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Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Phenomena Identification and Ranking Tables (PIRT) for GSI-191 Long-Term Cooling

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Comprehensive Analysis and Test Program for GSI-191 Closure (PA-SEE-1090) – Phenomena Identification and Ranking Tables (PIRT) for GSI-191 Long-Term Cooling

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Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	58 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.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee of Reactor Safeguards
ACS	American Chemical Society
AECL	Atomic Energy of Canada Limited
AIChE	American Institute of Chemical Engineers
Al	Aluminum
$Al(OH)_3$	Aluminum Hydroxide
$AlNa_{12}SiO_3$	Sodium Aluminosilicate
AlO(OH)	Aluminum Oxihydroxide
ANL	Argonne National Laboratory
APS	American Physical Society
B	Boron
B&W	Babcock and Wilcox
BAPC	Boric Acid Precipitation Control
BAST	Boric Acid Storage Tank(s)
BCEE	Board Certified Environmental Engineer
BMI	Bottom-mounted Instrumentation
B.S.	Bachelor of Science
BWST	Borated Water Storage Tank(s)
$Ca_3(PO_4)_2$	Calcium Phosphate
CAD	Computer Aided Design
Cal-Sil	Calcium Silicate
CANDU	Canadian Deuterium Uranium
CE	Combustion Engineering
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CHLE	Corrosion/Head Loss Experiments
Cl	Chlorine
CL	Cold Leg(s)
CLPD	Cold Leg Pump Discharge
CLPS	Cold Leg Pump Suction (Leg)
Co	Cobalt
CO_2	Carbon Dioxide
C_P	Heat Capacity
Cr	Chromium
CSNI	Committee on the Safety of Nuclear Installations
CSS	Containment Spray System

LIST OF ACRONYMS AND ABBREVIATIONS (cont.)

Cu	Copper
DC	Downcomer
DEG	Double-ended Guillotine
DFD	Division of Fluid Dynamics
DHC	Decay Heat Cooler
DLVO	Derjaguin, Landau, Verway and Overbeek
DOD	Department of Defense
ECCS	Emergency Core Cooling System
EDS	Energy Dispersive Spectroscopy
EM	Evaluation Model
EOP	Emergency Operating Procedure(s)
EPR	European Pressurized Reactor
EPRI	Electric Power Research Institute
EPU	Extended Power Uprate(s)
Fe	Iron
GSI	Generic Safety Issue
GL	Generic Letter
H	Hydrogen
H_2	Deuterium
H_2O	Water
H_2O_2	Hydrogen Peroxide
HCl	Hydrogen Chloride / Hydrochloric Acid
HELB	High Energy Line Break
HL	Hot Leg(s)
HLSO	Hot Leg Switchover
HVAC	Heating, Ventilation and Air Conditioning
HX	Heat Exchanger(s)
IAPWS	International Association for the Properties of Water and Steam
ICET	Integrated Chemical Effects Test
ID	Inner Diameter
IOZ	Inorganic Zinc (a type of protective coating that provides anodic protection)
LANL	Los Alamos National Laboratory
LBLOCA	Large Break LOCA
LiOH	Lithium Hydroxide
LOCA	Loss-of-Coolant Accident
LOCADM	Loss-of-Coolant Accident Deposition Model
LP	Lower Plenum

LIST OF ACRONYMS AND ABBREVIATIONS (cont.)

LPI	Low Pressure Injection
LTC	Long-term Cooling
M.E.	Masters of Engineering
MHI	Mitsubishi Heavy Industries
MIST	Multi-Loop Integral System Test
MIT	Massachusetts Institute of Technology
M.S.	Masters of Science
N_2	Nitrogen
NaOH	Sodium Hydroxide
NASA	National Aeronautics and Space Administration
NaTB	Sodium Tetraborate
NEA	Nuclear Energy Act
NEI	Nuclear Energy Institute
NIH	National Institute of Health
NP	Nuclear Power
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
NSSS	Nuclear Steam Supply System
O_2	Oxygen
p:f	Particulate to Fiber Ratio
PA	Project Authorization
PCT	Peak Cladding Temperature
P.E.	Professional Engineer
PFIAT	Potential Flow Interior Air Transport
pH	Hydrogen Concentration
Ph.D.	Philosophical Dissertation
PIRT	Phenomena Identification and Ranking Table(s)
PRA	Probabilistic Risk Analysis
PSU	The Pennsylvania State University
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor(s)
PWROG	Pressurized Water Reactor Owners Group
PZC	Point of Zero Charge
PZR	Pressurizer
RCP	Reactor Coolant Pump(s)
RCS	Reactor Coolant System

LIST OF ACRONYMS AND ABBREVIATIONS (cont.)

REDOX	Reduction Oxidation
RHR	Residual Heat Removal
RPV	Reactor Pressure Vessel
RV	Reactor Vessel(s)
RVVV	Reactor Vessel Vent Valve(s)
RWST	Refueling Water Storage Tank
SBLOCA	Small Break LOCA
SCC	Stress Corrosion Cracking
SCWR	Supercritical Water-cooled Reactor
SE	Safety Evaluation(s)
SEE	Systems & Equipment Engineering
SG	Steam Generator
Si	Silicon
SL	Surge Line
SoK	State of Knowledge
SG	Steam Generator(s)
STP	South Texas Project
TH	Thermal-hydraulic(s)
TIGER	Technical Integration Group Engaged in Research
TMI	Three Mile Island
TSC	Technical Support Center
TSP	Trisodium Phosphate
UHS	Ultimate Heat Sink
UP	Upper Plenum
UPI	Upper Plenum Injection
U.S.	United States
WCAP	Westinghouse Technical Report Number Preface (formerly Westinghouse Commercial Atomic Power)
Zn	Zinc

1 EXECUTIVE SUMMARY

On September 13, 2004, the Nuclear Regulatory Commission (NRC) issued Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors (PWRs)," (Reference 8) as the primary vehicle for addressing and resolving concerns associated with Generic Safety Issue (GSI)-191. The GL requested that all PWR licensees use an NRC-approved method to:

1. Perform a mechanistic evaluation of the potential for post-accident debris blockage and operation with debris-laden fluids to impede or prevent the recirculation functions of the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS) following all postulated accidents for which these recirculation functions are required.

2. Implement plant modifications or other corrective actions that the evaluation identifies as necessary to ensure system functionality.

The PWR Owners Group (PWROG) has actively pursued closure of GSI-191 through its conduct of a number of programs directed at closure of GSI-191. This includes, but is not limited to, the funding of the development of the following documents:

1. Guidance for performing condition assessments of debris sources inside PWR containments (Reference 2).

2. Guidance for evaluating post-accident sump screen performance (Reference 3).

3. Guidance for evaluating ex-vessel downstream effects of debris-laden coolant on performance of ECCS and CSS (Reference 4).

4. Guidance for evaluating post-accident chemical effects in the containment sump (Reference 5).

5. Guidance for evaluating long-term cooling (LTC) of the reactor core considering the effects of debris laden coolant (Reference 6).

The NRC staff has issued Safety Evaluations (SE) accepting the material and methods advanced in Reference 3 through Reference 6 as modified by conditions and limitations identified in the respective SE.

Reference 6 identifies that LTC of the core is not impeded if the plant-specific fibrous debris load is less than or equal to 15 grams of fiber per fuel assembly for all United States (U.S.) fuel and U.S. PWR designs. The NRC SE for Reference 6 accepts 15 grams of fiber per fuel assembly as a hot leg (HL) break limit for all PWR and sets a 7.5 gram per fuel assembly limit for cold leg (CL) breaks. The SE goes on to identify actions to be taken by licensees should they choose to increase their acceptable fiber limit above the 15 grams and 7.5 grams per fuel assembly limits.

A number of licensees believe that LTC can be demonstrated for post-Loss-of-Coolant Accident (LOCA) fibrous debris quantities greater than the 15 grams and 7.5 grams per fuel assembly fiber limits now accepted by the NRC. The PWROG has undertaken a comprehensive test and analysis program to increase the fibrous debris limits per fuel assembly. An important part of this effort is associated with assessing the influence of post-accident chemical effects on head loss (i.e., pressure drop) across debris beds.

