PWROG
PWR Owners Group

Program Management Office
4350 Northern Pike
Monroeville, Pennsylvania 15146

Project No. 694

July 3, 2007

OG-07-300

Document Control Desk
U. S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Pressurized Water Reactor Owners Group
Program to Establish Consistent Criteria for Post Loss-of-Coolant (LOCA) Calculations: Draft Report WCAP-16745-NP, Rev. 0, "Boric Acid Reactor Vessel Mixing/Transport Phenomena Identification and Ranking Table (PIRT)"

References:
1. NRC Letter (ML062690017), "Summary of August 23, 2006 Meeting with the Pressurized Water Reactor Owners Group (PWROG) to Discuss the Status Of Program to Establish Consistent Criteria for Post Loss-Of-Coolant (LOCA) Calculations," October 3, 2006.

PWROG representatives met with the NRC staff on August 23, 2006 to discuss Post-LOCA (Loss-of-Coolant-Accident) boric acid precipitation analysis methodology. The purpose of the meeting was to present the status of the PWROG program to establish a consistent methodology and criteria for calculating an appropriate post-LOCA hot leg recirculation switchover time and/or other actions to preclude post-LOCA boric acid precipitation. One of the planned activities discussed at this meeting was the development of a boric acid reactor vessel mixing/transport PIRT (Phenomena Identification and Ranking Table). During this discussion, the NRC staff requested the opportunity to comment on the draft PIRT report when it became available.

Enclosed is a draft copy of WCAP-16745-NP, Rev. 0, "Boric Acid Reactor Vessel Mixing/Transport Phenomena Identification and Ranking Table (PIRT)". Although it is being provided for information only, feedback from the NRC staff is welcome. The PWROG does not request NRC review and approval, nor are NRC review fee invoices expected. The draft report is the product of a panel of 'internal' vendor/industry experts. After a review by 'external' academic/industry experts, the final report will be issued. Consistent with intentions reported in the August 23, 2006 meeting with the NRC staff, this initial draft PIRT addresses only low levels of pass-through containment sump debris and chemicals. A follow-up initiative is in progress to consider the effect of moderate-to-severe levels of pass-through containment sump chemical and particulate debris on the draft PIRT scenarios, figure-of-merit, and phenomena identification/rankings.

D048
NRO

The PWROG will continue to periodically report the status of this program to the NRC staff as specific tasks are completed. If you require further information, please contact Mr. Ken Vavrek in the PWR Owners Group Program Management Office at 412-374-4302 or Mr. David Fink at the Westinghouse Systems and Safety Analysis Department at 412-374-4912.

If you have any questions concerning this matter, please feel free to call Christine DiMuzio at 412-374-5680.

Sincerely yours,

Ken J Vavrek for

Frederick P. "Ted" Schiffley, II, Chairman
Pressurized Water Reactor Owners Group

FPS:KJV:mjl

Enclosure

cc: PWROG Steering Committee
PWROG Analysis Subcommittee
PWROG Project Management Office
R. Landry, USNRC
S. Peters, USNRC
J. Nakoski, USNRC
L. Ward, USNRC
R. Schomaker, AREVA NP
C. Boyd, Westinghouse
J. Cleary, Westinghouse
D. Fink, Westinghouse
C. B. Brinkman, Westinghouse
J. A. Gresham, Westinghouse

WCAP-16745-NP
Revision 0-DRAFT

April 2007

Boric Acid Reactor Vessel Mixing/Transport Phenomena Identification and Ranking Table (PIRT)

WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-16745-NP
Revision 0-DRAFT

Boric Acid Reactor Vessel Mixing/Transport Phenomena Identification and Ranking Table (PIRT)

W. L Brown
D. J. Fink
B. E. Kellerman
LOCA Integrated Services II

April 2007

Approved: C. H. Boyd *
Manager, LOCA Integrated Services II

Approved: Gordon C. Bischoff *
PWROG Program Management Office

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

This work was performed under PWR Owners Group Project Number PA-ASC-0264 Rev. 1

*Electronically approved records are authenticated in the electronic document management system.

LEGAL NOTICE

COPYRIGHT NOTICE

DISTRIBUTION NOTICE

PWR OWNERS GROUP MEMBER PARTICIPATION* FOR PROJECT/TASK PA-ASC-0264 REV. 1			
Utility Member	Plant Site(s)	Participant	
		Yes	No
AmerenUE	Callaway (W)	X	
American Electric Power	D. C. Cook 1&2 (W)	X	
Arizona Public Service	Palo Verde Unit 1, 2, & 3 (CE)	X	
Constellation Energy Group	Calvert Cliffs 1 & 2 (CE)	X	
Constellation Energy Group	Ginna (W)	X	
Dominion Connecticut	Millstone 2 (CE)	X	
Dominion Connecticut	Millstone 3 (W)	X	
Dominion Kewaunee	Kewaunee (W)	X	
Dominion VA	North Anna 1 & 2, Surry 1 & 2 (W)	X	
Duke Energy	Catawba 1 & 2, McGuire 1 & 2 (W), Oconee 1, 2, 3 (B&W)	X	
Entergy Nuclear Northeast	Indian Point 2 & 3 (W)	X	
Entergy Operations South	Arkansas 2, Waterford 3 (CE), Arkansas 1 (B&W)	X	
Exelon Generation Co. LLC	Braidwood 1 & 2, Byron 1 & 2 (W), TMI 1 (B&W)	X	
First Energy Nuclear Operating Co	Beaver Valley 1 & 2 (W), Davis-Besse (B&W)	X	
Florida Power & Light Group	St. Lucie 1 & 2 (CE)	X	
Florida Power & Light Group	Turkey Point 3 & 4, Seabrook (W)	X	
Nuclear Management Company	Prairie Island 1&2, Pt. Beach 1&2 (W)	X	
Nuclear Management Company	Palisades (CE)	X	
Omaha Public Power District	Fort Calhoun (CE)	X	
Pacific Gas & Electric	Diablo Canyon 1 & 2 (W)	X	
Progress Energy	Robinson 2, Shearon Harris (W), Crystal River 3 (B&W)	X	
PSEG - Nuclear	Salem 1 & 2 (W)	X	
Southern California Edison	SONGS 2 & 3 (CE)	X	
South Carolina Electric & Gas	V.C. Summer (W)	X	
So. Texas Project Nuclear Operating Co.	South Texas Project 1 & 2 (W)	X	
Southern Nuclear Operating Co.	Farley 1 & 2, Vogtle 1 & 2 (W)	X	
Tennessee Valley Authority	Sequoyah 1 & 2, Watts Bar (W)	X	
TXU Power	Comanche Peak 1 & 2 (W)	X	
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)	X	

* Project participants as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending this document to participants not listed above.

PWR OWNERS GROUP INTERNATIONAL MEMBER PARTICIPATION* FOR PROJECT/TASK PA-ASC-0264 REV. 1			
		Participant	
Utility Member	Plant Site(s)	Yes	No
British Energy	Sizewell B	X	
Electrabel (Belgian Utilities)	Doel 1, 2 & 4, Tihange 1 & 3	X	
Kansai Electric Co., LTD	Mihama 1, Ohi 1 & 2, Takahama 1 (W)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 Yonggwang 1 & 2 (W)	X	
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 , 5 & 6(CE)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	54 Units	X	

* This is a list of participants in this project as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending documents to participants not listed above.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

AOR	Analysis of Record
B&W	Babcock and Wilcox
BACCHUS	Mitsubishi Heavy Industries Boric Acid Concentration Core Mixing Tests
BAMT	Boric Acid Makeup Tank (typical CE plant terminology)
CCFL	Counter Current Flow Limitation
CE	Combustion Engineering
CEA	Control Element Assembly (typical CE plant terminology)
CENPD	CE Technical Report Number Preface
CLPD	Cold Leg Pump Discharge (Leg)
CLPS	Cold Leg Pump Suction (Leg)
ECCS	Emergency Core Cooling System
EOP(s)	Emergency Operating Procedure(s)
EPRI	Electric Power Research Institute
EPU	Extended Power Uprate
FLECHT	Full Length Emergency Core Heat Transfer (Tests)
LBLOCA	Large Break LOCA
LOCA	Loss-of-Coolant Accident
LPI	Low Pressure Injection
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owners Group
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RV	Reactor Vessel
RVVV	Reactor Vessel Vent Valves
RWST	Refueling Water Storage Tank (typical Westinghouse plant terminology)
SBLOCA	Small Break LOCA
SI	Safety Injection
SOK	State of Knowledge
UPI	Upper Plenum Injection
VVER	Vodo-Vodni Energiini Reqktor, also known as Water-Water Energy Reactor
WCAP	Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power)
WOG	Westinghouse Owners Group (now PWR Owners Group)

1 EXECUTIVE SUMMARY

All three US Pressurized Water Reactor (PWR) designs use boron as a core reactivity control method and are subject to concerns regarding potential boric acid precipitation in the core for scenarios that preclude direct Safety Injection (SI) flow through the core for extended periods following a Loss-of-Coolant Accident (LOCA). All three plant designs have Emergency Core Cooling System (ECCS) features that include an active core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. The common approach for demonstrating adequate boric acid dilution in a post-LOCA scenario includes the use of simplified methods with conservative boundary conditions and assumptions. These simplified methods are used with limiting scenarios in calculations that determine the time at which appropriate operator action must be taken to initiate an active boric acid dilution flow path or alternately, to show that boric acid precipitation will not occur. Simplified methods require assumptions regarding mixing in the reactor vessel. These assumptions affect the calculated rate of boric acid build-up in the core and the potential for boric acid precipitation. It is common to use assumptions that credit complete mixing in some areas (e.g., the core region) and partial mixing in some regions (e.g., the lower plenum) while ignoring the effect of mixing in other regions (hot leg piping).

Improved boric acid precipitation analysis methodologies require insights on the phenomena that effect transport and mixing in the reactor vessel after a LOCA. A Phenomena Identification and Ranking Table (PIRT) is useful in identifying and ranking such phenomena and can be used as guidance when developing new evaluation models. Specifically the PIRT can be used to provide a basis for developing analytical mixing models and can support scaled testing and plant evaluation model development.

Section 2 provides brief background information on boric acid precipitation analysis methodology issues for US PWRs. Section 3 provides information on Westinghouse, Combustion Engineering (CE), and Babcock and Wilcox (B&W) plant designs and typical boric acid precipitation analysis methodology. Sections 4 through 9 present the PIRT process and results. Section 10 provides a high-level assessment of how containment sump debris and GSI-191 issues may impact the PIRT rankings. Section 11 presents the high-ranked phenomena important to boric acid mixing and transport within a reactor vessel following LOCAs. Section 12 makes recommendations for practical use of the PIRT and suggests future areas of focus.

2 INTRODUCTION

All three US PWR designs (Westinghouse, CE, and B&W) use boron as a core reactivity control method and are subject to concerns regarding potential boric acid precipitation in the core for scenarios that preclude direct SI flow through the core for extended periods following a LOCA. All three plant designs have ECCS features that include an active core dilution mechanism to prevent the core region boric acid concentration from reaching the precipitation point. These dilution mechanisms may or may not require operator action. The common approach for demonstrating adequate boric acid dilution in a post-LOCA scenario includes the use of simplified methods with conservative boundary conditions and assumptions. These simplified methods are used with limiting scenarios in calculations that determine the time at which appropriate operator action must be taken to initiate an active boric acid dilution flow path or alternately, to show that boric acid precipitation will not occur. The three US PWR designs have different ECCS designs, different procedures for preventing boric acid precipitation, and different methodologies for evaluating the potential for boric acid precipitation. Nevertheless, there are common approaches, assumptions and simplifications that have been used in virtually all PWR calculations that address the potential for boric acid precipitation. Recent Extended Power Uprates (EPUs) have provided the opportunity for the Nuclear Regulatory Commission (NRC) to challenge some of these common approaches, assumptions and simplifications with regard to regulatory compliance and technical justification. In November 2005, the NRC issued a letter (Reference 1) to the Westinghouse Owners Group (WOG, now Pressurized Water Reactor Owners Group (PWROG)) requesting that the Owners Group members confirm that they have sufficient safety margin to core cooling requirements to support continued operation. The PWROG responded to the NRC in Reference 2. In Reference 1, the NRC also asked that future methodologies justify the mixing assumptions used in predicting the build-up of boric acid in the reactor vessel after a LOCA. Throughout the US PWR fleet, it is common to find boric acid precipitation Analysis of Record (AOR) calculations that use simplifying assumptions regarding mixing in the reactor vessel after a LOCA. Such assumptions have typically credited complete mixing in some areas while ignoring the effect of mixing in other regions.

3 BACKGROUND ON POST-LOCA BORIC ACID PRECIPITATION ANALYSIS METHODOLOGY

For typical plant designs (Westinghouse 2-loop Upper Plenum Injection (UPI) plants excluded) the limiting scenario for boric acid precipitation is a large cold leg (pump discharge) break where the downcomer is eventually filled and the excess SI flows out the break. The SI flow into the core region is largely limited to that quantity boiled off in the core to remove the decay heat. The steam generated in the core travels around the intact hot leg(s) (or through the internals Reactor Vessel Vent Valves (RVVVs) in the B&W-designed plants) to exit the break. Boric acid left behind accumulates in the core region and the boric acid concentration in the core region increases. The calculated rate of increase in boric acid concentration in the core region after a LOCA is directly affected by the assumed liquid volume. During this time, the core and upper plenum are filled with a two-phase mixture whose liquid content is dependent on the degree of voiding in the core and upper plenum region. The degree of voiding is a function of the core decay heat and Reactor Coolant System (RCS) pressure, and the pressure drop around the loop (or through the RVVVs) as it affects the hydrostatic balance between the downcomer head and the collapsed liquid level in the core. At low RCS pressures and high decay heat levels, the boiling in the core is vigorous, and the volume of liquid in the core region is smaller. As the decay heat drops off, the boiling becomes less vigorous and more liquid is retained in the core region.

Westinghouse US 2-loop plants differ from typical PWR designs in that they utilize low pressure upper plenum safety injection (or UPI). For these plants, the limiting large break LOCA boric acid precipitation scenario is a hot leg break where the cold leg high pressure SI may be terminated at or prior to sump recirculation. This scenario is relevant only with the very conservative assumption that all UPI flow in excess of core boil-off bypasses the core region and flows directly out the break (i.e., no mixing in the core and upper plenum).

For Westinghouse-designed and CE-designed plants boric acid precipitation calculations are used to determine the appropriate time to switch to some or all the ECCS sump recirculation flow to the hot leg or to otherwise show that boric acid precipitation will not occur. For B&W-designed plants, boric acid precipitation calculations are used to justify plant-specific active boric acid dilution methods or limitations on the dilution methods (e.g., plant specific auxiliary pressurizer spray flows, protection of the sump screens, prevention of potential water-hammer scenarios in the decay heat piping, challenges to Net Positive Suction Head (NPSH) limits for Low Pressure Injection (LPI) pumps, hot and cold fluid mixing limits, prevention of boric acid precipitation inside the decay heat cooler, etc.).

The cold leg break post-LOCA boric acid precipitation scenario is represented in Figures 3-1 through 3-3.

3.1 WESTINGHOUSE PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For Westinghouse-designed PWRs under Westinghouse cognizance, the post-LOCA boric acid precipitation calculations have typically used the following simplifying assumptions in regard to liquid mixing volume:

- Volume does not include any portion of the lower plenum.

- Volume in the core equal to the collapsed liquid volume calculated assuming a hydrostatic balance between the core and the downcomer with the downcomer filled with saturated liquid up to the bottom elevation of the hot leg piping. The loop pressure drop is assumed to be small and is ignored.
- Volume does not include the vessel volume above the bottom of hot leg elevation.
- Volume does not include any portion of the hot leg volume.
- Volume does not include any portion of the bypass regions (thimble tubes, barrel/baffle regions).
- Volume does not include any portion of the downcomer.
- Mixing in the core region is complete.

