l/s Subcooling of inj water= 105 K

References

5.0 Tasaka et. al., ROSA-III Double-Ended Break Test series for a Loss-of-Coolant Accident in a BWR," Nucl. Tech. Vol. 68, Jan 1985, pp.77-93.

6.0 Kumamaru, H. et. al., "Similarity Study of ROSA-III and FIST Large Break Counterpart Tests to BWR Large Break LOCA," Nucl. Engr. And Design 103, pp223-238, June 1986.

7.0 NUREG/CR-2571, "BWR Refill-Reflood Program Task 4.8 – TRAC-BWR Model Qualification for BWR Safety Analysis Final Report,"October 1983.

Table A-23 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown, refill, reflood				
PIRT Parameter	**Critical Heat Flux**				
	Plant Range	Correlations			
Plant Parameter		Biasi	CISE	Zuber	
Pressure (MPa)	0.1 – 5.0	0.1-14.2	7.0	0.1 – 5.0	
Mass Flux(kg/m^2-s)	0 – 6000	100- 6000	300 -1400	< 100	
Quality	0.1 – 1.0	0.2 – 1.0			
Void	0.7 – 1.0				
Comments				Zuber is applied if flow is countercurrent	

References

1. L. Biasi, et al, " Studies on Burnout: Part 3,", Energ. Nucl. 14, 1967, pp.530-536.

2. CISE: Heat Transfer Crisis in Steam-Water Mixtures, Energ. Nucl. 12, 1965

N. Zuber et al," The Hydrodynamic Crisis in Pool Boiling of Saturated and Subcooled Liquids,", Int. Developments in Heat Transfer, 2, 1961, pp.230-236.

Table A-24 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill, reflood, long term coling				
PIRT Parameter	**Natural Circulation**				
	Plant Range	Test Facility			
Plant Parameter		ROSA-III Test NC-1 ....NC-5	FRIGG Test FT 36a 36b, &36c	FIST 6PNCI-4	
Pressure (MPa)	0.1- 7.0	7.35, 2.06	1 –7.0	7.0	
Inlet Subcooling (K)	0- 60	0	3 – 58	0.0	
Exit Qual %	10- 80		3 - 73	0-7	
Mass Flux (kg/m2-s)	0.0-1500	100 - 400	195 – 2160	0-1022	
Heat Flux (MW/m2)	0.0-0.555	Core power: 7-20%	0.21-0.89	0.222	
Downcomer Level(m)	1.6	0.6 – 1.7		1 – 1.6	
Comments	-	The ROSA Nat Circ tests were conducted by changing pressure, core power, and downcomer liquid level (below the scram level) as test parameters			

1.0 Nyland, O. et. al., "Hydrodynamic and Heat Transfer Measurements on a Full Scale Simulated 36-Rod Marviken Fuel Element with Uniform Heat Flux Distribution, FRIGG Loop Project, FRIGG-2g, 1968.

2.0 K. Taska et. al., "Steam Line Break, Jet Pump Drive Line Break and Natural Circulation Tests in ROSA-III Program for BWR LOCA/ECCS Integral Tests," Eleventh water Reactor Safety Research information Meeting, Gaithersburg, MD, October 24-28, 1983.

Table A-25 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Refill, reflood				
PIRT Parameter	**Stored Heat in Fuel and Metal Structures**				
	Plant Range	Test Facility (See Tables D-17a & 17b)			
Plant Parameter					
Temp (K)	570 - 1000				
Comments	Metal to volume ratio is an important parameter				

Table A-26 Key Parameters and Their Ranges for High Ranked PIRT Phenomena

Plant	BWR				
Transient	Large-Break Loss-of-Coolant Accident (LBLOCA)				
Transient Phase	Blowdown				
Phenomenon/Justification	**Fuel Gap Heat conductance** Governs temperature distribution and removal of stored heat				
	Plant Range	Test Facility (See Table 12a & 12b)			
Key Physical Parameter					
Pellet:					
k (W/m-K)	(7.5-18.5)10E+3				
T (K)	>530				
Gap:					
h (W/sq.m-K)	(3.3-13.1)10E+3				
Burnup (MWD/T)	0-40000				
Comments					