Chemical effects are broadly defined as any chemically induced phenomenon that might contribute to either head loss across the sump screen or deleterious system performance caused by downstream effects.

This includes the collection of chemical effects on debris beds at the entrance to and within the fuel resulting in an increase in head loss across those debris beds and a corresponding reduction in flow such that LTC is challenged.

To support the assessment of chemical reaction products on the acceptable fibrous debris limit per fuel assembly, the Phenomena Identification and Ranking Table (PIRT) process was initiated. The objective of the PIRT process is to identify and rank phenomena that are important to chemical effects, thermal-hydraulic (TH) and transport associated with the post-accident operation of the ECCS in the recirculation mode over the time period of interest. This report documents the efforts of the panel of experts convened to develop a PIRT to support the comprehensive test and analysis program undertaken by the PWROG to increase the 15 grams and 7.5 grams per fuel assembly limit identified in Reference 6.

The PIRT panel consisted of six experts in the diverse technical disciplines related to GSI-191 including, but not limited to reactor TH, reactor chemistry, TH testing, materials and chemistry testing, general TH as well as various types of testing performed in support of understanding and closing GSI-191. The PIRT panel considered phenomena and processes that could be broadly categorized as TH transport and chemical effects. Section 7 of the PIRT is for chemical effects and Section 8 is for TH transport phenomena. The development of the tables recognized that there was likely some overlap of the two types of phenomena in the definitions of the affected phenomena and processes.

The PIRT panel advanced the following recommendations for consideration by the PWROG upon completion of identifying the phenomena, the ranking of the importance of the phenomena and the assigning of a State of Knowledge (SoK) to the phenomena.

Those phenomena and processes that are ranked "H" in importance and "L" for a SoK are candidates for additional study to improve the SoK associated with that phenomena or process. Specifically, from the PIRT, these phenomena and processes include:

- Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.[1]
- For a CL break, fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.

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[1] This phenomenon is ranked as "N/A" in periods P1 and P2, as "M" in period P3 and as "H" in periods P4 and P5. Although the focus of this PIRT is on period P3, this phenomenon is included in this list for completeness.

- For a CL break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.
- For a HL break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.
- Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.
- Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for CL injection for CL breaks) within reactor.
- Deposition. Chemical products formed during all periods may deposit on other surfaces.

In addition, there may be some advantage to gaining additional information for some phenomena or processes that are ranked "H" in importance but whose SoK is ranked as "M." For these phenomena, it is further suggested that a cost-benefit exercise be undertaken before work is undertaken to determine if the increase in SoK is worth the cost of obtaining the information.

2 INTRODUCTION

On September 13, 2004, the NRC issued GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors (PWRs)," (Reference 8) as the primary vehicle for addressing and resolving concerns associated with GSI-191. The GL requested that all PWR licensees use an NRC-approved method to:

1. Perform a mechanistic evaluation of the potential for post-accident debris blockage and operation with debris-laden fluids to impede or prevent the recirculation functions of the ECCS and CSS following all postulated accidents for which these recirculation functions are required.
2. Implement plant modifications or other corrective actions that the evaluation identifies as necessary to ensure system functionality.

The PWROG has actively pursued closure of GSI-191 through its conduct of a number of programs directed at closure of GSI-191. This includes, but is not limited to, the funding of the development of the following documents:

1. Guidance for performing condition assessments of debris sources inside PWR containments (Reference 2).
2. Guidance for evaluation of post-accident sump screen performance (Reference 3).
3. Guidance for evaluation of ex-vessel downstream effects of debris-laden coolant on performance of ECCS and CSS (Reference 4).
4. Guidance for evaluation of post-accident chemical effects in the containment sump (Reference 5).
5. Guidance for evaluating LTC of the reactor core considering the effects of debris-laden coolant (Reference 6).

The NRC staff has issued SE accepting the material and methods advanced in Reference 3 through Reference 6 as modified by conditions and limitations identified in the respective SE.

Reference 6 identifies that LTC of the core is not impeded if the plant-specific fibrous debris load is less than or equal to 15 grams of fiber per fuel assembly for all U.S. fuel and U.S. PWR designs. The NRC SE for Reference 6 accepts the 15 grams of fiber per fuel assembly as a HL break limit for all PWR and sets a 7.5 gram per fuel assembly limit for CL breaks. The SE goes on to identify actions to be taken by licensees, should they choose to increase their acceptable fiber limit above the 15 grams and 7.5 grams per fuel assembly limits.

A number of licensees believe that LTC can be demonstrated for post-LOCA fibrous debris quantities greater than the 15 grams and 7.5 grams per fuel assembly fiber limits now accepted by the NRC. The PWROG has undertaken a comprehensive test and analysis program to increase the fibrous debris limits per fuel assembly. An important part of this effort is associated with assessing the influence of post-accident chemical effects on head loss (i.e., pressure drop) across debris beds. Chemical effects are broadly defined as those phenomena that occur due to the presence of chemical species in the post-LOCA sump fluid and that can potentially contribute to either head loss across the sump screen or deleterious system performance caused by downstream effects. This includes the collection of precipitates on debris beds at the entrance to and within the fuel assemblies, resulting in increased head loss across those debris beds and a corresponding reduction in flow such that LTC is challenged.

To support the assessment of chemical effects on the acceptable fibrous debris limit per fuel assembly, the PIRT process was initiated. The objective of the PIRT is to identify and rank phenomena that are important to chemical effects, TH and transport associated with the post-accident operation of the ECCS in the recirculation mode over the time period of interest. This report documents the efforts of the panel of experts convened to develop a PIRT to support the comprehensive test and analysis program undertaken by the PWROG to increase the 15 grams per fuel assembly limit identified in Reference 6.

3 BACKGROUND ON GENERIC SAFETY ISSUE (GSI)-191

GSI-191, "Assessment of Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance," (Reference 22) was established to assess the potential for debris transport and accumulation of debris generated during a LOCA and the ability of this debris to impede or degrade ECCS performance in operating commercial PWR. The ECCS is required to meet the criteria of Title 10, Section 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors," of the *Code of Federal Regulations* (10 CFR 50.46) (Reference 7). In 10 CFR 50.46(b)(5), the U.S. NRC requires that licensees design the ECCS with capability for LTC. Per 10 CFR 50.46(b)(1) through 10 CFR 50.46(b)(4), the ECCS must provide adequate cooling to maintain the peak cladding temperature (PCT) below 2200°F, limit cladding oxidation, limit hydrogen (H) generation, and sustain a core geometry that is amenable to cooling.

On September 13, 2004, the NRC issued GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors (PWRs)," (Reference 8) as the primary vehicle for addressing and resolving concerns associated with GSI-191. The GL requested that all PWR licensees use an NRC-approved method to:

1. Perform a mechanistic evaluation of the potential for post-accident debris blockage and operation with debris-laden fluids to impede or prevent the recirculation functions of the ECCS and CSS following all postulated accidents for which these recirculation functions are required.

2. Implement plant modifications or other corrective actions that the evaluation identifies as necessary to ensure system functionality.

In response to this GL, the PWROG developed generic guidelines to address post-accident sump screen performance (Reference 2). The NRC staff reviewed and issued a SE on the Nuclear Energy Institute (NEI) generic sump screen performance guidance (Reference 3). The NEI report, as modified by the SE, provides an NRC-approved method for evaluating PWR sump performance as requested in GL 2004-02.

The scenario generally addressed by GSI-191 is a high-energy line break (HELB) inside PWR containment that could damage and dislodge materials near the break. Examples of these materials are thermal insulation, protective coatings (e.g., paints), and concrete. The PWROG supported the development of generic walkdown guidance published by NEI to identify in-containment debris sources (Reference 2).

In response to the HELB, the CSS actuates and washes a fraction of this debris and pre-existing debris in containment (i.e., latent debris) onto the containment floor. Simultaneously, while the containment floor is gradually filling with CSS effluent, coolant is injected into the reactor. The coolant contains sufficient boron to keep the core from going critical, typically at a concentration greater than 2000 ppm. This borated water is injected from accumulators and the refueling water storage tank (RWST) or borated water storage tank (BWST). Once the reactor has been refilled, this coolant will either spill out the break or be converted to steam and then condense outside the reactor. This flow will wash additional debris into the pool that is building on the containment floor.