In addition, some plants credit the small increase in core volume that would result from an increased downcomer level that is represented by the "weir height" of the liquid flowing out the break. This credit is commonly referred to as "downcomer overfill" and represents a small volume as compared to the total mixing volume.

Recent analyses for EPU programs have revised the traditional assumptions above in order to address some of the NRC concerns cited in Reference 1. Most notably, the calculation of liquid volume in the core region explicitly considers core voiding and partial mixing in the lower plenum is assumed.

A reactor vessel outline drawing for the Westinghouse PWR design is provided as Figure 3-4.

3.2 CE PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For CE-designed PWRs under Westinghouse cognizance, the post-LOCA boric acid precipitation calculations have typically used the following simplifying assumptions in regard to liquid mixing volume:

- 100% of the volume of the lower plenum.
- Volume in the core equal to the collapsed liquid volume calculated assuming a hydrostatic balance between the core and the downcomer with the downcomer filled with saturated liquid up to the bottom elevation of the Reactor Coolant Pump (RCP) discharge legs and with the core collapsed liquid volume further decreased by the differential pressure required to depress the liquid in the downsides of the RCP loop seals to the elevation of the top of the horizontal portion of the loop seal piping.
- Volume inside the Control Element Assembly (CEA) guide tubes up to the elevation credited for the core volume.
- Volume in the core barrel/baffle region up to the elevation credited for the core volume.

- Mixing in the core region is complete.

Recent analyses for the Waterford EPU program have revised the traditional assumptions above in order to address some of the NRC concerns cited in Reference 1. Most notably, the calculation of liquid volume in the core region explicitly considers core voiding and only partial mixing in the lower plenum is assumed.

A reactor vessel outline drawing for the CE PWR design is provided as Figure 3-5.

3.3 B&W PWR PLANT DESIGN POST-LOCA BORIC ACID PRECIPITATION MIXING VOLUME ASSUMPTIONS

For most B&W-designed PWRs under Areva cognizance, the post-LOCA boric acid precipitation calculations have used the following assumptions in regard to liquid mixing volume:

- The core liquid mixing volume was assumed to be a constant depending on break size, conservatively determined using applicable LOCA thermal-hydraulic codes modeled for the B&W-designed plants. For at least one plant the core liquid mixing volume varies as a function of decay heat levels and system pressure.
- Mixing volume includes the liquid in the core, core bypass, core baffle region, core upper plenum, and outlet annulus.
- The steam void fraction in these regions reduces the available mixing volume.
- Liquid in the core lower plenum and the horizontal runs of the hot legs was not credited.
- The effects of boiling and core inlet subcooling were included.
- Mixing in the core region is complete.

The analyses for one plant differed from above in that a simple constant core liquid mixing volume was used. The mixing volume included the core, core bypass, core baffle region, and core lower plenum. Liquid in the reactor vessel (RV) above the top of core was not credited. No core voiding was considered although the effects of boiling were credited for providing the internal circulation necessary to give a homogeneous boric acid concentration in the mixing volume.

A reactor vessel outline drawing for the B&W PWR design is provided as Figure 3-6.