At some time after the initiation of the event, and depending on the size of the break, the RWST/BWST is depleted, and both the CSS and ECCS pumps are realigned to draw suction from the containment sump. This provides for the recirculation of debris-laden water collected in the pool formed on the containment floor. Once recirculation starts, some of the debris in the coolant pool is transported to the sump screen where it either accumulates or is ingested through the sump screen into the pump suction line. If debris accumulates on the sump screen, the head loss across the screen will increase. If enough debris accumulates, it may be possible that a critical loading is achieved such that the net positive suction head (NPSH) is insufficient to ensure the successful operation of the ECCS and CSS pumps. The PWROG supported the development of generic guidance that was published by NEI (Reference 3) to conservatively evaluate debris generation, transport to and consequences of the collection of debris on sump screens.

Debris that passes through the sump screen could possibly degrade the function of different equipment within the reactor and the ECCS. Collectively, the actions of debris in the system after the sump screen are referred to as "downstream effects." The debris that is passed through the sump screen could plug or cause excessive wear of close-tolerance components or deposit on surfaces within the ECCS or CSS. Plugging or wear might cause a component to degrade to the point where its performance characteristics fall below the design-basis requirements. Additionally, debris blockage at flow restrictions within the ECCS could impede coolant recirculation through the reactor core, leading to inadequate core cooling. Debris could also deposit on the reactor fuel, reducing the efficiency of heat transfer from the fuel rod to the circulating fluid. The PWROG supported the development of methods to conservatively evaluate the wear, abrasion and erosion caused by debris-laden coolant on performance of pumps, valves, orifices and other components in the ECCS and CSS that are downstream of the sump screens (Reference 4). These effects are often called "ex-vessel" downstream effects.

The NRC SE for NEI 04-07 (Reference 3) requires licensees to address chemical effects on a plant-specific basis. The guidance in NEI 04-07 recognized that there may be post-accident chemical effects (e.g., corrosion products) in the coolant pool formed on the containment floor post-accident, and that these corrosion products may impact head loss (i.e., pressure drop) across a debris bed. However, guidance to address the effects of corrosion products on head loss was deferred until the testing was completed and the data have been appropriately evaluated.

For the purpose of GSI-191 closure, chemical effects are broadly defined as any chemically induced phenomenon that might contribute to either:

1. Head loss across the sump screen
2. Deleterious system performance caused by downstream effects
3. Head loss across a debris bed formed on the core inlet debris filter or within the core.

Possible chemical effects include the formation of chemical products (e.g., formation of precipitates or scale) caused by the interaction of containment materials with the post-LOCA environment and degradation of containment materials caused by chemical processes within the post-LOCA environment. In this context, containment materials encompass all materials present in containment and include LOCA-generated debris, latent debris, structural materials for reactor system components (e.g., piping, reactor vessel (RV), steam generators (SG), heat exchangers (HX), reactor internal structures, etc.), containment structural materials, ECCS pump, valve, and HX internal components, intact insulation, electrical materials and reactor fuel. The PWROG supported a program to conservatively evaluate post-accident chemical effects (Reference 5). Included in this evaluation is a spreadsheet tool that allows licensees to conservatively evaluate the 30-day production of chemical effects that may be used in sump screen performance testing.

In response to questions from the Advisory Committee on Reactor Safeguards (ACRS) and the NRC staff, the PWROG also sponsored an effort to evaluate the effect of particulate, fibrous and post-accident chemical products on LTC. This effort involved a combination of analyses, fuel debris capture testing, and the development of a tool to predict deposition of debris on the fuel due to boiling (Reference 6).

Reference 6 reports the results of fuel debris capture testing performed with both conservative particulate, fibrous and chemical debris, as well as parametric testing performed varying the particulate-to-fiber ratio (p:f). From the results of these tests, it is concluded that, for all U.S. PWR designs, the available data support a maximum debris loading of 15 grams per fuel assembly to assure that LTC of the core is not impeded for postulated HL breaks. The NRC SE on Reference 6 accepts the 15 grams of fiber per fuel assembly as a HL break limit for all PWR, and sets a 7.5 grams per fuel assembly limit for CL breaks. The SE goes on to identify actions to be taken by licensees should they choose to increase their acceptable fiber limit above the limits identified in the SE.

A number of licensees believe that LTC can be demonstrated for post-LOCA fibrous debris quantities greater than the 15 grams and 7.5 grams per fuel assembly fiber limits now accepted by the NRC. The PWROG has undertaken a comprehensive test and analysis program to increase the HL and CL break limits on allowable fibrous debris per fuel assembly. An important part of this effort is associated with assessing the influence of post-accident chemical effects on head loss (i.e., pressure drop) across debris beds. Chemical effects are broadly defined as any chemically induced phenomena that might contribute to either head loss across the sump screen or deleterious system performance caused by downstream effects. This includes the collection of chemical products on debris beds at the entrance to and within the fuel that results in an increase in head loss across those debris beds and a corresponding reduction in flow such that LTC is challenged.

To support the assessment of chemical effects on the acceptable fibrous debris limit for fuel in the PWROG comprehensive analysis and test program, a PIRT effort was initiated. The objective of the PIRT was to identify and rank phenomena that are important to chemical and debris-related effects associated with the post-accident operation of the ECCS in the recirculation mode over the time period of interest. This report documents the efforts of the panel of experts convened to develop the PIRT to support the comprehensive test and analysis program undertaken by the PWROG to increase the limits on fibrous debris per fuel assembly identified in Reference 6.

Furthermore, this PIRT was developed so that it applies to all U.S. PWR designs, regardless of vendor. Examples of a large double-ended guillotine (DEG) CL break for Westinghouse, Combustion Engineering (CE) and Babcock & Wilcox (B&W) plants are shown in Figures 3-1, 3-2 and 3-3, respectively. Diagrams showing cross-sectional views of Westinghouse, CE and B&W plants are shown in Figures 3-4, 3-5 and 3-6, respectively. Unique design features of the reactor vessels (RV), reactor internals and reactor systems on phenomena and processes were accounted for and addressed in the development of the PIRT. When phenomena or processes were influenced or affected by unique design features, this was noted in the rationale tables associated with those phenomena and processes.

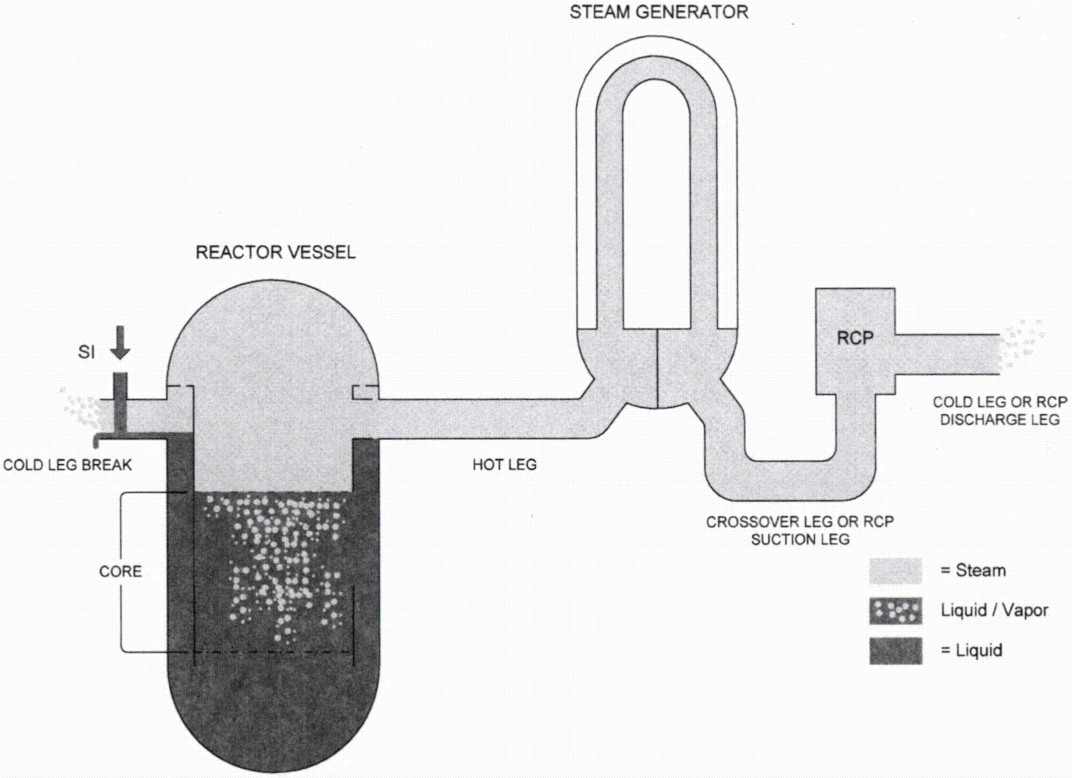

Figure 3-1 Cold Leg Pump Discharge (CLPD) Break, Westinghouse PWR

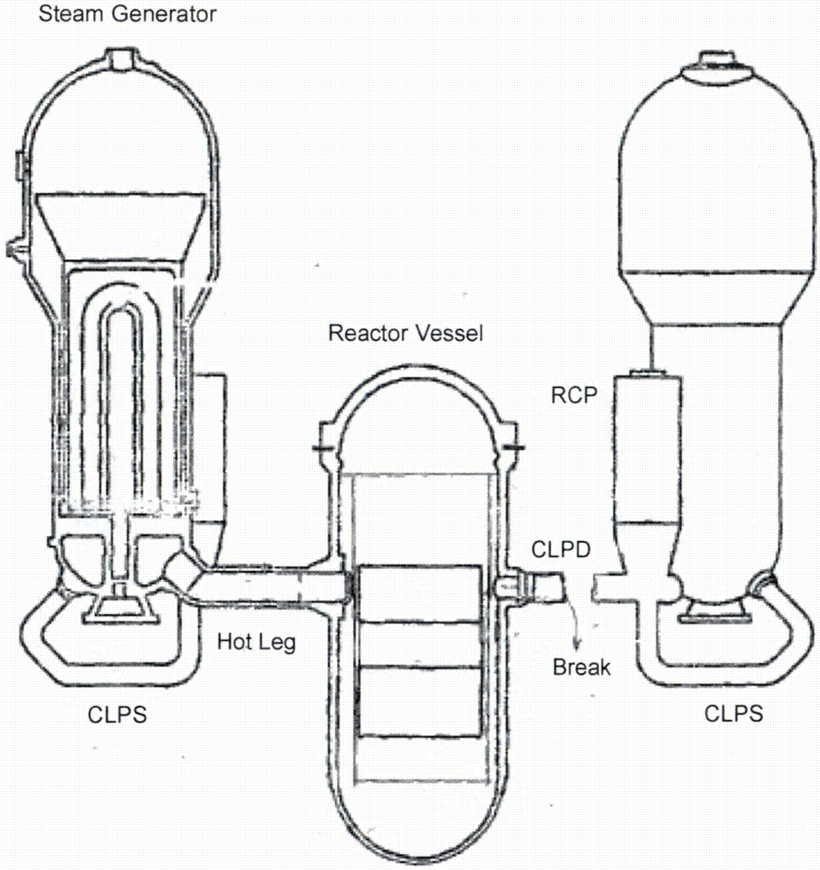

Figure 3-2 CLPD Break, CE PWR

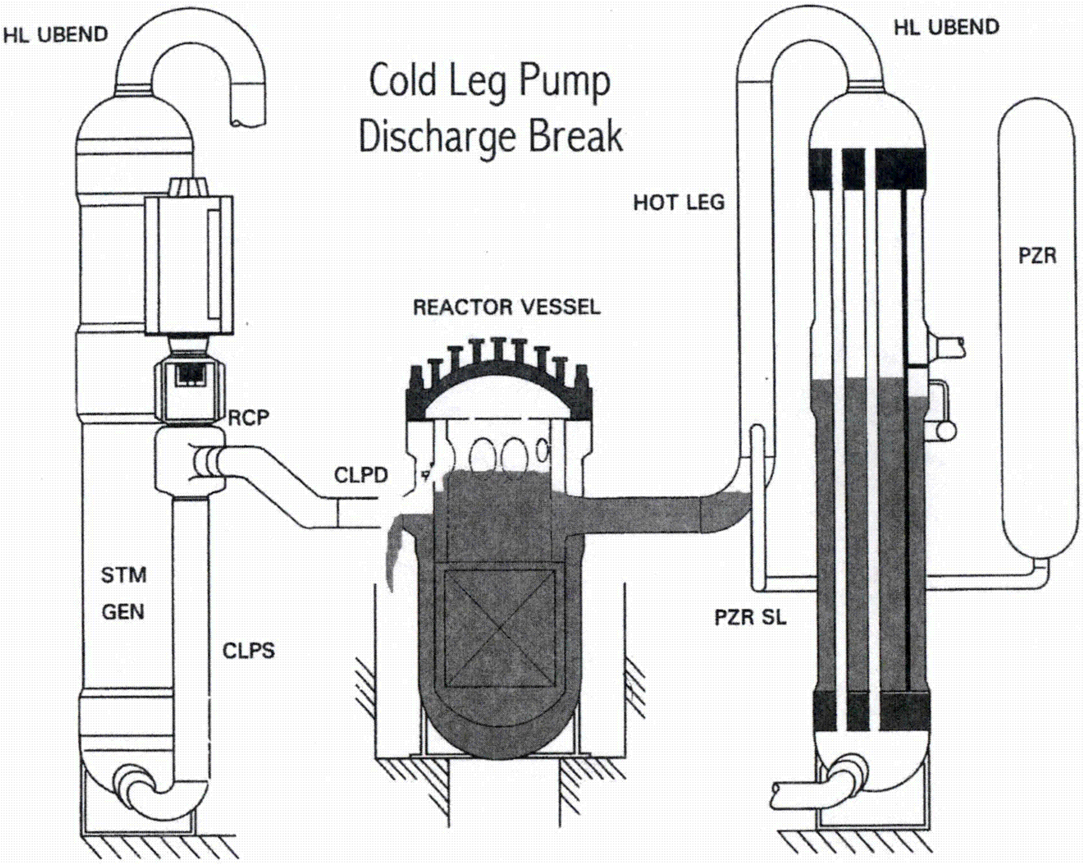

Figure 3-3 CLPD Break, B&W PWR

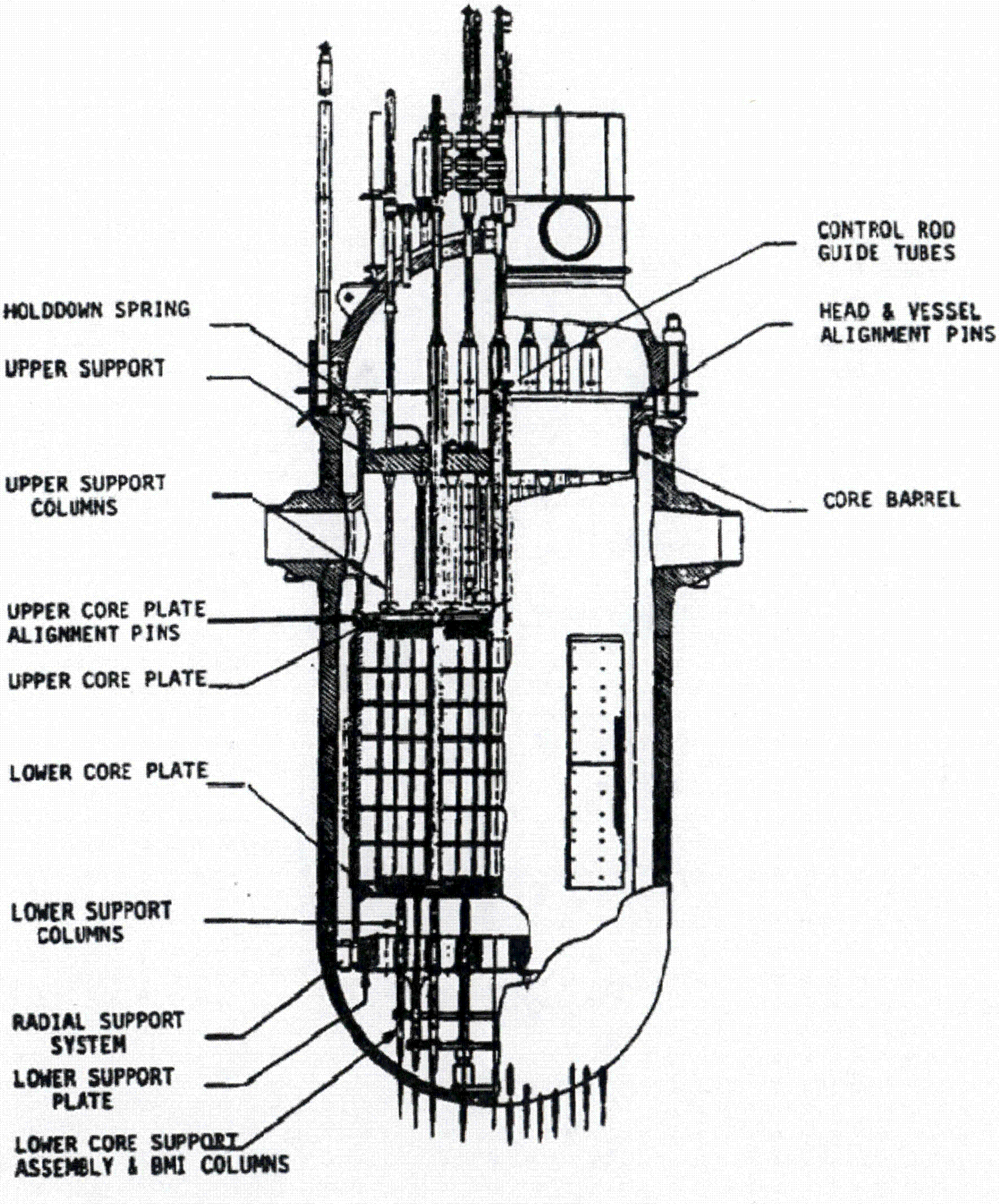

Figure 3-4 Typical Westinghouse Reactor Vessel and Internals Arrangement

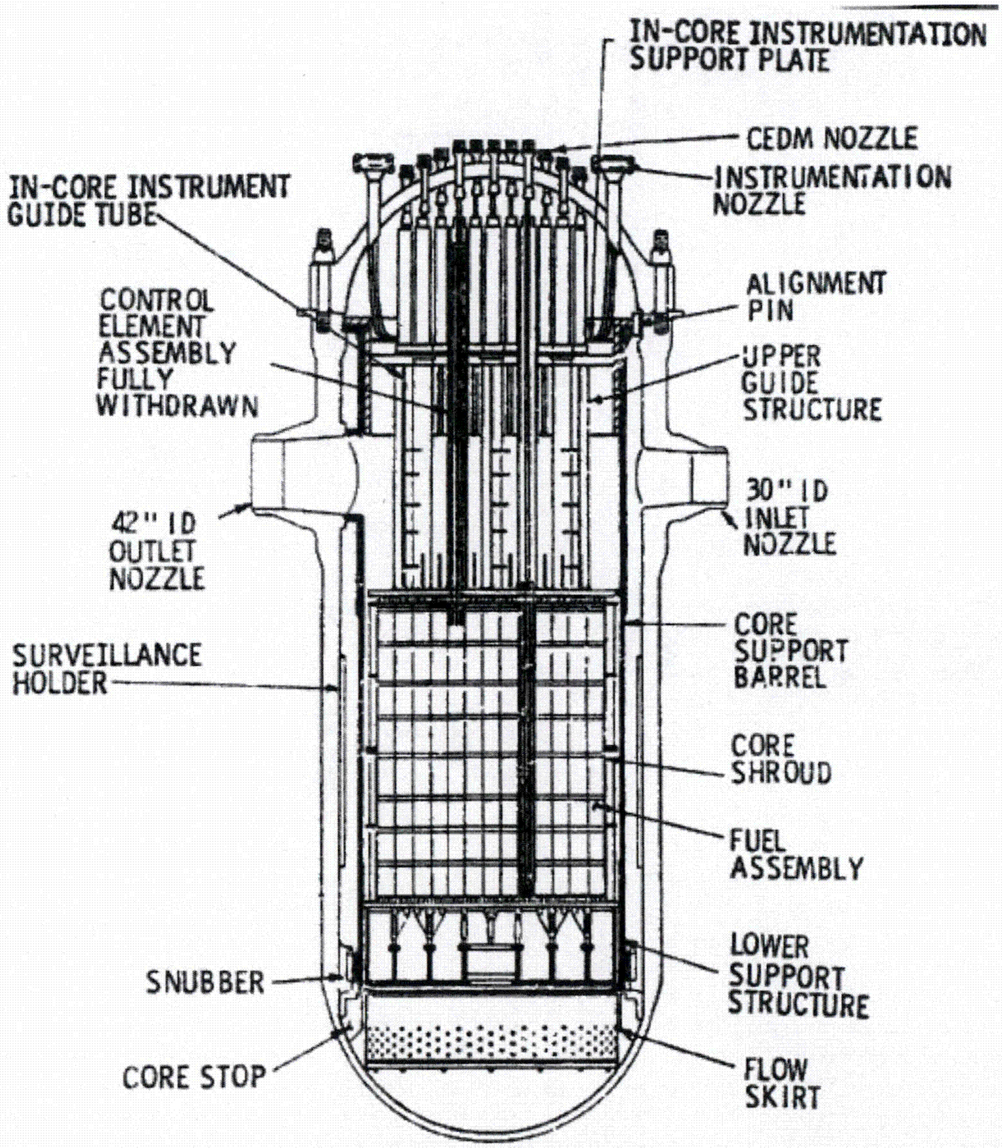

Figure 3-5 Typical CE Reactor Vessel and Internals Arrangement

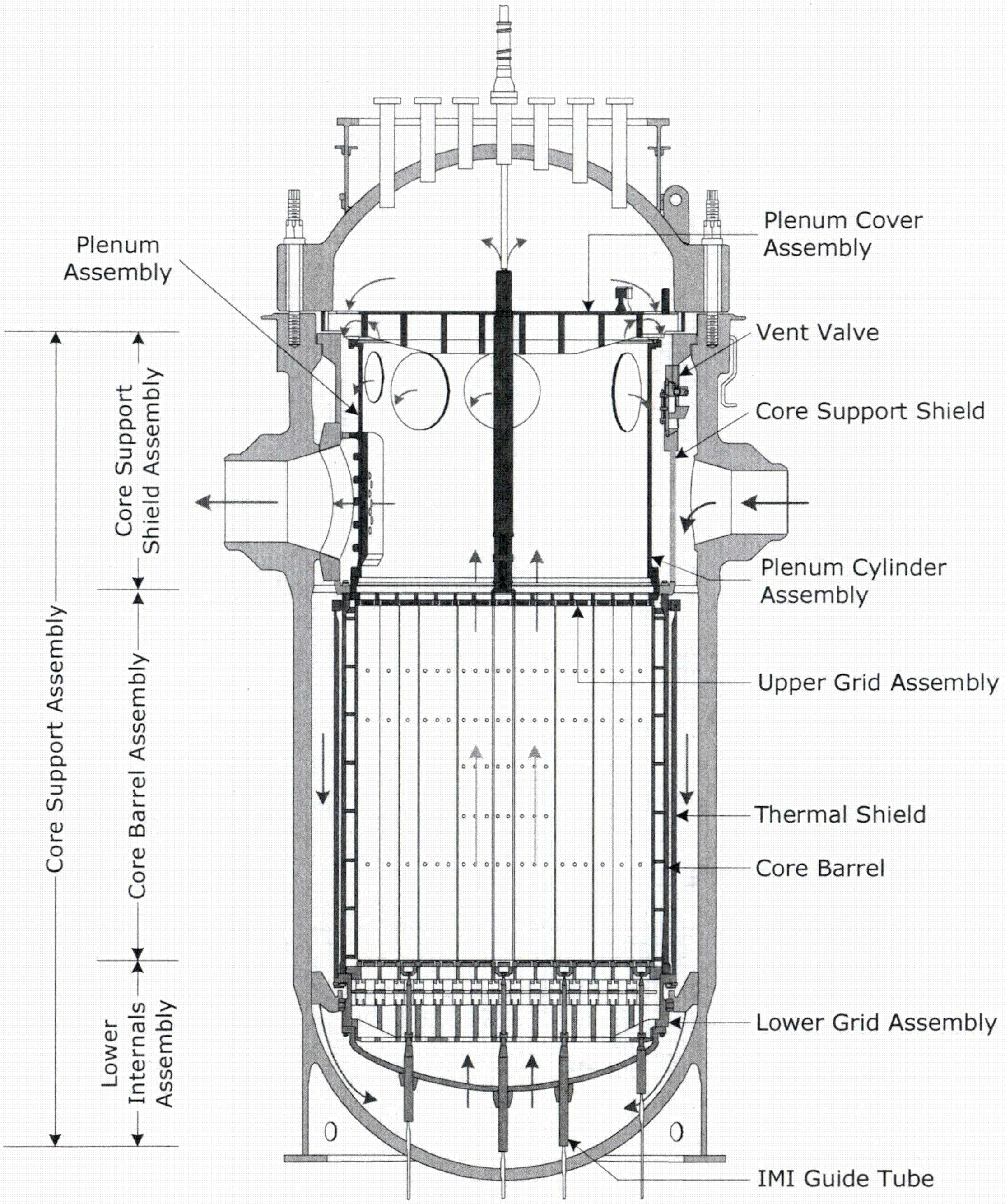

Figure 3-6 **Typical B&W Reactor Vessel and Internals Arrangement**

4 PIRT PROCESS

The PIRT was developed following the approach outlined by Boyack (Reference 9). First, a list of plausible phenomena was prepared. Next, phenomena were ranked for importance through the various periods identified for the transient and the SoK was assessed based upon the diverse experience of the PIRT review team.

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

H = The phenomenon is considered to have high importance relative to the evaluation criterion (i.e., figure of merit). Accurate test facility scaling or predictive model of the phenomenon during the particular period is considered to be crucial to obtain the correct or conservative test result or numeric simulation during the particular period.

M = The phenomenon is considered to have medium importance relative to the evaluation criterion but is expected to have less impact than those ranked high. The phenomenon needs to be modeled with sufficient detail in the test facility scaling or predictive model to obtain accuracy in the test result or numeric simulation during the particular period.

L = The phenomenon is considered to have low importance relative to the evaluation criterion. The phenomenon could be modeled in the test facility scaling or predictive model but inaccuracies in modeling this phenomenon are not considered likely to have a significant impact on the overall test result or numeric simulation during the particular period.