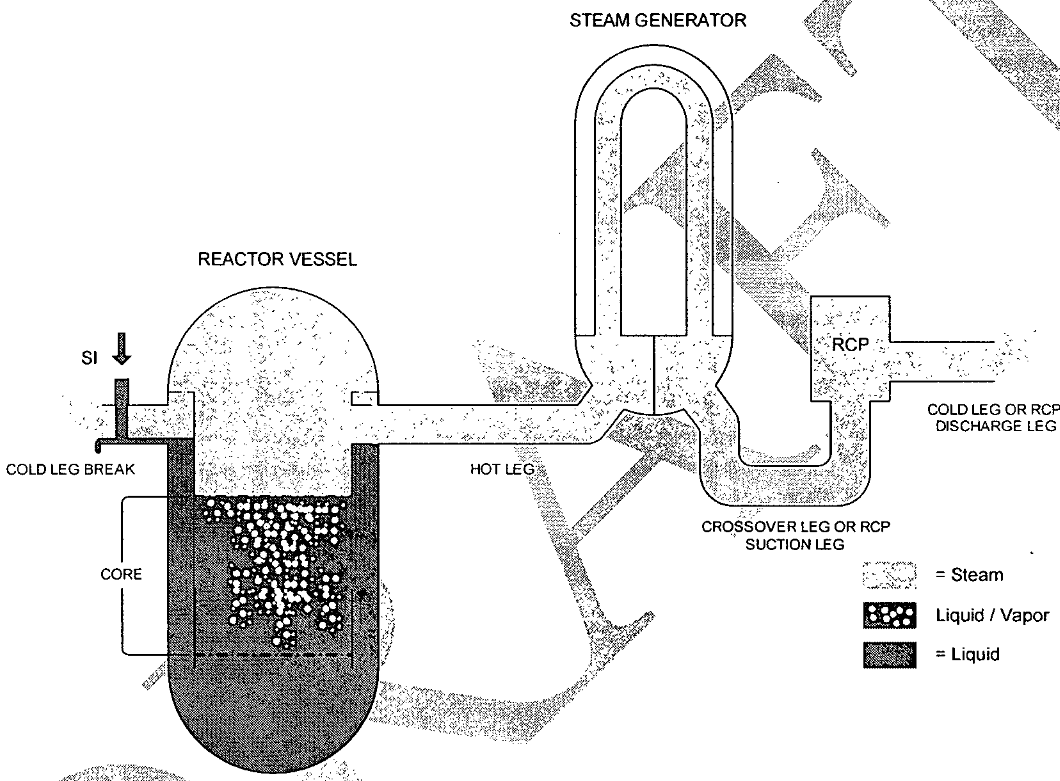

Figure 3-1 Cold Leg Pump Discharge Break, Westinghouse PWRs

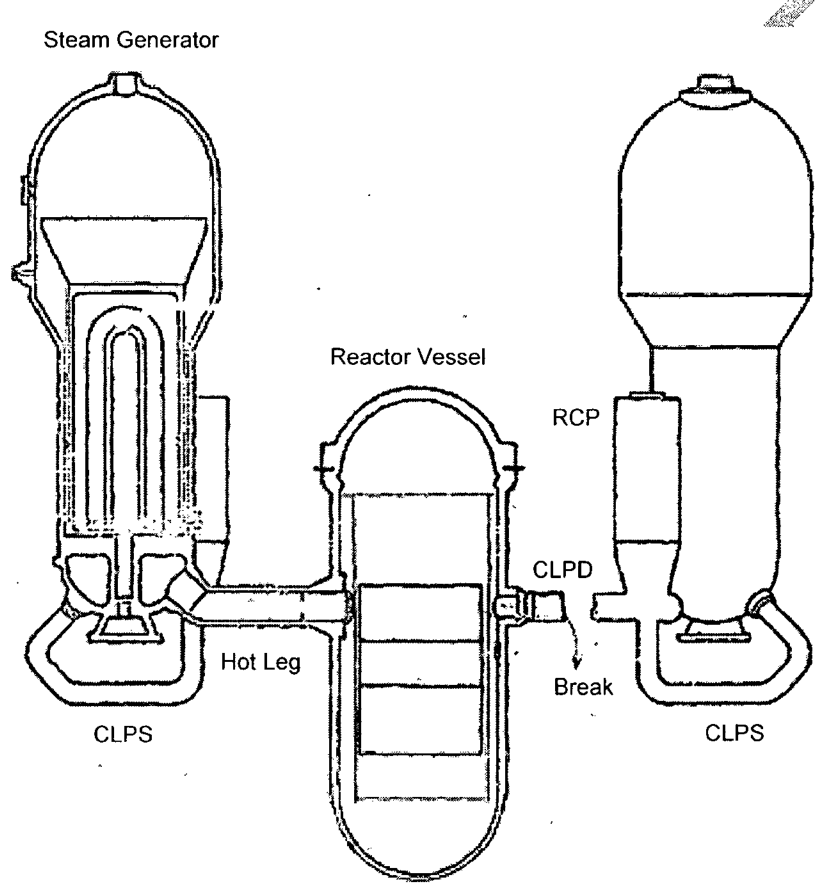

Figure 3-2 Cold Leg Pump Discharge Break, CE PWRs

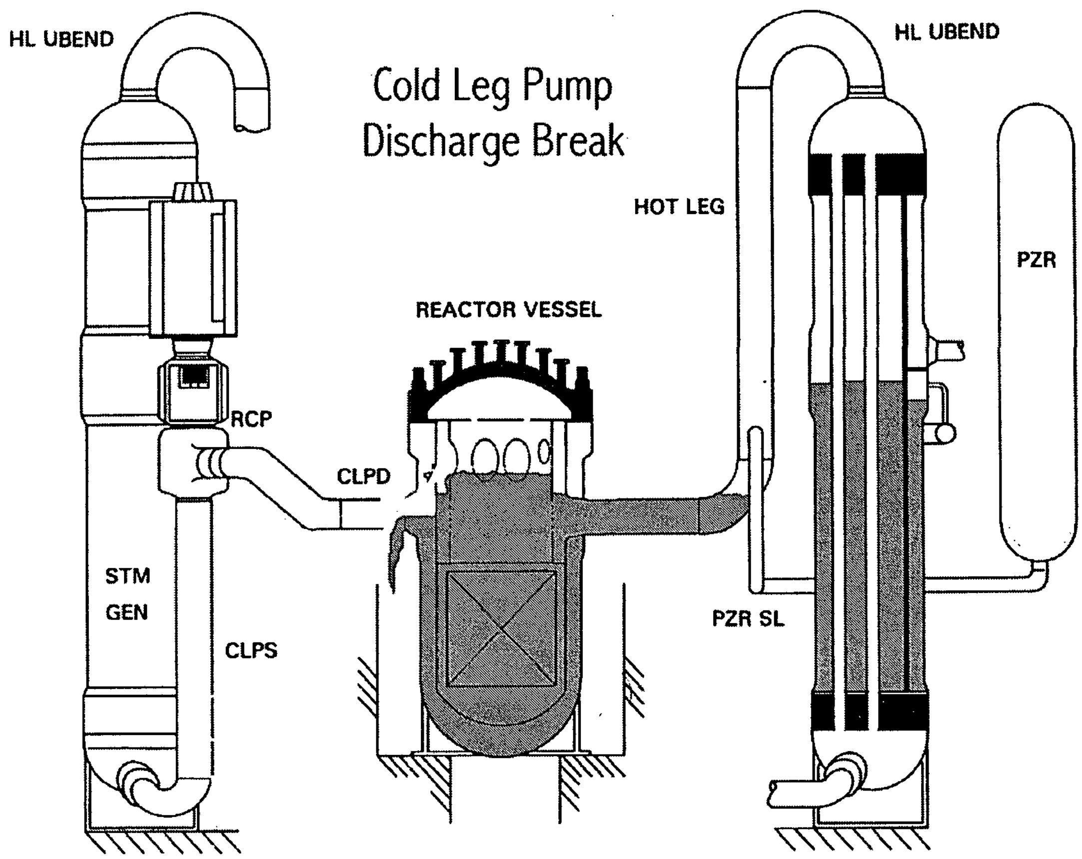

Figure 3-3 Cold Leg Pump Discharge Break, B&W PWRs

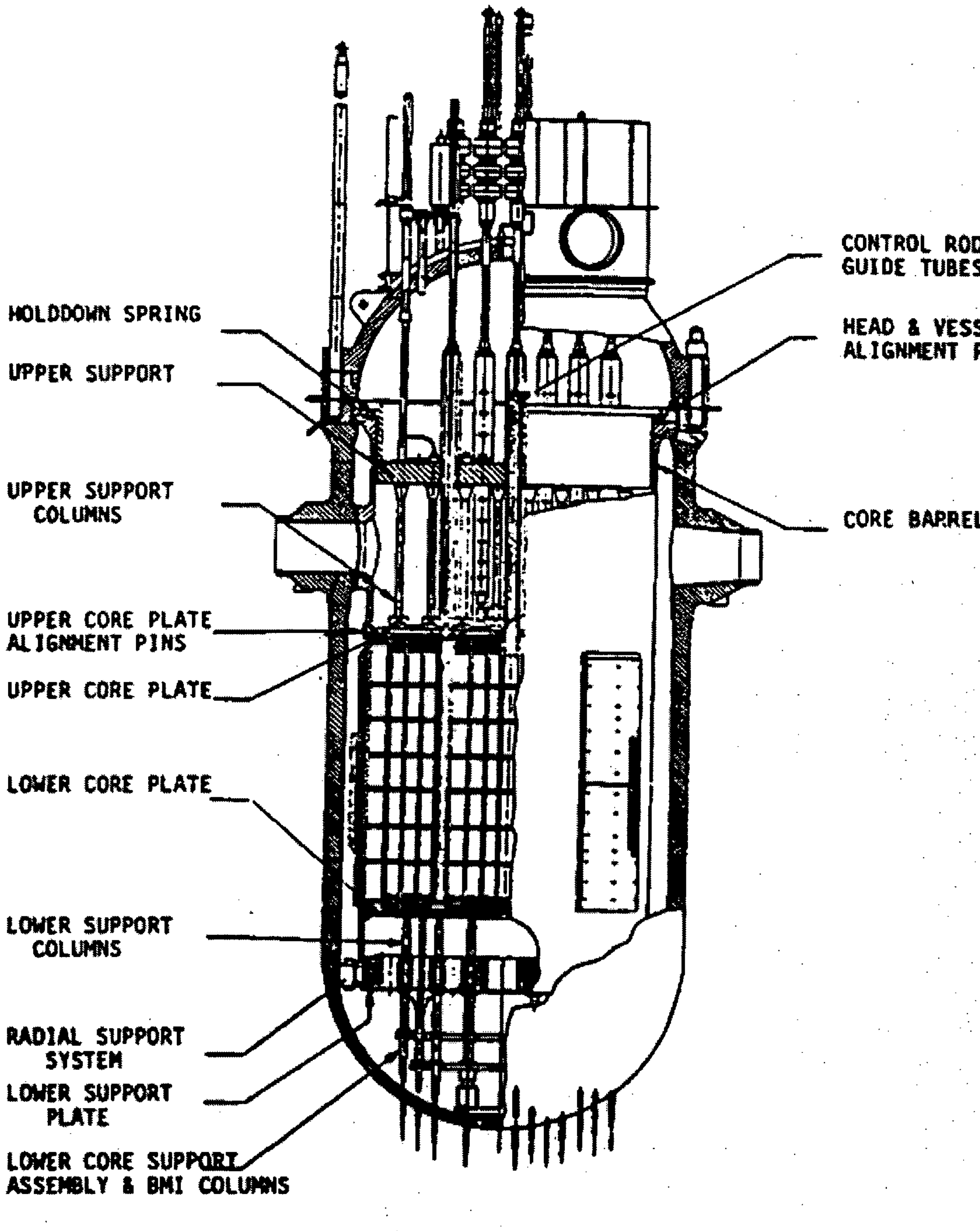

Figure 3-4 Typical Westinghouse Reactor Vessel and Internals Arrangement

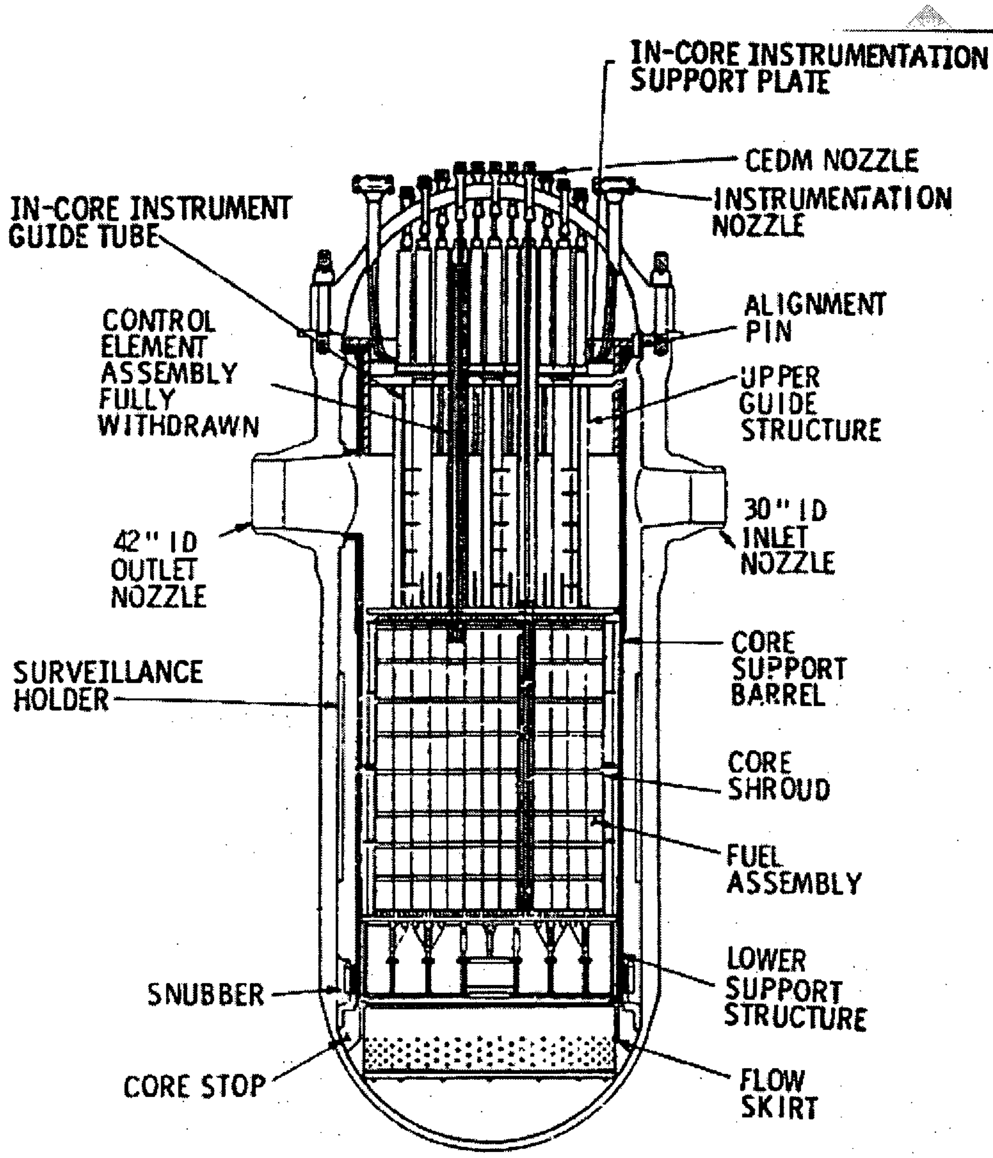

Figure 3-5 Typical CE Reactor Vessel and Internals Arrangement

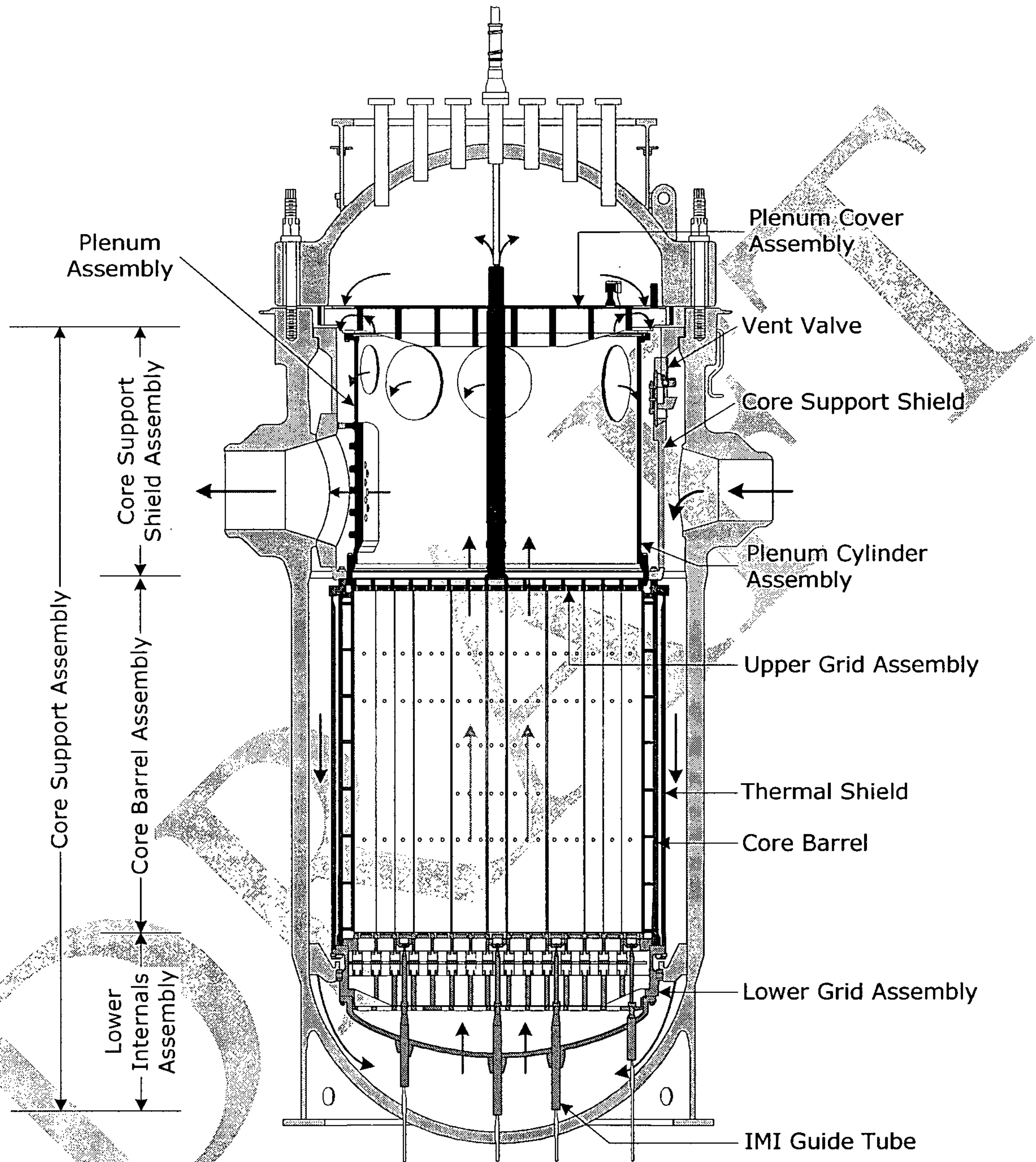

Figure 3-6 Typical B&W Reactor Vessel and Internals Arrangement

4 PIRT PROCESS

The PIRT was developed following the approach outlined in Reference 8. First, a list of plausible phenomena was prepared. Next, phenomena were ranked for importance through the various periods identified for the transient and the state of knowledge was assessed based upon the diverse experience of the PIRT review team. For phenomena that were ranked low and/or N/A for all transient periods, the state of knowledge was not assessed.

Relative rankings of the phenomena in the PIRT were assigned using the following criteria:

H = The phenomenon is considered to have high importance. Modeling of the phenomenon during the particular period is considered to be crucial to obtain the correct or conservative prediction of the transient.

M = The phenomenon is considered to have medium importance. The phenomenon must be modeled with sufficient detail to obtain accuracy in the simulation; however, the phenomenon is expected to have less impact on the overall results than those ranked high.

L = The phenomenon is not considered to be very important during the transient. The phenomenon needs to be modeled in the code (or accounted for in the methodology), but inaccuracies in modeling these phenomenon are not considered likely to have a significant impact on the overall transient results.

N/A = The phenomenon is considered insignificant, or does not occur at all. This phenomenon need not be modeled or be taken into consideration, as it has an insignificant impact on results.

The state of knowledge rankings in the PIRT were assigned using the following criteria:

H = The state of knowledge of the phenomenon is considered to be high. Relevant test data exists and mature calculation methods exist. There is sufficient understanding of these phenomena such that they could be treated in a conservative or bounding manner in a model and no new testing or model development is needed to predict these phenomena.

M = The state of knowledge of the phenomenon is considered to be medium. Test data and/or calculation methods that exist may not be directly applicable to the scenario or geometry under consideration. There is sufficient understanding of these phenomena such that they may be treated in a conservative or bounding manner in a model although additional tests or model development will likely be necessary to properly account for these phenomena if the phenomena are high ranked.

L = The state of knowledge of the phenomenon is considered to be low. Little or no relevant test data exists and calculation methods that may exist have not been applied to the scenario or geometry under consideration. There is insufficient understanding of these phenomena such that they cannot be treated in a conservative or bounding manner in a model so tests and/or model development will be necessary to properly account for these phenomena if the phenomena are high ranked.

Tables 7-1, 7-3, 7-5, 7-7, 7-9, 7-11, 7-13, 7-15, 7-17, and 7-19 summarize the plausible phenomena, relative rankings, and state of knowledge assessments. Tables 7-2, 7-4, 7-6, 7-8, 7-10, 7-12, 7-14, 7-16, 7-18, and 7-20 provide the rationale for the ranking assigned to phenomena. The high-ranked phenomena are summarized in Table 8-1 and detailed discussion of these high-ranked phenomena is provided in Section 9.

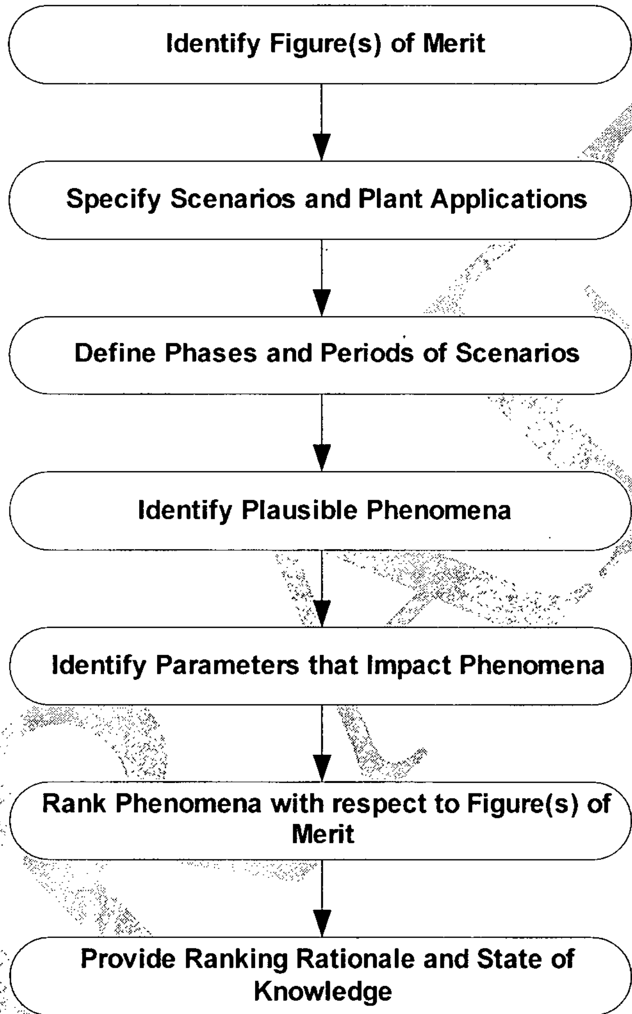

Figure 4-1 PIRT Process

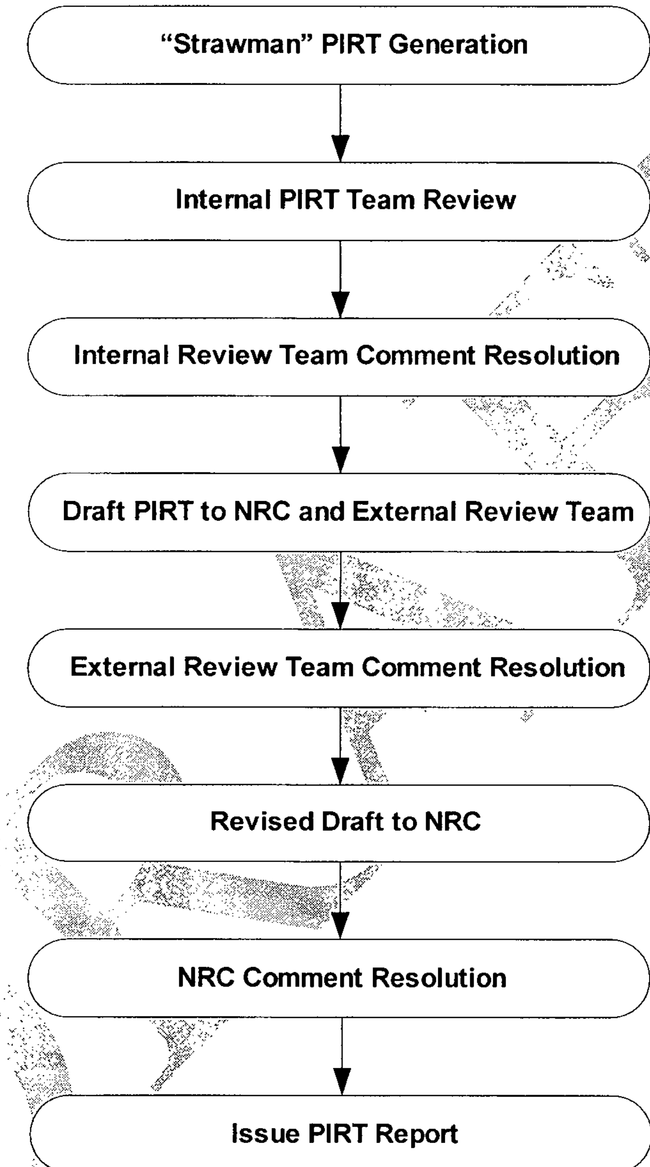

Figure 4-2 PIRT Review Process

5 PIRT REVIEW TEAM

5.1 INTERNAL EXPERTS

William L. Brown

William L. Brown is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office with 27 years of experience in thermal-hydraulic engineering. He obtained his B.A.E. degree from Penn State University and M.S. degree in Mechanical Engineering from the University of Pittsburgh. He spent several years in thermal-hydraulic-acoustic design, analysis, and testing for U.S. Naval nuclear submarines such as the Seawolf, Trident, and Los Angeles class submarines. He successfully led PIRT, scaling, testing, and analysis work to support the development and licensing of new passive commercial nuclear power plants such as the AP600, SPWR, EP1000, IRIS, and AP1000. He received several George Westinghouse Signature Awards for his work in new plant designs including the company's highest level honor in 2001 for AP1000. More recently, Mr. Brown has focused on analysis and testing related to ultrasonic flow meters and turbulent flow phenomena in reactor vessels. Mr. Brown has been an invited lecturer at several universities, an adjunct instructor of engineering mechanics at Penn State University, published several technical papers, and serves as a reviewer of technical papers for Nuclear Technology journal. He is a registered professional engineer licensed in the state of Pennsylvania and a member of ASME.

Joseph M. Cleary

Joseph M. Cleary is a Principal Engineer at Westinghouse Electric Company's Windsor, Connecticut, office and has 30+ years in LOCA safety analysis. He obtained his M.S. in Nuclear Engineering from University of New Mexico. He has expertise in large break LOCA, small break LOCA and post-LOCA long-term cooling safety analysis. His primary expertise is in the application of Appendix K ECCS performance evaluation models to Combustion Engineering PWRs for standard licensing analyses and non-standard applications. He has also been involved in model development, training, and special projects. Mr. Cleary has held various positions within his organization including supervisor of LOCA safety analysis group and certified project manager.