N/A = The phenomenon is considered inconsequential relative to the evaluation criterion, or does not occur at all. This phenomenon need not be modeled in the test facility scaling or predictive model as it has an insignificant impact on the test result or numeric simulation during the particular period.

The SoK rankings in the PIRT are assigned using the following criteria:

H = Sufficient understanding to make assessment of practical ramifications and small uncertainty exists or magnitude is limited.

M = Partial knowledge and understanding and moderate to large uncertainty remains.

L = Totally unknown or very limited knowledge and uncertainty cannot be characterized.

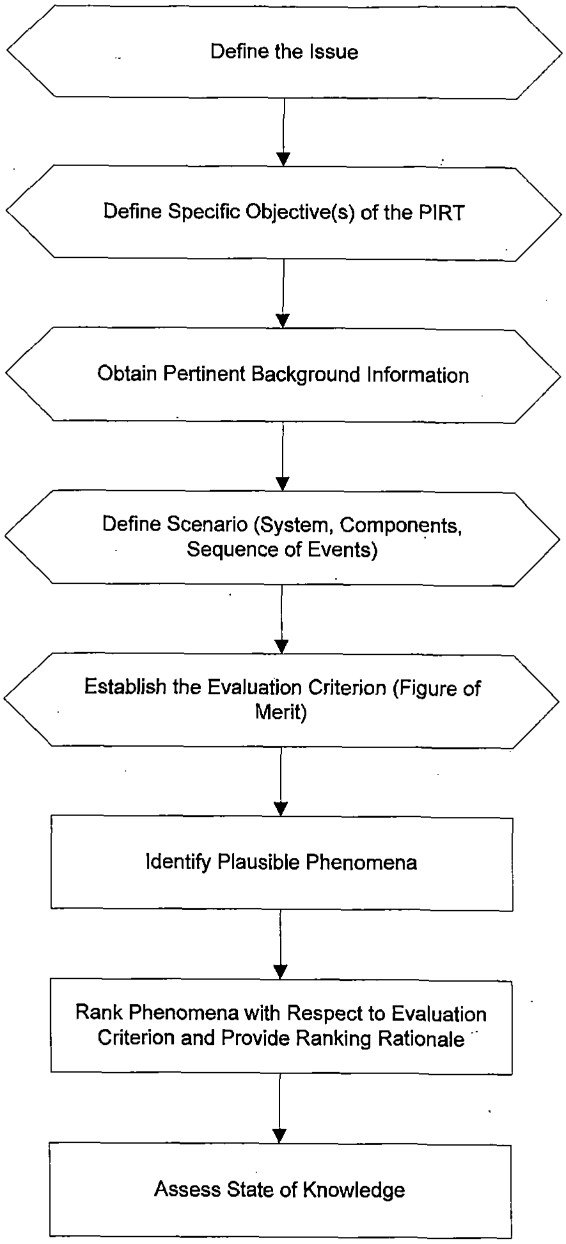

Figure 4-1 PIRT Process

5 PIRT REVIEW TEAM

A deliberate effort was made to achieve a broad representation of expertise on the PIRT review team. To accomplish this, review team membership is comprised of representatives from the Nuclear Steam Supply System (NSSS) vendors who are categorized as "internal experts," while review team members from academia or non-NSSS vendors are categorized as "external experts." Also, recognizing that there is likely considerable overlap in the TH mixing phenomena between GSI-191 and boric acid precipitation control (BAPC) issues, representation of at least one team member from previous BAPC PIRT efforts was solicited. Listed in this section are the "external experts" and the "internal experts" for the PWROG-GSI-191 PIRT Panel, along with the two facilitators for this effort.

5.1 EXTERNAL EXPERTS

The external experts who comprise the PIRT review team represent the chemical, environmental, and nuclear engineering disciplines:

- Dr. Ali Borhan, Professor of Chemical Engineering, The Pennsylvania State University
- Dr. David Guzonas, Principal Chemist, Atomic Energy of Canada Limited (AECL)
- Dr. Kerry Howe, Associate Professor of Environmental Engineering, The University of New Mexico
- Dr. Bruce C. Letellier, Chief Scientist of Technology Solutions, Alion Science and Technology

Dr. Ali Borhan

Dr. Ali Borhan, holds M.S. and Ph.D. degrees in Chemical Engineering, from Stanford University and B.S. degrees in Chemical Engineering and Mathematics, as well as an M.S. in Chemical Engineering Practice, from Massachusetts Institute of Technology (MIT). Dr. Borhan performed his doctoral research under the direction of Professor Andreas Acrivos, focusing on the effect of suspension concentration on the stability of inclined settlers. Following a postdoc at the IBM Almaden Research Center, Dr. Borhan joined the faculty of the Chemical Engineering Department at The Pennsylvania State University (PSU) as an Assistant Professor in 1989. He was granted tenure and promoted to Associate Professor in 1995, and then to Professor in 2000.

Professor Borhan's research interests include fluid dynamics and hydrodynamic stability of multiphase systems, interfacial transport phenomena, dynamics of complex fluids, and wetting and capillary phenomena. His research program has been aimed at understanding the dynamics of multiphase systems through a combination of theory and experiments, with particular emphasis on free-surface flows associated with gas-liquid and liquid-liquid systems. Recent research projects have focused on interfacial tension-driven flows, non-Newtonian flows, wetting behavior of physically-patterned solid surfaces, dynamics of drops and bubbles, stability of two-phase flows, dynamics of nanomotors and nanorotors, transport and uptake of reactive gases in the respiratory system, and the effects of surface-active species (surfactants) on the dynamics of two-phase systems. Various aspects of Professor Borhan's work have been supported by grants from National Science Foundation (NSF), National Aeronautics and Space

Administration (NASA), National Institutes of Health (NIH), the Engineering Foundation, and the American Chemical Society (ACS).