Milorad B. Dzodzo

Dr. Milorad B. Dzodzo is a Fellow Engineer in the Thermal, Fluid and Nuclear Engineering Group at the Westinghouse Science and Technology Department and is currently working in support of ongoing operations at Westinghouse nuclear divisions and development of advanced nuclear systems. He obtained a B.S. in Mechanical Engineering, M.S. and Ph.D. from University of Belgrade, Serbia. From 1977 to 1978 he was in "Energoproject – Engineering and Consulting Company" and from 1979 to 1992 at the University of Belgrade, Serbia. He was British Council Fellow (1985/1986 school year) and research associate (September 1986 – February 1987) at Imperial College, Computational Fluid Dynamic Unit, London, England. From 1992 to 1996 he was research associate and visiting assistant professor at The University of Akron, Ohio, USA. He has worked at the Westinghouse Science and Technology Center in Pittsburgh, Pennsylvania, USA since 1996.

Dr. Dzodzo works in the thermal-hydraulic area. His expertise covers the entire range, from analytical approach (like scaling, development of heat transfer correlations, or applying analytical methods for heat transfer and hydraulic problems) to numerical (by developing new and/or improving existing numerical models, or utilizing commercial CFD codes) and experimental (developing new test facilities, modifying existing ones, developing test plans, organizing and performing measurements). His areas of expertise are analysis, numerical modeling and experimental testing in a variety of fields such as: Heat Transfer (natural and forced convection, heat exchangers, stratification and natural circulation inside passive cooled containments of nuclear reactors, heat transfer in the nuclear reactor core), detailed experimental scaling using NRC-approved methodology [applied to the International Reactor Inherently Safe (IRIS) project for Small Break Loss-of-Coolant Accident (SBLOCA) testing], Computational Fluid Dynamics (development of the CFD codes, implementation of higher order numerical schemes in the existing general purpose CFD program, application of NASA developed codes, and application of commercial CFD codes as TascFlow, Star-CD and CFX), Flow Visualization, Tribology, Turbomachinery, Thermodynamics, Heating, Ventilation and Air Condition and Solar Energy conversion.

Michael Epstein

Michael Epstein is Vice President of Consulting Services at Fauske & Associates, LLC. He received his Ph.D. degree in Mechanical Engineering from the Polytechnic Institute of Brooklyn in 1970. He joined Fauske & Associates in 1980 after nine years of research experience at Argonne National Laboratory, where he was Manager of the Post Accident Heat Removal Section in the Reactor Analysis and Safety Division. He served as a consultant to various industries and on several government (NRC & DOE)/industrial review panels.

Dr. Epstein has published over 100 (archival) journal articles in the areas of fluid mechanics, convective energy and mass transport, phase transformations, aerosol phenomena, and chemical reaction mechanisms. In 1984, he received a National Science Foundation Award to conduct fundamental research on density-driven natural convection. In 1987, he was co-recipient of the William H. Doyle Award for the best paper at the New Orleans Loss Prevention Symposium. He has also participated as an invited speaker and lecturer at several universities and technical symposia and he has served as an advisor to graduate students at several universities. He was a Technical Editor of the ASME Journal of Heat Transfer (1979-1985) and was Chairman of the AIChE's Committee on Safety of Chemical Processes and Hazardous Materials (1988-1991).

Cesare Frepoli

Cesare Frepoli is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania office. He has 15 years experience in the nuclear industry and 27 years in the area of experience in thermal-hydraulic engineering. He received a Ph.D. in Nuclear Engineering from Penn State University and an M.E. in Nuclear Engineering from the Politecnico di Milano. Dr. Frepoli is a recognized expert in the area of thermal-hydraulic, fluid-dynamics, numerical methods and physical models for computer simulation of nuclear reactors. He has led various development programs and teams within the industry and authored several publications in the area. He is cognizant of the various licensing and regulatory aspects of safety analyses methodologies, operation and maintenance of PWRs, as well as design certification and safety analysis for new generation nuclear power plants (AP600/AP1000, IRIS, APWR, APR1400).

Brett E. Kellerman

Brett E. Kellerman is a Senior Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He has been on the Westinghouse staff for 9 years. He obtained his B.S. degree in Nuclear Engineering from Penn State University. Prior to joining Westinghouse, he spent several years working in laboratories primarily involved in radiation measurement and metallurgy. At Westinghouse, he has performed the full range of licensing basis LOCA safety analyses including Appendix K and Best Estimate large break LOCA ECCS performance, Appendix K small break LOCA ECCS performance, LOCA blowdown forces, and long term cooling with a particular emphasis on Westinghouse 2-loop upper plenum injection plant designs. For the last several years he has primarily been involved in long term cooling methodology development in support of extended power upratings.

John A. Klingenfus

John A. Klingenfus an Advisory Engineer at AREVA NP's Lynchburg, Virginia, office. He obtained his B.S. and M.E. Degrees in Engineering Physics with specialties in the thermal and nuclear sciences from the University of Louisville and began work in 1980 in the Babcock and Wilcox nuclear division in Lynchburg, VA. He has been on the AREVA NP staff (formally B&W as well as various other names) for 26 years in various engineering, teaching, and supervisory roles with the primary focus on LOCA analysis code and methods development. He has been responsible for system thermal-hydraulic code benchmarks and performed numerous code development activities for various codes including CRAFT2 and RELAP5/MOD2-B&W system thermal-hydraulic codes. His has led or participated in numerous SBLOCA, LBLOCA, and non-LOCA model and method development tasks for applications on B&W, Westinghouse, CE, and the new US EPR plants. He led the development effort and authored the RELAP5/MOD2-B&W-based LOCA deterministic evaluation model for B&W-designed plants. He also provides regular consultation to the Emergency Operating and Inadequate Core Cooling procedure writers and has developed and supported methods for LOCA mass and energy release and Appendix R analysis efforts. In addition, he has developed methods for demonstrating compliance to the coolable core geometry and long-term core cooling criteria of 10 CFR 50.46. This work included development of the current generic post-LOCA boric acid precipitation methods for small and large LOCA events for the B&W-designed plants.

Mitchell E. Nissley

Mitchell E. Nissley is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He obtained his B.S. and M.E. Degrees in Nuclear Engineering from Rensselaer Polytechnic Institute. He has worked for Westinghouse Electric Company for 26 years, and has led or consulted with the teams responsible for the development, licensing and application of the various realistic large break LOCA analysis codes and methodologies employed by Westinghouse. His contributions to the nuclear industry include the development and licensing of critical heat flux correlations for advanced PWR and VVER (Vodo-Vodni Energiini Reqktor, also known as Water-Water Energy Reactor) fuel designs, and the development and licensing of realistic large break LOCA evaluation models for Westinghouse PWR designs (cold leg injection, upper plenum injection, AP600/AP1000, and Combustion Engineering designs). He was an Electric Power Research Institute (EPRI)-nominated member of the NRC's High Burn-up Fuel PIRT Panel for the PWR Loss-of-Coolant Accident, and actively participates on the EPRI

Fuel Reliability Program's interactions with the NRC regarding high burn-up LOCA testing results. He has several journal and conference publications.

Katsuhiro Ohkawa

Katsuhiro Ohkawa is a Fellow Engineer at Westinghouse Electric Company's Monroeville, Pennsylvania, office. He has 24 years experience in the nuclear industry. He received a B.S. degree in Physics from Sophia University in Tokyo, Japan and M.S. and Ph.D. degrees in Nuclear Science and Engineering from Rensselaer Polytechnic Institute. His experience at Westinghouse includes the development of Advanced Liquid Metal Nuclear Plants, BWR and PWR safety methods and the real time thermal-hydraulic systems code. Since 1990, he has been involved in the development of Best Estimate LOCA Analysis Methods. Currently he is leading the development efforts for the Best Estimate Full Spectrum LOCA Methodology.

6 PIRT PURPOSE/SCOPE, FIGURE OF MERIT AND SCENARIO DISCUSSION

6.1 PURPOSE AND SCOPE OF BORIC ACID TRANSPORT AND MIXING PIRT

The primary purpose and scope of this PIRT is to identify and rank phenomena that impact boric acid transport and mixing in the reactor vessel prior to precipitation as initiation of active boric acid dilution measures during post-LOCA long-term cooling is expected to preclude precipitation. The PIRT process will identify high-ranked phenomena that must be addressed in plant boric acid evaluation methodologies and models. The PIRT process will also identify any high-ranked phenomena with a low state of knowledge that must be addressed via conservative or bounding analytical treatment and/or appropriately scaled tests. It should be stressed that the scope of this PIRT does not cover boric acid precipitation phenomena or thermal mixing as related to the solubility limit of boric acid. This PIRT addresses temperature distribution and thermal mixing only in the context of its impact on boric acid transport and mixing prior to precipitation (i.e., initiation of active boric acid dilution measures).

6.2 FIGURE OF MERIT

FIGURE OF MERIT
Boric Acid Concentration in the Reactor Vessel Liquid Mixing Volume

PIRT rankings reflect relative importance of mixing and transport phenomena with respect to their impact on the figure of merit; that being, boric acid concentration in the reactor vessel liquid mixing volume. It is not the intent of this PIRT to identify and rank phenomena that impact the solubility limit of boric acid. This is an important distinction. For example, the flashing of liquid to vapor during small break LOCAs would likely be ranked with high importance with respect to the solubility limit of boric acid since the solubility limit is a strong function of saturation temperature/pressure. However, with respect to the impact on concentration, flashing is ranked low since the make-up coolant provided by the ECCS will replace the amount of liquid that flashes to steam and maintain the system liquid inventory by offsetting the shrinkage as the saturated liquid specific volume decreases with system pressure.

6.3 PIRT FOR BORIC ACID TRANSPORT AND MIXING PRIOR TO PRECIPITATION DURING POST-LOCA LONG-TERM COOLING

In the PIRT development process, it is useful to divide the scenario into several periods to better identify and rank the phenomena. Many phenomena will be important during one period but may become insignificant or even non-existent during other periods. In order to successfully predict the entire evolution of the scenario, it is necessary to accurately predict the phenomena during their period of importance. Many of the PIRTs developed to date have looked at scenarios that are fairly well understood, e.g., the short-term small and large break LOCAs, and for which abundant amounts of experimental data exists. Long-term cooling has not received the same level of attention in terms of regulatory scrutiny and, consequently, experimental study, as the short-term transients for peak clad temperature, embrittlement, and hydrogen generation. Given that relatively little is understood about the scenario, it is imperative to rank not just the importance of the phenomenon itself but also the state of knowledge (SOK). This two-part ranking process will better serve to identify the key areas of focus for scaling, testing, and analytical methodology/analytical tool selection.

In reviewing the available information from the BACCHUS facility (Reference 4) tests, the data suggests that the long-term cooling scenario prior to initiating active boric acid dilution measures is characterized by three periods during which boric acid concentration levels increase in the reactor vessel and some passive boric acid dilution is achieved via phenomena such as turbulent convection in the core region associated with boiling and density-driven convection between core and lower vessel regions. The three periods are the core boric acid accumulation period, transition period, and convection transport dominated period. A fourth period, active boric acid dilution period, follows the concentration periods after active boric acid dilution measures are initiated. These periods are described in the following sections; however, the active boric acid dilution period is not addressed in the current PIRT. But first, it is necessary to define when the long-term cooling phase begins, for the full spectrum of break sizes, as it relates to the accumulation of boric acid in the reactor vessel prior to precipitation.

6.4 BEGINNING OF LONG-TERM COOLING – ACCUMULATION OF BORIC ACID

For Large Break LOCA (LBLOCA), this phase of the transient begins when the core begins to reflood after the accumulators have refilled the lower plenum following the initial blowdown of the RCS. For Small Break LOCA (SBLOCA), this phase of the transient begins once two-phase natural circulation (with continuous liquid phase flow regime in loop piping) breaks down (e.g., annular (countercurrent) or dispersed droplet flow regime in intact loop steam generators) thereby degrading the mechanism for transporting boric acid through the RCS and eventually out the break.

6.5 BORIC ACID ACCUMULATION AND PASSIVE DILUTION PHASE

6.5.1 CORE BORIC ACID ACCUMULATION PERIOD

The decay heat is at its highest during this period. To satisfy decay heat removal, flow from the downcomer, through the lower plenum, core, and upper plenum, then out of the reactor vessel will initially be significant but will decrease as the core decay heat diminishes. This high flow will generate turbulence as the coolant passes through the complex geometries of the reactor vessel internals. Therefore, turbulent dispersion will be the primary mixing mechanism. This turbulent mixing is expected to create reasonably well-mixed sub-regions within the reactor vessel but global mixing of boric acid throughout the reactor vessel would not occur. The experiments (References 4 and 5) show that the downcomer and lower plenum region boric acid concentration remain relatively close to the source (Refueling Water Storage Tank (RWST) or containment sump) concentration; whereas, the core and upper plenum regions are initially relatively close to the source concentration but continuously increase as the coolant boils away leaving behind the boric acid. The expected boric acid concentration distribution is depicted in Figure 6-2 along with a summary of high-ranked phenomena.

6.5.2 TRANSITION PERIOD

During this period, the coolant flow required to provide make-up for core decay heat boil-off diminishes. As such, the turbulent dispersion mixing mechanism correspondingly diminishes as the flow transitions from turbulent toward laminar. The flow may intermittently cycle between turbulent and laminar with decreasing frequency as the flow becomes more nearly laminar. As the turbulent dispersion of boric acid diminishes, both axial and radial concentration gradients will form thereby effectively 'un-mixing' the sub-regions (particularly in the core region) that were previously reasonably well mixed. Concentration gradients between the regions will be such that molecular diffusion will provide some small amount of boric acid transport between regions. The expected boric acid concentration distribution is depicted in Figure 6-3 along with a summary of high-ranked phenomena.

6.5.3 CONVECTION TRANSPORT DOMINATED PERIOD

As the decay heat further diminishes, flow to satisfy core cooling may become less turbulent and, with continued boil-off, this would produce concentration gradients in the reactor vessel. The boric acid gradient would primarily increase through the reactor vessel while the temperature gradient would decrease due to decay heat. Opposing concentration and temperature gradients can lead to stratification-type instability and hence convection.

If the boric acid concentration gradient is large enough so that the net density gradient in the rector vessel is unstable then convection due to fluid density instability (i.e., denser fluid over top of less dense fluid) certainly could occur analogous to Rayleigh-Bénard convection in single component convection.

The expected boric acid concentration distribution is depicted in Figure 6-4 along with a summary of high-ranked phenomena. This period ends when recirculation coolant flows are realigned prior to reaching the boric acid solubility limit in any region of the reactor vessel.

6.6 ACTIVE BORIC ACID DILUTION PHASE

At some point following a LOCA, the Emergency Operating Procedures (EOPs) typically instruct operators to take action to initiate a means of actively diluting the concentrated boric acid solution that would be present in the reactor vessel after a cold leg break. The action may involve switching some or all of the pumped safety injection from cold leg injection to hot leg injection (either directly or through pressurizer spray lines). Hot leg injection flow will force liquid flow through the core and out the break on the cold leg. Alternately, hot leg letdown lines may be opened to discharge RCS inventory to the sump thus allowing positive liquid flow through the core. In either case, forced liquid flow through the core (well in excess of decay heat boil-off), or "flushing flow" has been recognized as a highly effective means of diluting the boric acid in the reactor vessel. Since active boric acid dilution mechanisms are highly plant specific, and since the effectiveness of flushing flow on dilution has not been challenged in the regulatory arena, this phase is not being addressed in the current PIRT.

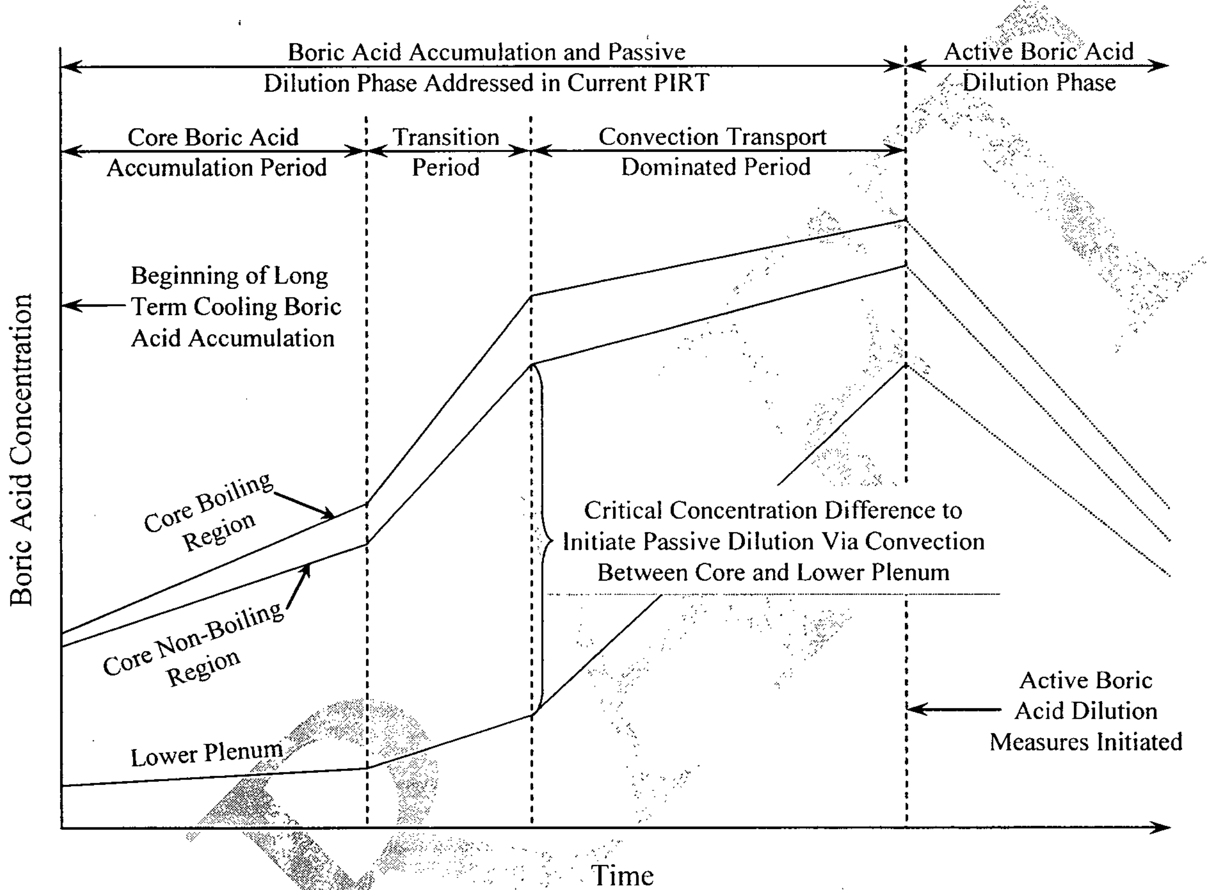

Figure 6-1 Primary Phases and Periods of Post-LOCA Boric Acid Mixing/Transport in Reactor Vessel

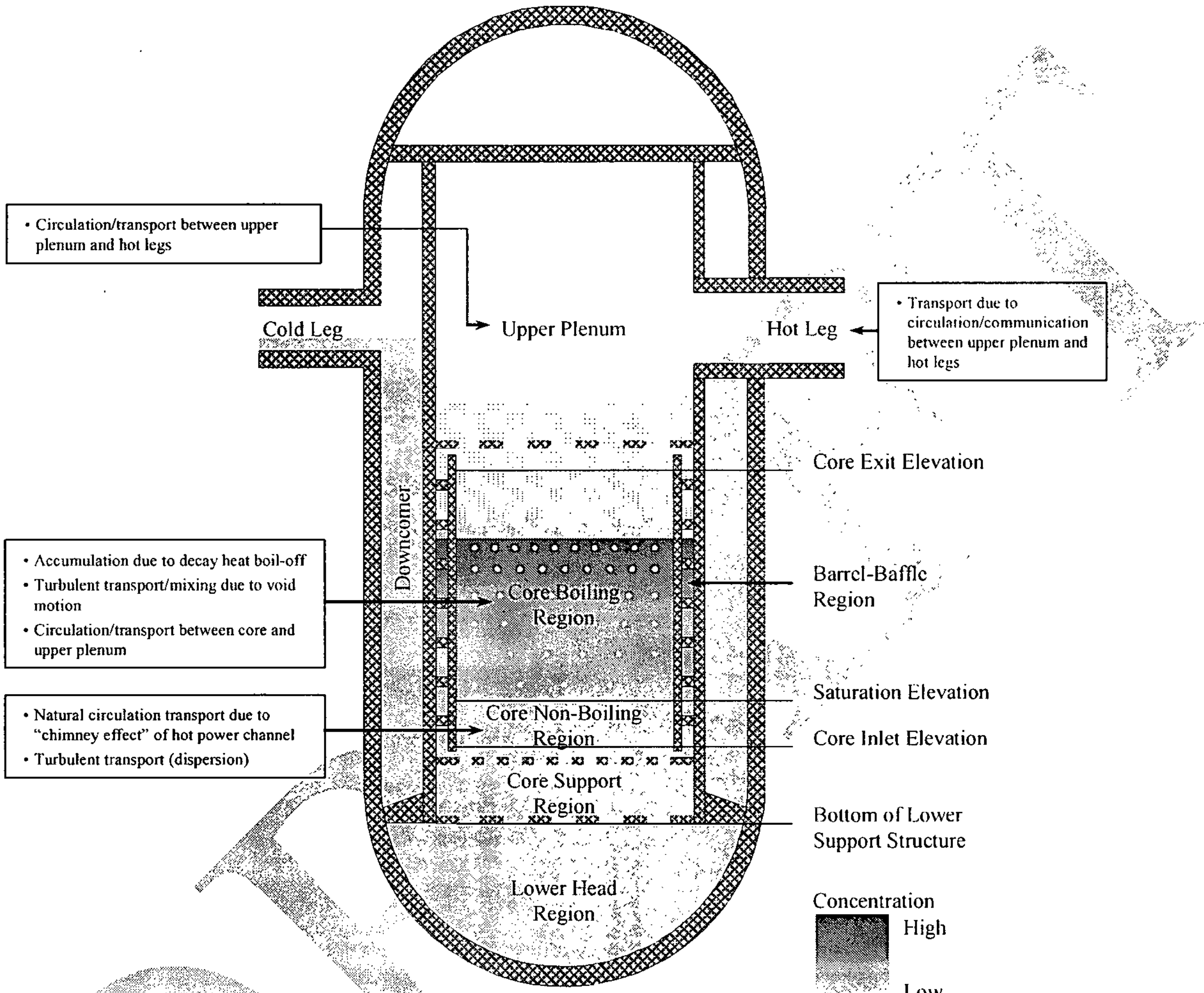

Figure 6-2 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Core Boric Acid Accumulation Period

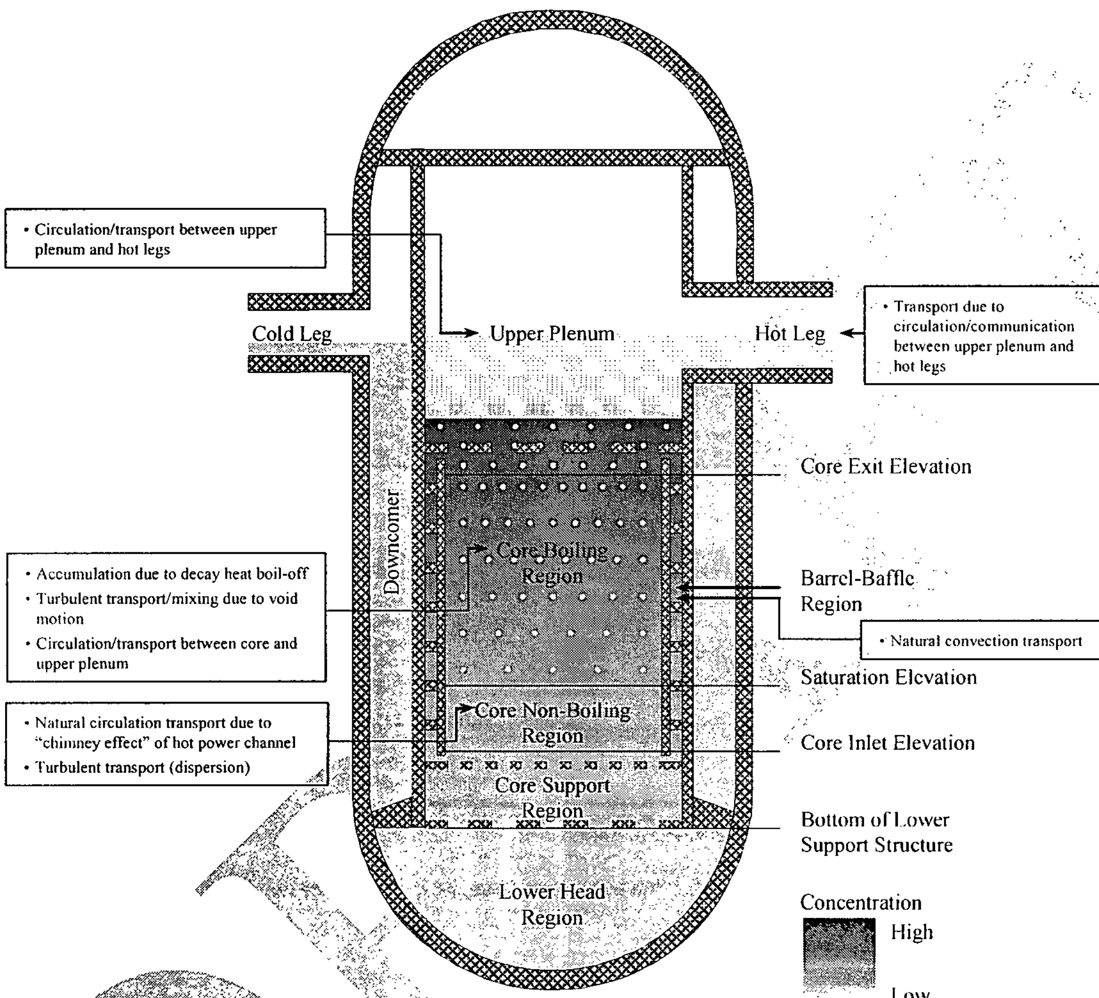

Figure 6-3 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Transition Period

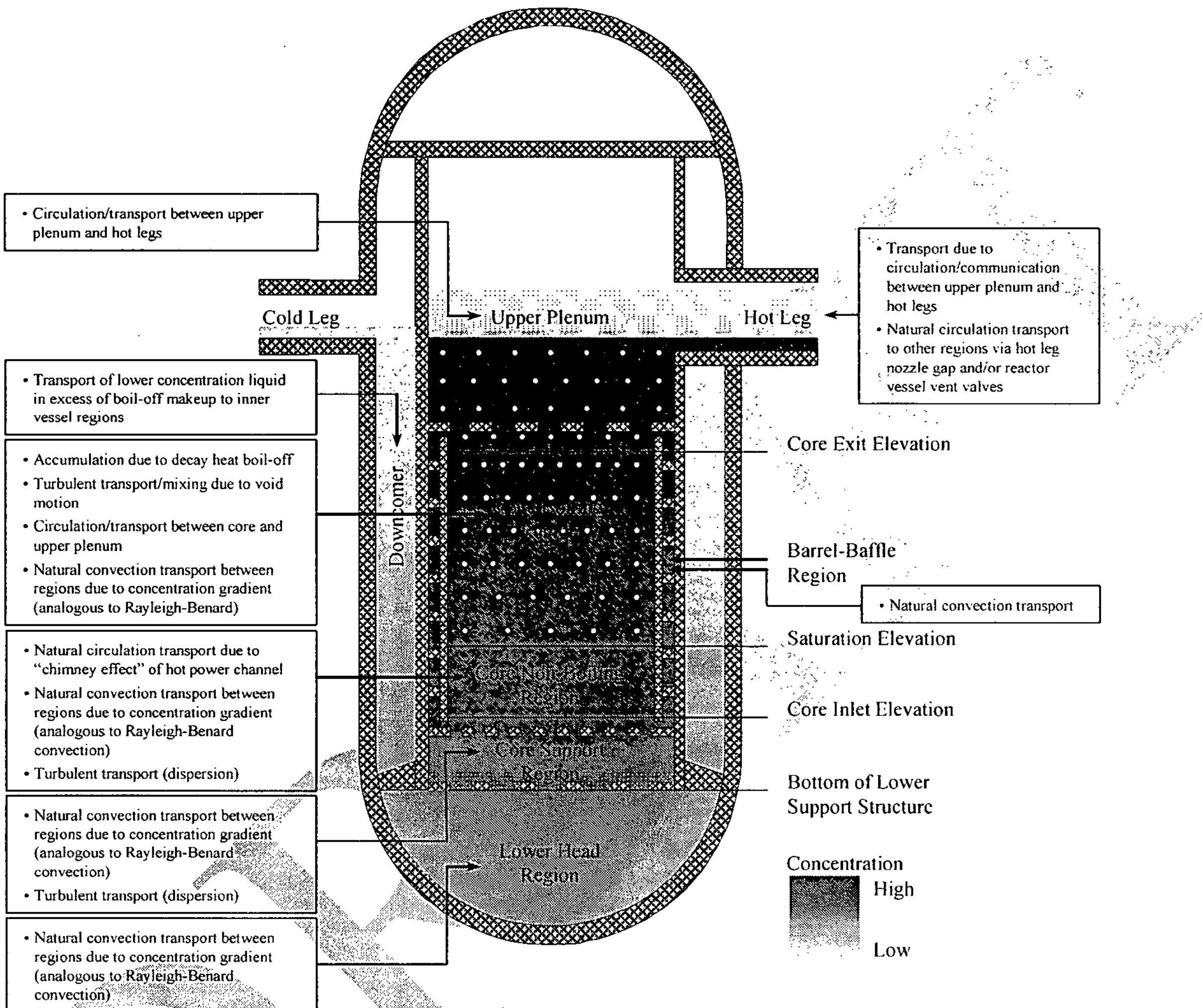

Figure 6-4 Expected Boric Acid Concentration Distribution and Summary of High-Ranked Phenomena During the Convection Transport Dominated Period

7 PIRT WITH RANKINGS AND RATIONALE

Table 7-1 Rankings for Core – Boiling (Decay Heat) Region

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Total accumulation of boric acid in liquid mixing volume due to decay heat boil-off of liquid mixing volume.	H		H		H	
a. Impact of radial/axial power and void distribution on boil-off if high void fraction or steam cooling occurs in core.	L	H	L	H	L	H
b. Impact of liquid mixing volume size on accumulation of boric acid.	H	M	H	L	H	L
c. Impact of boric acid properties on latent heat of vaporization.	L	M	L	M	L	M
d. Impact of boric acid miscibility in steam or vapor phase.	L	M	L	M	L	M
2. Turbulent transport/mixing (convection/dispersion) of boric acid liquid due to void (i.e., vapor phase) motion within core boiling region.	H		H		H	
a. Impact of two-phase flow regime associated with void motion.	H	M	H	M	H	M
b. Impact of decay heat boiling on void generation, size, and population.	H	M	H	M	H	M
c. Impact of boric acid properties (density, viscosity, surface tension).	L	M	L	M	L	M
d. Impact of radial/axial power distribution on void distribution.	M	M	M	M	M	M
e. Impact of interfacial drag between void and boric acid liquid solution on transport of boric acid liquid.	M	H	M	H	M	H

Table 7-1 Rankings for Core – Boiling (Decay Heat) Region (cont.)