Dr. Borhan has published over 80 refereed journal articles, has chaired numerous technical sessions on fundamental research in fluid mechanics at national and international conferences, and has reviewed over 100 articles for the top journals in his field. He has also reviewed over 100 research proposals for funding agencies such as NSF, NIH, NASA, and ACS, and has served on various review/advisory panels for NASA, NIH, Department of Defense (DOD), and NSF. Professor Borhan received the Penn State Engineering Society (PSES) Outstanding Teaching Award in 1995, the PSES Premier Teaching Award in 2007, and the Penn State Graduate Faculty Teaching Award in 2012.

Dr. David Guzonas

Dr. Guzonas is currently a Principal Chemist at AECL. He obtained his Ph.D. in Physical Chemistry from the University of Waterloo. Dr. Guzonas was an Industrial Research Fellow at the Xerox Research Centre Canada and then a Research Associate at Virginia Polytechnic Institute and State University, utilizing direct measurement of interaction forces, surface vibrational spectroscopy, and contact angle measurements to study polymer interactions and the role of non-DLVO (Derjaguin, Landu, Verway and Overbeek) forces in the recovery of minerals by flotation.

At AECL, Dr. Guzonas developed and applied a broad expertise in water chemistry of nuclear reactor systems, working on optimization of chemical cleaning reagents, corrosion inhibitors and dispersants, characterization of reactor artifacts, and development of chemistry specifications for Canadian Deuterium Uranium (CANDU) reactors. Dr. Guzonas is an AECL expert on CANDU activity transport, analyzing and modeling activity transport and radiation field growth and optimizing purification to reduce radiation fields. He was chemistry lead on projects related to chemical interactions in post-LOCA sump water (e.g., chemical effects) and their impact on Emergency Core Cooling strainer performance for both Canadian and US customers, and chaired the Nuclear Energy Act (NEA) Committee on the Safety of Nuclear Installation (CSNI) Task Group on Sump Clogging, which recently completed an update of the knowledge base document.

More recently, Dr. Guzonas has played a lead role in the Canadian Supercritical Water-cooled Reactor (SCWR) Materials and Chemistry Program, serving as Canadian representative on the Generation IV International Forum SCWR Materials and Chemistry Project Management Board (Chair from 2007-2011). He is an active collaborator on twelve university projects related to SCWR materials and chemistry. He is Past Chair of the Canadian National Committee of the International Association for the Properties of Water and Steam (IAPWS), and current IAPWS Vice-President. Since joining AECL, Dr. Guzonas has been author or co-author of about 100 AECL and commercial reports, and about 100 external publications and conference papers.

Dr. Kerry Howe

Dr. Kerry J. Howe, P.E., BCEE is an Associate Professor of Environmental Engineering at the University of New Mexico. He has a B.S. in Civil and Environmental Engineering from the University of Wisconsin-Madison, an M.S. in Environmental Health Engineering from the University of Texas at Austin, and a Ph.D. in Environmental Engineering from the University of Illinois at Urbana-Champaign. He is a registered professional engineer and is a Board Certified Environmental Engineer (BCEE) by the American Academy of Environmental Engineers. He has over 25 years of experience in the water treatment industry. He has both academic and professional engineering experience, having worked for engineering consulting firms for 12 years before entering academia. Since entering academia, he has focused on membrane technologies and desalination and has substantial research experience in these areas. He has investigated fouling of and pretreatment for membrane filtration, methods for increasing the recovery of reverse osmosis systems by controlling scaling, potential beneficial uses for reverse osmosis concentrate salts, and use of reverse osmosis to treat wastewater for water reuse applications. He was an investigator for the Integrated Chemical Effects Test (ICET) program, which evaluated the corrosion of a variety of materials under prototypical LOCA conditions. He is also an investigator on the Corrosion/Head Loss Experiments (CHLE) program being conducted for the South Texas Project. In working on these projects, he has developed experience with the water chemistry and the relevant corrosion and precipitation reactions during a LOCA. He is published in a number of environmental engineering journals and is the lead author for the textbook *Principles of Water Treatment* and a co-author of the textbook *MWH's Water Treatment: Principles and Design.*

Dr. Bruce C. Letellier

Dr. Bruce C. Letellier received his B.S., M.S., and Ph. D. in Nuclear Engineering from Kansas State University. Dr. Letellier recently joined Alion Science and Technology as Chief Scientist of the Technology Solutions Group to pursue opportunities in risk-informed nuclear power operations safety. This transition follows a 23 year career at Los Alamos National Laboratory (LANL) as a member of the Probabilistic Risk Analysis (PRA) Group where he performed accident-phenomenology and health-consequence modeling for nuclear facility and weapon safety studies. Most recent applications of PRA and systems analysis include co-development of the CO_2PENS systems analysis model for geologic carbon dioxide sequestration, and co-development of a techno-economic maturation assessment for carbon dioxide capture technologies.

For 7 years he served as team leader of a multidisciplinary effort to support the NRC in the research and regulatory resolution of GSI-191 that affects the operability of emergency-cooling recirculation systems in all U.S. PWR. GSI-191 research was performed in collaboration with the University of New Mexico and included the following topics:

- Integrated chemical effects testing involving a series of five 30-day closed-loop simulations of reactor accident environments, concurrent bench-scale chemical analyses, and diagnostic examinations of sample materials.
- Investigation of sump-screen penetration by debris and downstream blockage of high-pressure pumps and throttle valves.

- Measurement and theoretical prediction of pressure loss in prototypical debris beds containing fibrous insulation and mixed particulate matter.

- Computational fluid dynamics (CFD) simulations of complex flow geometries in PWR containment buildings with benchmarks to 1/10-scale experiments.

- Characterization of water-borne-debris transport properties.

Dr. Letellier resumed GSI-191 work in 2010 when, as a team member of the South Texas Project (STP) pilot study for risk informed closure, he authored the CASA Grande analysis framework for uncertainty propagation and risk quantification. CASA enables the automated analysis of LOCA accident sequences from break initiation to sump strainer and fuel channel performance in the presence of debris using supplementary information provided by plant Computer Aided Design (CAD) geometry, TH analyses and chemical effects testing.

Past work has included interior- and atmospheric-transport modeling of aerosols and gases (including chemicals, fission products, and other radiological inhalation hazards) that are driven by fires, explosions, depressurization of tanks and pipelines, and complex forced-air Heating, Ventilation and Air Conditioning (HVAC) systems. Atmospheric model experience includes: MAACS, QUIC-URB, CalPuff, HOTMAC, ERAD, and others.

Dissertation work included radiation transport simulations of neutral particles in soil and Bayesian inversion of gamma-ray spectra to determine subsurface contamination profiles. The theoretical construct of that research has recently been applied to the problem of material identification using transmitted gamma spectra incident on an object of unknown composition (e.g., active interrogation).

Research interests include development of an intermediate physics code for in-facility aerosol transport called Potential Flow Interior Air Transport (PFIAT) that can be coupled to urban transport models for modeling realistic evacuation and sheltering scenarios. With the addition of energy tracking, this model can be used for economic energy analyses of buildings. Expertise in interior aerosol transport was gained by supervising construction of a full HVAC system simulation of the LANL plutonium facility using the MELCOR control volume suite, and by participating in the construction of similar models for the Albuquerque Convention Center, the Salt Lake City Delta Center and the DOD Device Assembly Facility at the Nevada Test site.