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
f. Impact of geometry such as fuel lattices or fuel assembly gaps on void motion induced mixing/circulation.	M	M	M	M	M	M
g. Impact of turbulent mixing generated in wake region of moving void.	M	M	M	M	M	M
h. Impact of turbulence generated from chaotic boiling.	H	M	H	M	H	M
i. Impact of turbulence generated from flow across fuel assemblies and associated structures such as grids (vortex shedding, shear flow instability, flow separation).	H	M	H	M	H	M
3. Transport of boric acid due to circulation/communication between core and upper plenum regions of liquid mixing volume.	H		H		H	
a. Impact of liquid entrainment/de-entrainment including pool type liquid entrainment and liquid film-type entrainment from solid surfaces.	H	M	H	M	H	M
b. Impact of two-phase mixture level swell.	H	H	H	H	H	H
c. Impact of flooding/Counter Current Flow Limitation (CCFL) at upper core plate on liquid circulation/communication.	H	M	L	M	L	M
d. Impact of boric acid properties (density, viscosity, surface tension) on liquid entrainment/de-entrainment.	L	M	L	M	L	M
e. Impact of "chimney effect" from hot power channel on circulation pattern.	M	M	M	M	M	M
f. Impact of two-phase flow regime on circulation/communication.	H	M	H	M	H	M

Table 7-1 Rankings for Core – Boiling (Decay Heat) Region (cont.)

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
4. Molecular diffusion transport of boric acid between liquid and vapor phases.	L		L		L	
5. Transport/mixing of boric acid between core region and other reactor vessel regions due to double diffusive convection.	L		L		L	
6. Molecular diffusion transport of boric acid within liquid mixing volume of core boiling region.	L		L		L	
7. Molecular diffusion transport of boric acid from core boiling region to barrel/baffle region.	L		L		L	
8. Natural convection transport of higher concentration boric acid from core region to other regions of reactor vessel where boric acid concentration is lower (fluid density instability type convection driven by boric acid concentration gradient in reactor vessel analogous to Rayleigh-Benard convection).	L		M		H	
a. Impact of hydraulic resistance.	L	H	M	H	M	H
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L	L	M	L	H	L
c. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	L	L	L	L
9. Transport/mixing of boric acid within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	L		L		L	

Table 7-1 Rankings for Core – Boiling (Decay Heat) Region (cont.)						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
10. Pseudo-turbulent transport of boric acid within core region from oscillatory or unsteady mean flow in reactor vessel (two-phase manometer type instability or flow separation type instability).	L		L		L	
11. Accumulation of boric acid due to boiling from metal heat and stored energy in the fuel.	L		N/A		N/A	
12. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	

Table 7-2	Rationale for Core – Boiling (Decay Heat) Region
1.	Decay heat boil-off is high ranked overall as decay heat boiling is the primary phenomenon that leads to boric acid concentration increase in the liquid mixing volume as boric acid is not very miscible in steam. a. Total accumulation/generation of boric acid is not expected to be significantly affected by axial/radial power distribution unless substantial core uncovery or dry-out occurs. b. The concentration of boric acid is directly related to the size of the liquid mixing volume. c. The presence of boric acid is not expected to significantly affect latent heat of vaporization (relative to pure water) (refer to Full Length Emergency Core Heat Transfer (FLECHT) data for 2000 ppm borated coolant – Section 4.1.9 of Reference 6). d. Not important due to very low miscibility of boric acid in steam/vapor (refer to Section 6 of Reference 7).
2.	Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor) motion within the core region is ranked high overall as it represents the primary phenomena responsible for transport/mixing of boric acid liquid within the core boiling region. a. Two-phase flow regime (i.e., bubbly, slug, churn, etc.) is directly related to motion of void. b. Important since decay heat drives boiling process which impacts void formation and motion. c. The presence of boric acid is not expected to significantly affect solution properties relative to pure water. d. Moderate importance due to impact of void distribution on liquid flow pattern (i.e., increased void generation at lower elevation influences more of the liquid circulation region as opposed to a top-skewed power distribution). e. Moderate importance due to influence of interfacial drag (between liquid and vapor phases) on distribution of boric acid in liquid mixing volume (i.e., interfacial drag of lower concentration liquid to region of higher concentration as void moves upward in core boiling region). f. Moderate importance due to influence of geometry on void motion as it influences circulation and distribution of boric acid. g. Moderate importance as turbulence generated in wake of void induces mixing and circulation of boric acid. h. Important since high turbulence levels can be generated from vortex shedding, flow separation, and shear flow instability. i. Chaotic motion of void expected to enhance turbulent dispersion/mixing in liquid mixing volume.

Table 7-2	Rationale for Core – Boiling (Decay Heat) Region (cont.)
3.	Transport of boric acid due to circulation/communication between core and upper plenum regions of liquid mixing volume is considered a high-ranked phenomenon since it is the primary phenomenon by which higher concentration boric acid from core region liquid mixing volume is "diluted" with liquid mixing volume in upper plenum region. a. High importance as liquid entrainment provides primary means of communication between core and upper plenum liquid mixing volumes when two-phase mixture level is low or high void fraction exists in upper region of core. b. Two-phase mixture level swell is important as it impacts liquid mixing volume in core and upper plenum regions. c. Counter current flow at upper core plate is expected to have an important impact on boric acid liquid flow back into core region early as steam velocity is high; low importance later as steam velocity decreases with decay heat level. d. The presence of boric acid is not expected to significantly affect solution properties relative to pure water. e. "Chimney effect" is expected to have some effect on circulation pattern on flow to and from core region but not as much impact as two-phase flow regime, mixture level, or entrainment/de-entrainment. f. Two-phase flow regime is ranked high since flow path between core and upper plenum liquid mixing volumes is two-phase.
4.	Low importance since boric acid is not very miscible in steam.
5.	Low importance due to weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms.
6.	Low importance due to extremely weak transport/mixing mechanism compared to boiling/bubble motion, turbulence, entrainment, and density-driven convection mechanisms.
7.	Low importance due to extremely weak transport/mixing mechanism compared to density-driven convection mechanisms.
8.	Natural convection driven by boric acid concentration (analogous to Rayleigh-Benard convection) is ranked high as it is expected to have important impact on transport of boric acid in reactor vessel liquid mixing volume. a. Importance of hydraulic resistance increases as boric acid concentration gradient increases. b. Convection pattern is important as it impacts effectiveness of transport/mixing. c. Concentration gradient relative to temperature gradient is of low importance in core region as temperature difference is small in boiling region (saturated conditions).
9.	Low ranking as secondary flow not as effective as turbulent mixing and mixing is usually confined to secondary flow region itself whereas turbulence is expected to diffuse beyond region of turbulence generation.
10.	Low importance since large oscillations or unsteady mean flow are not expected to occur.

Table 7-2	Rationale for Core – Boiling (Decay Heat) Region (cont.)
11.	Low importance early as metal heat from structures and stored energy from fuel may cause localized boiling hence accumulation/build-up of boric acid; N/A later on because metal heat and stored energy from fuel has been released.
12.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.

Table 7-3 Rankings for Core – Non-Boiling Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Natural circulation transport of boric acid within core region due to "chimney effect" of hot power channel.	H		H		H	
a. Impact of hydraulic resistance.	H	M	H	M	H	M
b. Impact of circulation pattern.	H	L	H	L	H	L
2. Natural convection transport of higher concentration boric acid from core region to other regions of reactor vessel where boric acid concentration is lower (fluid density instability type convection driven by boric acid concentration gradient in reactor vessel analogous to Rayleigh-Benard convection).	L		M		H	
a. Impact of hydraulic resistance.	L	M	M	M	H	M
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L	L	M	L	H	L
c. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L
3. Turbulent transport (dispersion) of boric acid within core region.	H		H		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability, flow separation) across fuel assemblies and associated structures such as grids.	H	M	H	M	H	M

Table 7-3 Rankings for Core – Non-Boiling Region (cont.)						
	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK
4. Transport/mixing of boric acid within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	M		M		M	
a. Impact of non-axisymmetrical fuel assembly geometry on wall turbulence and hence secondary flows.	M	M	M	M	M	M
5. Double diffusive convection transport of boric acid between non-boiling region of core and other regions of reactor vessel.	L		L		L	
6. Molecular diffusion transport of boric acid from boiling region of core to non-boiling region.	L		L		L	
7. Molecular diffusion transport of boric acid from non-boiling core region to barrel/baffle region.	L		L		L	
8. Pseudo-turbulent transport of boric acid within core region from oscillatory or unsteady mean flow in reactor vessel.	L		L		L	
9. Accumulation of boric acid due to boiling from metal heat and stored energy in the fuel.	L		N/A		N/A	
10. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	

Table 7-4	Rationale for Core – Non-Boiling Region
1.	"Chimney effect" is important as it is expected to have important impact on natural circulation transport in non-boiling region of core. a. High importance since drag/resistance impacts convection velocity. b. High importance since pattern determines extent of convection transport.
2.	Natural convection driven by boric acid concentration impact on fluid density increases in importance as the concentration gradients increase within the core region. a. Becomes more important as concentration-driven convection increases in importance. b. Flow regime determines strength of convection transport. Its importance increases as the concentration increases later in time and this mode of convection becomes stronger. c. Becomes more important as concentration-driven convection increases in importance.
3.	Turbulence is important as is it is very highly effective mixing/transport phenomenon. a. High importance due to level of turbulence intensity expected from turbulent flow through complex core geometry.
4.	Secondary flows are given a moderate ranking as they are not quite as effective as turbulent mixing and mixing is usually confined to secondary flow region itself whereas turbulence is expected to diffuse beyond region of turbulence generation. a. Moderate importance since secondary flows are expected to be produced in fuel assembly geometry when flow is turbulent.
5.	Low importance due to weaker transport/mixing mechanism compared to Rayleigh-Benard type density-driven convection mechanisms.
6.	Low importance due to extremely weak transport/mixing mechanism compared to turbulence and density-driven convection mechanisms.
7.	Low importance due to extremely weak transport/mixing mechanism compared to turbulence and density-driven convection mechanisms.
8.	Low importance since large oscillations or unsteady mean flow are not expected to occur or produce significant turbulence.
9.	Low importance early as metal heat from structures and stored energy from fuel may cause some localized boiling hence accumulation/build-up of boric acid; N/A later on because metal heat and stored energy from fuel has been released.
10.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.

Table 7-5 Rankings for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Molecular diffusion transport between core and lower plenum regions.	L		L		L	
2. Natural convection (due to concentration driven fluid density in stability analogous to Rayleigh-Benard convection) transport of higher concentration boric acid between core region and lower head region liquid mixing volume where boric acid concentration is lower.	L		M		H	
a. Impact of lower core support plate hole geometry.	L	L	M	L	H	L
b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L
3. Double diffusive convection transport/mixing of boric acid between core and lower head regions.	L		L		L	
4. Accumulation of boric acid due to boiling (metal heat release) from structures.	M	H	N/A		N/A	
5. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	
6. Turbulent transport (dispersion) of boric acid within core support region.	L		M		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across structures.	L	M	M	M	H	M

Table 7-6	Rationale for Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)
1.	Low importance early due to low concentration difference in reactor vessel. Low importance later due to molecular diffusion being a weak transport/mixing mechanism compared to turbulence and density-driven convection phenomena.
2.	Natural convection driven by boric acid concentration impact on fluid density increases in importance as the concentration gradients increase within the core support region. a. Low importance early due to low concentration difference; more important later as concentration increases leading to density-driven convection as hole geometry influences convection pattern. b. Low importance early due to low concentration difference; more important later as concentration increases.
3.	Low importance early on as concentration gradient is low; low later as double diffusive is weaker compared to transport/mixing mechanism compared to concentration-driven convection analogous to Rayleigh-Benard type convection.
4.	Moderate importance early as metal heat from structures may cause localized boiling hence accumulation/build-up of boric acid; N/A later on because heat already removed.
5.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
6.	Turbulence becomes high ranked as concentration of boric acid increases in this region and it is very highly effective mixing/transport phenomenon. a. Low importance early as low boric acid concentration in this region; becomes more important as boric acid concentration increases later in transient.

Table 7-7 Rankings for Lower Head Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Natural convection (due to concentration driven fluid density instability analogous to Rayleigh-Benard convection) transport of higher concentration boric acid from core support region to lower head region liquid mixing volume.	L		M		H	
a. Impact of lower head structures on hydraulic resistance.	L	M	M	M	H	M
b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L
2. Turbulent transport (dispersion) of boric acid within lower head region.	L		M		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across lower plenum structures such as support columns, instrumentation tubes and flow skirts.	L	M	M	M	H	M
b. Impact of downcomer flow (velocity distribution and turbulence level) on turbulence within the lower head region.	L	M	L	M	L	M
3. Transport of boric acid within lower plenum due to secondary flow patterns generated within the lower head region.	L		L		L	
4. Molecular diffusion transport of boric acid from core support to lower head region.	L		L		L	
5. Accumulation of boric acid due to boiling (metal heat release) from lower head structures.	L		N/A		N/A	

Table 7-7 Rankings for Lower Head Region (cont.)						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
6. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	
7. Double diffusive convection transport/mixing of boric acid from core support region to lower head region of lower plenum.	L		L		L	

Table 7-8	Rationale for Lower Head Region
1.	Natural convection (analogous to Rayleigh-Benard convection) driven by boric acid concentration increases in importance as the concentration gradients increase within the reactor vessel. a. Low importance early due to low concentration difference; more important later as concentration increases leading to density-driven convection as lower head structure geometry influences convection pattern. b. Low importance early due to small concentration gradient; importance increases as boric acid concentration gradient increases relative to temperature gradient and density instability leads to boric acid transport via natural convection analogous to Rayleigh-Benard convection.
2.	Turbulence becomes high ranked as concentration of boric acid increases in this region and it is very highly effective mixing/transport phenomenon. a. Low importance early due to low concentration; importance increases as boric acid transported from core and support region to lower head region. b. Low importance as lower head structure geometry influences flow pattern.
3.	Low importance due to expected dominance of concentration-driven convection and turbulent dispersion.
4.	Low importance as concentration-driven convection (analogous to Rayleigh-Benard convection) and turbulent dispersion transport will dominate over molecular diffusion.
5.	Low importance early as metal heat from structures that may cause localized boiling and hence accumulation/build-up of boric acid is less important than that occurring in core region; N/A later on because metal heat has been released.
6.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
7.	Low importance early on as concentration gradient is low; low later on as double diffusive convection is weaker compared to concentration-driven convection.

Table 7-9 Rankings for Barrel/Baffle Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Natural convection transport of boric acid due to concentration gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	M		H		H	
a. Impact of presence of holes.	M	H	H	H	H	H
b. Impact of gap/hole/former hydraulic resistance.	M	H	H	H	H	H
c. Impact of fluid temperature gradient on concentration-driven convection.	L	L	L	L	L	L
2. Turbulent transport/mixing of boric acid between former elevations.	L		L		L	
3. Molecular diffusion transport of boric acid within barrel/baffle region or between the core and barrel/baffle regions.	L		L		L	
4. Double diffusive convection transport/mixing of boric acid within barrel/baffle region or between the core and barrel/baffle regions.	L		L		L	
5. Accumulation of boric acid due to boiling from metal heat.	L		N/A		N/A	
6. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	

Table 7-10	Rationale for Barrel/Baffle Region
1.	Density-driven natural convection due to concentration impact on density is ranked medium to high as boric acid concentration increases in core region. a. High importance as the presence of holes is required for circulation transport of boric acid to/from this region. Importance is moderate in early phase as the concentration gradient is not large to drive strong convection. b. Important as hydraulic resistance impacts the circulation rate and hence the transport of boric acid. c. Low importance as convection gradient is expected to dominate over temperature gradient with respect to convection.
2.	Low importance as circulation velocities and therefore turbulence is expected to be low.
3.	Low importance as transport by molecular diffusion is expected to be very weak compared to density-driven circulation.
4.	Low importance as transport by double diffusive convection is expected to be dominated by density-driven convection.
5.	Low importance early as metal heat from structures that may cause localized boiling and hence accumulation/build-up of boric acid is less important than that occurring in core region; N/A later on because metal heat has been released.
6.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.

Table 7-11 Rankings for Upper Plenum Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport of boric acid due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	H		H		H	
a. Impact of liquid entrainment including pool type liquid entrainment (when two-phase mixture level is in upper plenum or liquid pool exists).	H	M	H	M	H	M
b. Impact of upper plenum structures such as guide tubes on de-entrainment of liquid.	M	M	M	M	M	M
c. Impact of boric acid properties (density, viscosity, surface tension) on liquid entrainment/de-entrainment.	L	M	L	M	L	M
d. Impact of two-phase flow regime on circulation/communication.	H	M	H	M	H	M
e. Impact of two-phase mixture level swell.	H	M	H	M	H	M
2. Molecular diffusion transport of boric acid between liquid and vapor phases.	L		L		L	
3. Turbulent transport/mixing of boric acid within upper plenum region due to steam sparging and turbulence generated from upper plenum structure such as guide tubes.	M	M	M	M	M	M
4. Accumulation of boric acid due to boiling off of upper plenum structures.	L		N/A		N/A	
5. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	
6. Net liquid entrainment transport of boric acid above two-phase mixture level in upper plenum/hot leg regions.	L		L		L	

Table 7-12	Rationale for Upper Plenum Region
1.	High importance is given to transport of boric acid between upper plenum and hot leg region due to circulation and mixing. a. High importance early due to decay higher steam velocity to entrain liquid. High importance later when 2-phase mixture level in upper plenum as entrainment of liquid is more likely. b. Moderate importance as tests (Dallman & Kirchner) shows significant de-entrainment across (several) guide tubes. c. The presence of boric acid is not expected to significantly affect solution properties relative to pure water. d. Important as two-phase flow regime impacts level swell (direct communication) and entrainment/de-entrainment (indirect communication). e. Important as two-phase mixture level provides direct communication when mixture level is above bottom of hot leg and impacts entrainment when mixture level is below bottom of hot leg.
2.	Low importance since boric acid is not very miscible in steam.
3.	Moderate importance as steam velocity in upper plenum and turbulence levels are expected to be lower than core region.
4.	Low importance since most metal heat already removed (post quench); N/A later on because metal heat already removed.
5.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
6.	Low importance as the amount of entrained liquid droplets above two-phase mixture level is expected to be small.

Table 7-13 Rankings for Downcomer Region						
	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport of lower concentration boric acid liquid (in excess of make-up for boil-off) from downcomer to inner reactor vessel liquid mixing volume regions.	M		M		H	
a. Impact of downcomer gravity head on supplying liquid mixing volume.	M	H	M	H	M	H
b. Impact of Boric Acid Makeup Tank (BAMT) injection (CE only).	M	M	N/A		N/A	
2. Accumulation of boric acid in liquid phase due to downcomer boiling.	M	H	N/A		N/A	
3. Accumulation of boric acid due to flashing (SBLOCA depressurization).	L		L		L	
4. Transport and generation of turbulence in downcomer region as related to boric acid turbulent transport/mixing within lower plenum/core regions.	L		L		L	
5. Transport and generation of secondary flow patterns generated within downcomer as related to mixing in lower plenum/core regions.	L		L		L	

Table 7-14	Rationale for Downcomer Region
1.	The boric acid concentration of the make-up flow is initially higher for some ECCS designs. As the boric acid concentration increases in the lower plenum/core regions, the inflow of more dilute make-up flow from the downcomer promotes density-driven convection due to the concentration gradient in the reactor vessel. Excess make-up flow increases the liquid mixing volume in the inner reactor vessel. a. Moderate importance as it influences rate at which make-up flow is transported to the core region. b. Moderately important early as this high concentration/low flow rate source will mix with lower concentration/high flow rate sources which provide make-up flow; N/A later since the BAMT will have emptied.
2.	Moderate importance early as metal heat from structures that may cause localized boiling and hence accumulation/build-up of boric acid is less important than that occurring in core region; N/A later on because metal heat has been released.
3.	Low importance as make-up coolant provided by the ECCS will replace the liquid flashing to steam and maintain (or potentially increase) liquid mass inventory by offsetting the shrinkage due to the saturated liquid specific volume decreasing with system pressure.
4.	Low importance as turbulence level resulting from lower plenum structures is expected to be much more dominant relative to downcomer region.
5.	Low importance due to expected dominance of lower internals structures and turbulent dispersion relative to downcomer induced secondary flows on mixing/transport in reactor vessel liquid mixing volume.

Table 7-15 Rankings for Hot Leg Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport of boric acid due to circulation/communication between upper plenum and liquid mixing volume hot leg region.	H		H		H	
a. Impact of two-phase flow regime.	H	M	H	M	H	M
b. Impact of boric acid properties (density, viscosity, surface tension) on liquid entrainment/de-entrainment.	L	M	L	M	L	M
c. Impact of gravity drain back to upper plenum when mixture level in upper plenum is low.	H	M	H	M	H	M
d. Impact of two-phase mixture level swell.	H	M	H	M	H	M
e. Impact of liquid entrainment/de-entrainment.	H	M	H	M	H	M
2. Natural circulation of higher concentration boric acid from upper plenum/hot leg to other regions such as downcomer region via hot leg nozzle gap and/or RVVVs for B&W plants.	L		M		H	
a. Impact of differential expansion on hot leg gap flow path dimension.	L	H	M	H	H	H
b. Impact of gap hydraulic resistance.	L	H	M	H	H	H
3. Net liquid entrainment transport of boric acid above two-phase mixture level in the hot leg.	L		L		L	

Table 7-16	Rationale for Hot Leg Region
1.	Once the liquid flow between upper plenum and hot leg is no longer counter current flow limited, the liquid volume in the hot leg will communicate with the upper plenum thus expanding the liquid volume available for mixing. The communication can occur via two-phase mixture level swell or liquid entrainment/de-entrainment. a. High importance as flow regime impacts two-phase mixture level and entrainment/de-entrainment. b. The presence of boric acid is not expected to significantly affect solution properties relative to pure water. c. High importance as de-entrained high concentration boric acid solution drains back toward core. d. Important as two-phase mixture level impacts liquid entrainment (indirect communication) when level is below hot leg and provides direct communication when level is above bottom of hot leg. e. Important as entrainment/de-entrainment is primary means of communication between liquid mixing volume of core/upper plenum region and liquid mixing volume of hot leg when two-phase mixture level is below hot leg elevation.
2.	Higher concentration boric acid solution can be transported out of the upper plenum/core region after the mixture level reaches the hot leg and/or RVVV elevation. a. Low importance early as the concentration is low; importance increases as the concentration increases. This is the primary mechanism for removing boric acid from liquid mixing volume. b. Low importance early as the concentration is low; importance increases as the concentration increases.
3.	Low importance as the amount of entrained liquid droplets above two-phase mixture level is expected to be small.

Table 7-17 Rankings for Steam Generator Region						
	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
Phenomena Description	Rank	SOK	Rank	SOK	Rank	SOK
1. Impact of plate-out of boric acid on steam generator tubes.	L		L		L	
2. Impact of boric acid droplet carryover through steam generator.	L		L		L	

Table 7-18 Rationale for Steam Generator Region	
1.	Low importance as boric acid deposited as a thin film on the tubes (large surface area) will have a negligible impact on pressure drop or more localized deposition on tube sheet/tube entrance not expected to result in sufficient blockage to significantly impact pressure drop due to the large flow area in the tube region.
2.	Low importance as boric acid droplets expected to de-entrain in steam generator tubes and as decay heat level decreases droplet carryover into steam generator decreases.

Table 7-19 Rankings for Cold Leg/Pump Region						
Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
1. Transport of liquid to loop seal causing refilling and potential level depression in the inner reactor vessel and reducing liquid mixing volume in inner reactor vessel.	M	M	M	M	M	M
2. Transport and generation of turbulence associated with cold leg discharge as related to boric acid turbulent transport/mixing with lower plenum/core regions.	L		L		L	
3. Transport and generation of secondary flow patterns generated within cold legs as related to mixing in lower plenum/core regions.	L		L		L	

Table 7-20 Rationale for Cold Leg/Pump Region	
1.	Moderate importance as refilling the loop seal piping could impact the core region liquid mixing volume due to mixture level depression; not ranked high as level swell phenomena as expected to be more important in determining two-phase mixture level.
2.	Low importance as turbulence level is expected to be lower due to less complex geometry compared to lower plenum/core region.
3.	Low importance as convection and turbulence mechanisms in the lower plenum/core regions are expected to be more important.

8 SUMMARY OF HIGH-RANKED PHENOMENA

Table 8-1 Summary Table of High-Ranked Phenomena

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
Core – Boiling (Decay Heat) Region						
1. Total accumulation of boric acid in liquid mixing volume due to decay heat boil-off of liquid mixing volume.	H		H		H	
a. Impact of radial/axial power and void distribution on boil-off if high void fraction or steam cooling occurs in core.	L	H	L	H	L	H
b. Impact of liquid mixing volume size on accumulation of boric acid.	H	M	H	L	H	L
2. Turbulent transport/mixing (convection/dispersion) of boric acid liquid due to void (i.e., vapor phase) motion within core boiling region.	H		H		H	
a. Impact of two-phase flow regime associated with void motion.	H	M	H	M	H	M
b. Impact of decay heat boiling on void generation, size, and population.	H	M	H	M	H	M
c. Impact of interfacial drag between void and boric acid liquid solution on transport of boric acid liquid.	M	H	M	H	M	H
d. Impact of turbulence generated from chaotic boiling.	H	M	H	M	H	M
e. Impact of turbulence generated from flow across fuel assemblies and associated structures such as grids (vortex shedding, shear flow instability, flow separation).	H	M	H	M	H	M

Table 8-1 (cont.) Summary Table of High-Ranked Phenomena

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
3. Transport of boric acid due to circulation/communication between core and upper plenum regions of liquid mixing volume.	H		H		H	
a. Impact of liquid entrainment/de-entrainment including pool type liquid entrainment and liquid film-type entrainment from solid surfaces.	H	M	H	M	H	M
b. Impact of two-phase mixture level swell.	H	H	H	H	H	H
c. Impact of flooding/CCFL at upper core plate on liquid circulation/communication.	H	M	L	M	L	M
d. Impact of two-phase flow regime on circulation/communication.	H	M	H	M	H	M
4. Natural convection transport of higher concentration boric acid from core region to other regions of reactor vessel where boric acid concentration is lower (fluid density instability type convection driven by boric acid concentration gradient in reactor vessel analogous to Rayleigh-Benard convection).	L		M		H	
a. Impact of hydraulic resistance.	L	H	M	H	H	H
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L	L	M	L	H	L
Core – Non-Boiling Region						
1. Natural circulation transport of boric acid within core region due to "chimney effect" of hot power channel.	H		H		H	
a. Impact of hydraulic resistance.	H	M	H	M	H	M
b. Impact of circulation pattern.	H	L	H	L	H	L

Table 8-1 (cont.) Summary Table of High-Ranked Phenomena

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	**SOK**	**Rank**	**SOK**	**Rank**	**SOK**
2. Natural convection transport of higher concentration boric acid from core region to other regions of reactor vessel where boric acid concentration is lower (fluid density instability type convection driven by boric acid concentration gradient in reactor vessel analogous to Rayleigh-Benard convection).	L		M		H	
a. Impact of hydraulic resistance.	L	M	M	M	H	M
b. Impact of convection pattern or regime (steady roll cell, unsteady or intermittent roll cell, turbulent).	L	L	M	L	H	L
c. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L
3. Turbulent transport (dispersion) of boric acid within core region.	H		H		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability, flow separation) across fuel assemblies and associated structures such as grids.	H	M	H	M	H	M
Core Support Region (Bottom of Active Fuel to Bottom of Core Support Plate)						
1. Natural convection (due to concentration driven fluid density in stability analogous to Rayleigh-Benard convection) transport of higher concentration boric acid between core region and lower head region liquid mixing volume where boric acid concentration is lower.	L		M		H	
a. Impact of lower core support plate hole geometry.	L	L	M	L	H	L
b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L

Table 8-1 (cont.) Summary Table of High-Ranked Phenomena

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
2. Turbulent transport (dispersion) of boric acid within core support region.	L		M		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across structures.	L	M	M	M	H	M
Lower Head Region						
1. Natural convection (due to concentration driven fluid density instability analogous to Rayleigh-Benard convection) transport of higher concentration boric acid from core support region to lower head region liquid mixing volume.	L		M		H	
a. Impact of lower head structures on hydraulic resistance.	L	M	M	M	H	M
b. Impact of reactor vessel concentration gradient relative to temperature gradient on fluid density instability driven convection.	L	L	M	L	H	L
2. Turbulent transport (dispersion) of boric acid within lower head region.	L		M		H	
a. Impact of turbulence generated from flow (vortex shedding, shear instability) across lower plenum structures such as support columns, instrumentation tubes and flow skirts.	L	M	M	M	H	M
Barrel/Baffle Region						
1. Natural convection transport of boric acid due to concentration gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	M		H		H	
a. Impact of presence of holes.	M	H	H	H	H	H

Table 8-1 (cont.) Summary Table of High-Ranked Phenomena

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
b. Impact of gap/hole/former hydraulic resistance.	M	H	H	H	H	H
Upper Plenum Region						
1. Transport of boric acid due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	H		H		H	
a. Impact of liquid entrainment including pool type liquid entrainment (when two-phase mixture level is in upper plenum or liquid pool exists).	H	M	H	M	H	M
b. Impact of two-phase flow regime on circulation/communication.	H	M	H	M	H	M
c. Impact of two-phase mixture level swell.	H	M	H	M	H	M
Downcomer Region						
1. Transport of lower concentration boric acid liquid (in excess of make-up for boil-off) from downcomer to inner reactor vessel liquid mixing volume regions.	M		M		H	
a. Impact of downcomer gravity head on supplying liquid mixing volume.	M	H	M	H	H	H
Hot Leg Region						
1. Transport of boric acid due to circulation/communication between upper plenum and liquid mixing volume hot leg region.	H		H		H	
a. Impact of two-phase flow regime.	H	M	H	M	H	M

Table 8-1 Summary Table of High-Ranked Phenomena (cont.)

Phenomena Description	Core Boric Acid Accumulation Period		Transition Period		Convection Transport Dominated Period	
	Rank	SOK	Rank	SOK	Rank	SOK
b. Impact of gravity drain back to upper plenum when mixture level in upper plenum is low.	H	M	H	M	H	M
c. Impact of two-phase mixture level swell.	H	M	H	M	H	M
d. Impact of liquid entrainment/de-entrainment.	H	M	H	M	H	M
2. Natural circulation of higher concentration boric acid from upper plenum/hot leg to other regions such as downcomer region via hot leg nozzle gap and/or RVVVs for B&W plants.	L		M		H	
a. Impact of differential expansion on hot leg gap flow path dimension.	L	H	M	H	H	H
b. Impact of gap hydraulic resistance.	L	H	M	H	H	H

9 DISCUSSION OF HIGH-RANKED PHENOMENA

9.1 TOTAL ACCUMULATION OF BORIC ACID IN LIQUID MIXING VOLUME DUE TO DECAY HEAT BOIL-OFF

Accumulation of boric acid in the liquid mixing volume occurs as a consequence of decay heat boil-off of the liquid inventory coupled with low miscibility of boric acid in the vapor phase (i.e., steam). As a result, accumulation of boric acid due to decay heat boil-off is considered a high-ranked phenomenon throughout all phases of boric acid mixing and transport. It is the primary phenomenon by which boric acid concentrates in the liquid phase inventory in the reactor vessel.

The size of the liquid mixing volume is ranked important to the total accumulation of boric acid as it impacts the bulk or average concentration of boric acid resulting from decay heat boil-off.

Based upon results obtained from FLECHT reflood heat transfer tests (Reference 3) with dilute concentrations of boric acid, it is expected that the thermal hydraulic properties and core heat transfer associated with the presence of boric acid will have a low impact on accumulation of boric acid within the liquid mixing volume. FLECHT tests with boric acid (4% by weight) showed a two percent increase in core heat transfer relative to that obtained with pure demineralized water.

Accumulation of boric acid due to stored energy related (from reactor vessel structures) boil-off was not considered to have a significant impact (relative to decay heat boil-off) on boric acid accumulation especially in the later phases of boric acid mixing and transport when stored energy has long been removed.

9.2 TURBULENT TRANSPORT/MIXING OF BORIC ACID (CONVECTION/DISPERSION) DUE TO VOID MOTION WITHIN BOILING REGION OF CORE

Void (i.e., vapor) motion in the boiling region of the core is a phenomenon that causes turbulent agitation and mixing (i.e., dispersion) of the liquid inventory. The chaotic motion of the voids pushes and drags liquid as the voids circulate through the core region. The two-phase flow regime is considered to have a very important impact on the void motion phenomenon. For example, churn-turbulent two-phase flow regime in the core region would be expected to provide more effective vigorous void motion and therefore turbulent mixing of boric acid in the liquid inventory relative to the bubby flow regime which is less turbulent.

As void motion significantly contributes to mixing and transport of boric acid within the core region of the liquid mixing volume it is considered a high-ranked phenomenon throughout all phases of boric acid mixing and transport. Even though the two-phase flow pattern or veracity of boiling-induced void motion may change with decay heat level or safety system design or alignment, boiling and associated turbulent transport/mixing will always be present in the core region.

9.3 NATURAL CONVECTION TRANSPORT OF HIGHER CONCENTRATION BORIC ACID FROM CORE REGION TO OTHER REGIONS WHERE BORIC ACID CONCENTRATION IS LOWER SUCH AS CORE SUPPORT, BARREL/BAFFLE, AND LOWER HEAD REGIONS

Natural convection mixing and transport within the core region and between the core region and other regions is a high-ranked phenomenon for many phases of boric acid mixing and transport. Natural convection is a fluid density instability phenomenon driven by density gradients in the fluid. In the reactor vessel there are three primary driving mechanisms behind these density gradients that cause natural convection, namely, temperature, void fraction, and boric acid concentration gradients.

- Convection associated with the temperature and void fraction gradients within the core region are high-ranked phenomena throughout all phases of boric acid mixing and transport as core decay heating is always present to establish a temperature or void fraction gradient. The temperature and void fraction gradients which increase from the core inlet toward the core exit region have the effect of causing the fluid density to decrease with elevation through the core region.

- Convection associated with the concentration gradients of boric acid between the core and other regions becomes more important as the boric acid concentration difference increases due to decay heat boil-off. Consequently, concentration-driven convection is a high-ranked phenomenon in the later phase of boric acid mixing and transport. The concentration gradient which increases from the lower regions of the reactor vessel toward the upper regions has the effect of increasing the fluid density with elevation in opposition to the temperature and void fraction gradient impact on fluid density.

9.4 TURBULENT MIXING (DISPERSION) AND TRANSPORT OF BORIC ACID WITHIN NON-BOILING REGION OF CORE, CORE SUPPORT REGION, AND LOWER HEAD REGION

Turbulent mixing or more specifically turbulent dispersion phenomena occurs throughout the liquid mixing volume in the reactor vessel as turbulence is generated from flow across numerous complex hydraulic structures such as fuel assemblies and grids, core support plates, and lower internals structures. Flow across these structures generates turbulence via flow separation, vortex shedding, and shear flow instability.

Another possible mechanism or route for turbulence generation is that associated with shear instability from convection phenomena. For instance, at low Rayleigh numbers, laminar rotating convection cells may be established. As Rayleigh number increases due to increase in density difference (due to concentration or temperature difference), chaotic convection cell patterns may occur. With further increase in Rayleigh number, convection pattern may transition to turbulent pattern.

In the boiling region of the core, turbulence is also imparted to the liquid mixing volume due to chaotic boiling and void motion. It is expected that high turbulence intensity levels will result from boiling and void motion coupled with turbulence generated from flow across fuel assemblies and grids. Therefore turbulence is considered a high-ranked phenomenon in the core region during all phases of boric acid mixing and transport.

Turbulence is not considered a high-ranked phenomenon in other regions of the reactor vessel such as the core support region or lower head regions in the early phase not because turbulence levels are insufficient for mixing but rather there is not significant accumulation of boric acid until later phases when convection processes transport higher concentration boric acid from core region to regions such as the core support region and lower head regions. Consequently, as boric acid is transported from the core region to lower reactor vessel regions during later phases, turbulence becomes more important as it contributes to mixing and transport of boric acid within those regions.

9.5 TRANSPORT OF BORIC ACID DUE TO CIRCULATION/COMMUNICATION BETWEEN CORE, UPPER PLENUM AND HOT LEG REGIONS OF LIQUID MIXING VOLUME

Higher concentration boric acid in the core region may be circulated (diluted) with the liquid volumes in the upper plenum and hot leg. The phenomena that allows this communication may be more direct via two-phase mixture level swell into upper plenum or hot leg regions. Or it may be indirect communication via liquid entrainment from the core region to the upper plenum/hot leg where liquid de-entrains, mixes with liquid mixing volume in those regions and liquid returns back toward core region.

9.6 NATURAL CIRCULATION TRANSPORT OF BORIC ACID WITHIN CORE NON-BOILING REGION DUE TO "CHIMNEY EFFECT" OF HOT POWER CHANNEL

The "chimney effect" of the hot power channel produces natural circulation of boric acid within the core non-boiling region. The hot power channel increases local buoyancy of the fluid (relative to nearby fluid channels) and induces a secondary flow circulation pattern that enhances mixing of boric acid liquid. Although this "chimney effect" phenomenon may occur in the boiling region as well it is not ranked as high as in the non-boiling region of the core since turbulent transport/mixing associated with boiling and void motion dominates in the boiling region of the core. Therefore, the "chimney effect" of the hot power channel is ranked high for the non-boiling region of the core.

9.7 TRANSPORT OF LOWER CONCENTRATION BORIC ACID LIQUID (IN EXCESS OF MAKE-UP FOR BOIL-OFF) FROM DOWNCOMER TO INNER REACTOR VESSEL LIQUID MIXING VOLUME REGIONS

As the boric acid concentration increases in the core support and lower head regions, the inflow of lower concentration boric acid to make up for core boil-off promotes a boric acid dilution effect in these regions. This phenomenon contributes to promoting density-driven convection of boric acid from the core region toward the lower reactor vessel regions and contributes to maintaining/increasing liquid mixing volume.

9.8 NATURAL CIRCULATION TRANSPORT OF HIGHER CONCENTRATION BORIC ACID FROM UPPER PLENUM/CORE TO DOWNCOMER VIA HOT LEG NOZZLE GAP AND/OR RVVVS (B&W PLANTS)

The transport of higher concentration boric acid out of the upper plenum/core regions after the mixture level in the reactor vessel reaches the hot leg and/or RVVV elevation is a high-ranked phenomenon as it contributes to dilution of boric acid in the core region. This phenomenon is ranked high later in the transient as boric acid concentration increases in the upper plenum/core regions.

10 IMPACT OF SUMP DEBRIS ON PIRT AND RANKINGS

The PWR Owners Group has funded a number of initiatives to address post-LOCA ECCS performance issues with regard to NRC Generic Safety Issue GSI-191 (Reference 9) and the subsequent NRC Generic Letter 2004-02 (Reference 10). Initiatives included the development of approaches to evaluate the downstream impact of sump debris, the development of approaches to evaluate chemical effects on the performance of ECCS systems, and alternate sump pH buffering agents (References 11, 12 and 13). Most recently, the PWROG funded an initiative to development an approach for evaluating sump debris and chemical effects on long term cooling (Reference 14). Insights gained from these initiatives underscore the potential for sump debris and chemical effects to impact phenomena and mixing mechanisms in the reactor vessel and consequently the potential to impact the build-up of boric acid in the core region after a LOCA.

For low levels of sump debris or chemistry effects it is expected that no new important phenomena would be introduced in the boric acid mixing and transport PIRT. It is expected that overall the mixing and transport phenomena may be degraded or altered somewhat for low levels of sump debris or chemistry effects but not to the point that would alter the relative ranking of the most important phenomena.

For moderate to high levels of sump debris or chemistry effects it is expected that overall important mixing and transport phenomena would further degrade and that it is possible that new phenomena may be introduced or at least that the relative ranking of phenomena may change due to alteration of flow pattern or regime. It is conceivable that as the effects of sump debris increase, the relative ranking between concentration-driven natural convection and double diffusive convection or possibly molecular diffusion on the impact of boric acid transport from the core region to the core support, barrel/baffle, or lower head regions may change as a result of increased hydraulic resistance. Increased sump debris level may clog or restrict flow through the hot leg gap significantly degrading the effectiveness of boric acid transport from the core/upper plenum to the downcomer liquid volume via the hot leg gap. With respect to turbulent transport/mixing of boric acid, sump debris may have some opposing effects. For instance, collection of sump debris on reactor vessel structures/surfaces may enhance turbulence levels due to increased roughness or vortex shedding. On the other hand, additional sump debris in the boric acid may increase the effective fluid viscosity such that turbulence levels are reduced and turbulent mixing is degraded. Similarly turbulent void motion and flow regime could be significantly impacted in the presence of higher levels of sump debris.

The current PIRT therefore should be adequate to cover low levels of sump debris. However, as sump debris levels increase, it is expected that the current PIRT would need to be modified to address such situations.

11 CONCLUSIONS

The PIRT process yielded several high-ranked phenomena important to boric acid mixing and transport within a reactor vessel following LOCAs. In summary those high-ranked phenomena included the following:

- Boric acid accumulation due to decay heat boil-off.
- Turbulent convection/dispersion of boric acid due to void motion within the core region.
- Natural convection mixing and transport of boric acid due to boric acid concentration gradient between the core region and other regions within the reactor vessel such as the barrel/baffle region, core support region, and lower head region.
- Turbulent mixing and transport throughout the reactor vessel.
- Transport of lower concentration boric acid liquid in excess of make-up for boil-off from downcomer to inner reactor vessel liquid mixing volume regions.
- Natural circulation transport of boric acid from upper plenum/core to downcomer via hot leg nozzle gap and/or RVVVs (B&W plants).
- Transport of boric acid due to circulation/communication between core, upper plenum and hot leg regions of liquid mixing volume.
- Natural circulation transport of boric acid within core region due to "chimney effect" of hot power channel.

The state of knowledge for boric acid mixing and transport is considered in general to be sufficient for purposes of identifying and ranking phenomena and hence produce a useful PIRT. The state of knowledge for some high-ranked phenomena for purposes of modeling and analysis of boric acid mixing and transport in a reactor vessel for post LOCA conditions, however, is considered to be low. This is especially true for high-ranked boric acid mixing and transport phenomena related to natural convection driven by fluid density instability that is dependent upon concentration and temperature gradients and dependent upon the complex flow pattern/circulation and geometry of the reactor vessel. This points to the need for testing and supporting model development to improve the state of knowledge of this high-ranked phenomenon.

For low levels of sump debris or chemical effects it is expected that although some degradation of mixing and transport may occur, that no new, high-ranked phenomena would be introduced into the boric acid mixing and transport PIRT; the current PIRT should remain applicable to such situations. When higher levels of sump debris or chemical effects are introduced, however, it is more likely that some new phenomena may be introduced or at least the ranking of some currently identified plausible phenomena would change. The current PIRT should provide a good basis for this effort.

12 RECOMMENDATIONS

Based upon the results of the internal PIRT development process, the following recommendations are made for addressing boric acid mixing and transport issues:

- Using the current PIRT as a basis, develop a PIRT to address boric acid mixing and transport under high levels of sump debris or chemical effects.

- Using the results obtained from the PIRT and what may be available from the open literature, develop "first principles" type boric acid transport and mixing model(s) that address the high-ranked phenomena. The model(s) will serve to contribute to the state of knowledge and to provide a basis to support scaled testing and plant evaluation model development work.

- Plan and execute scaled testing and supporting model development program to improve the state of knowledge of boric acid mixing and transport. Improving the state of knowledge via testing and supporting model development is necessary for addressing NRC issues and provides the foundation for plant evaluation modeling even if a bounding or conservative type approach is eventually pursued to address boric acid mixing and transport related issues. Testing and supporting model development should focus upon high-ranked phenomena such as natural convection driven by boric acid concentration gradient as related to boric acid mixing and transport within the complex geometry of the reactor vessel.

13 REFERENCES

1. NRC letter dated November 23, 2005, D. S. Collins to G. Bischoff, "Suspension of NRC Approval for Use of Westinghouse Topical Report CENPD-254-P, 'Post LOCA Long Term Cooling Model', Due to Discovery of Non-Conservative Modeling Assumptions During Calculation Audit." (TAC No. MB1365).

2. OG-06-200, "Suspension of NRC Approval for Use of Westinghouse Topical Report CENPD-254-P, Post LOCA Long Term Cooling Model, Due to Discovery of Non-Conservative Modeling Assumptions During Calculation Audit, PA-ASC-0290," June 19, 2006.

3. WCAP-7665, "PWR FLECHT - (Full Length Emergency Cooling Heat Transfer) Final Report," F. F. Cadek, D. P. Dominicis, and R. H. Leyse, April 1971.

4. WCAP-16317-P, "Review and Evaluation of MHI BACCHUS PWR Vessel Mixing Tests," W. L. Brown and D. J: Fink, 2004.

5. Tuunanen, J., et al., 1994. Experimental and analytical studies of boric acid concentrations in a VVER-440 reactor during the long-term cooling period of loss-of-coolant accidents. Nuclear Engineering and Design 148, 217.

6. WCAP-7435, "PWR Full Length Emergency Cooling Heat Transfer (FLECHT) Group I Test Report," J. O. Cermak, A. S. Kitzes, F. F. Cadek, R. H. Leyse, and D. P. Dominicis, January 1970.

7. WCAP-1570, "Literature Values for Selected Chemical/Physical Properties of Aqueous Boric Acid Solutions," D. E. Byrnes and W. E. Foster, May 1960.

8. Boyack, B. E., and Wilson, G. E., Lessons Learned in Obtaining Efficient and Sufficient Applications of the PIRT Process, Proceedings of the International Meeting on Updates in 'Best Estimate' Methods in Nuclear Installation Safety Analysis (BE2004), Washington, DC (November 14-18, 2004).

9. Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance."

10. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," September 13, 2004.

11. WCAP-16406-P, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," T. S. Andreychek, P. V. Pyle, M. J. Asztalos, C. A. Belovesick, L. I. Ezekoye, R. Hundal, J. L. Robinson, and D. W. White, June 2005.

12. WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," A. E. Lane, T. S. Andreychek, W. A. Byers, R. J. Jacko, E. J. Lahoda, and R. D. Reid, February 2006.

13. WCAP-16596-NP, "Evaluation of Alternative Emergency Core Cooling System Buffering Agents," R. D. Reid, K. R. Crytzer, A. E. Lane, and T. S. Andreychek, July 2006.

14. PWROG Program PA-SEE-0312, "PWR Owners Group Project PA-SEE-0312, Evaluation of Long-Term Cooling Associated with Sump Debris Effects," June 2006.

APPENDIX A
APPENDICES