5.2 INTERNAL EXPERTS

The internal experts who comprise the PIRT review team represent the chemistry discipline and physics engineering discipline:

- Dr. William A. Byers, Fellow Engineer, Westinghouse Electric Company
- John A. Klingenfus, Advisory Engineer, AREVA NP

Dr. William A. Byers

Dr. Byers is a Fellow Engineer at the Westinghouse Electric Churchill Laboratories. He received his B.S. degree in Chemistry from Westminster College in 1976 and his Ph.D. in Chemistry from Purdue University in 1982. He has a wide range of teaching and research experience in the fields of nuclear water chemistry and materials characterization. While at Purdue, he developed instrumentation and computer software that related the surface adsorption and electrochemical reactions of nitrodiphenyl-ethers to their herbicidal activity. His early work in industry centered on the monitoring and control of high purity water processes. New methods were developed for the on-line detection of organic acids in nuclear power plant water cycles which solved chemical control problems which had plagued the industry for years. His work on oxygen diffusion in zirconium created acceptance for a new product line in the power industry. Much of Dr. Byers' research has involved the characterization of surfaces and processes occurring at surfaces. His work in the effect of zinc on corrosion processes helped develop zinc addition as PWR primary water additive for inhibition of SG SCC (stress corrosion cracking) and dose rate reduction. His most recent work has been directed at understanding of crud deposition and research into the root cause of the PWR Axial Offset Anomaly. Dr. Byers holds 11 U.S. Patents.

John A. Klingenfus

John A. Klingenfus is an Advisory Engineer at AREVA NP's Lynchburg, Virginia office. Mr. Klingenfus is currently a Level 2 TH and LOCA Specialist in the AREVA Worldwide College of Experts. 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 B&W nuclear division in Lynchburg, VA. He has been on the AREVA NP staff (formerly B&W as well as various other names) for 32 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 TH code benchmarks and performed numerous code development activities for various codes including CRAFT2 and RELAP5/MOD2-B&W system TH codes. Mr. Klingenfus participated in the design and benchmark analysis efforts on the Multi-Loop Integral System Test (MIST) facility. He has led or participated in numerous Small Break LOCA (SBLOCA), Large Break LOCA (LBLOCA), and non-LOCA model and method development tasks for applications on B&W, Westinghouse, CE, and the new U.S. EPR (European Pressurized Reactor) plants. He led the development effort and authored the RELAP5/MOD2-B&W-based LOCA deterministic evaluation model (EM) 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. Mr. Klingenfus participated on several previous PIRT panels on post-LOCA mass and energy release for containment response and the PWROG post-LOCA boric acid precipitation. In addition, he has developed methods for demonstrating compliance to the coolable core geometry and LTC criteria of 10 CFR 50.46 including assessment of GSI-191 downstream effects debris considerations. This work included development of the current generic post-LOCA BAPC methods for SBLOCA and LBLOCA events for the B&W designed plants.

5.3 FACILITATORS

The facilitators who comprise the PIRT review team represent the mechanical, nuclear, and industrial engineering disciplines:

- Timothy S. Andreychek, Fellow Engineer, Westinghouse Electric Company
- Brett Kellerman, Principal Engineer, Westinghouse Electric Company

Timothy S. Andreychek

Timothy S. Andreychek is a Fellow Engineer with Westinghouse Electric Company, LLC. He earned a B.S. in Mechanical Engineering, an M.S. in Mechanical Engineering and an M.S. in Industrial Engineering from the University of Pittsburgh. Mr. Andreychek began his career at Westinghouse in 1972. He is currently the overall technical lead for the Westinghouse effort to resolve and close GSI-191 related to post-accident sump performance and LTC.

Mr. Andreychek has been involved and led industry efforts since 1997 to address generic sump performance issues now known as GSI-191. During this time he has led efforts to develop industry methods to evaluate sump screen performance, participated in three (3) NRC-sponsored PIRT efforts, developed the test plan for the Integrated Chemical Effects Test (ICET) that was jointly sponsored by NRC, Electric Power Research Institute (EPRI) and the PWROG, led tasks to develop evaluation methods to assess wear, abrasion and erosion of components in the ECCS and CSS due to the recirculation of debris-laden coolant and testing of containment materials under loads from jet flows initiated at PWR pressures and temperatures.

During his tenure with Westinghouse, Mr. Andreychek has also led technical projects associated with performing ECCS heat transfer tests of advanced design Westinghouse fuel for PWR and the thermal design and analysis of reactor internals for liquid metal reactors. Mr. Andreychek has also led testing and evaluation efforts associated with safety systems for the Westinghouse advanced reactor designs, the AP600 and the AP1000. He was responsible for the analysis of data from tests of passive safeguards systems and participated in developing the analysis methodology to demonstrate the performance of the passive containment cooling system for the AP600 and AP1000.

Brett E. Kellerman

Brett E. Kellerman is a Principal Engineer at Westinghouse Electric Company Cranberry Woods, Pennsylvania office. He has been on the Westinghouse staff for 15 years. He obtained his B.S. degree in Nuclear Engineering from PSU. 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 LBLOCA ECCS performance, Appendix K SBLOCA ECCS performance, LOCA blowdown forces and LTC with a particular emphasis on Westinghouse 2-loop upper plenum injection (UPI) plant designs. For the past decade, he has primarily been involved in LTC methodology development in support of extended power uprates (EPU). During this time, he has also been engaged in all activities to develop a new boric acid precipitation analysis EM sponsored by the PWROG Analysis Sub-Committee, as well as, the advancement of current technology. His previous PIRT experience includes facilitation and participation in two PIRTs related to transport, mixing, and precipitation modes of boron solutes in the RV during LTC.

6 PIRT SCENARIO IDENTIFICATION, PHASES AND PERIODS

6.1 SCENARIO IDENTIFICATION

The scenarios of high importance for chemical effects in the recirculating coolant path post-accident are those accidents that:

1. Introduce debris into the coolant.
2. Require the plant to recirculate coolant from the reactor containment building sump.

The presence of transportable debris within the coolant is important since chemical products are thought to have the greatest effect when interacting with a debris bed to block flow. The alignment of the ECCS and the CSS to draw suction from the sump when the reactor coolant system (RCS) is at or near ambient containment conditions following an LBLOCA maximizes the transport of debris from about the containment floor to and possibly through the reactor containment building recirculation sump screen. Also, the initiation of the CSS provides for spraying systems, structures and components inside the reactor containment building with a chemical solution that may facilitate the production and transport of corrosion products.

To maximize the debris generation, and to provide for the evolution of the ECCS and CSS to evolve from injecting coolant from the RWST/BWST to recirculating coolant from the pool of spilled and debris-laden coolant on the containment building floor, an LBLOCA will be considered for development of this PIRT.

Two (2) scenarios were used for constructing these PIRT:

1. The large DEG HL break.
2. The large DEG CL break.

These scenarios provide for two (2) cases associated with chemical effects and LTC:

1. The large DEG HL break provides for the control of the concentration of post-accident chemicals and boron in the core by flushing the core due to the initial alignment of the ECCS to flow from the CL through the core to the break. The fluid in the core could be two-phase or subcooled depending on the ECCS flow and the core decay heat contribution.

2. The initial alignment of the ECCS to the CL for the DEG CL break does not flush the core. Rather, boiling in the core concentrates boron, post accident chemicals and particulate debris in the core region which includes the upper plenum, bypass regions such as instrument tubes and guide tubes, the baffle region for plants with an upflow baffle and some portion of the lower plenum following switchover to sump recirculation. The concentration of boron species in the core that are not volatile in steam, such as post accident chemicals and particulate debris, will increase until a dilution method (e.g., realignment of the ECCS or an alternate flow path) is established to flush the core.

Thus, the PIRT will be developed with consideration of both a hypothetical DEG HL break and a hypothetical DEG CL break.

6.2 PIRT SCENARIO PHASES AND PERIODS

For the purposes of the development of the PWROG GSI-191 PIRT, the accident, regardless of break location, was divided into five (5) phases. The phases and their durations were selected to be consistent with events of significance associated with both the DEG HL and CL breaks. The phases selected and their durations selected are identified in Table 6-1.

Table 6-1 PIRT Scenario Phases and Phase Duration

Phase	Duration	Description
P1	0 to 30 seconds	Initial depressurization of the RCS (i.e., blowdown)
P2	30 seconds to start of sump recirculation	1. Injection of the RWST/BWST into the RCS 2. Initiation of containment spray
P3[(1)]	Start of sump recirculation to 12 hrs	1. Beginning of LTC 2. Realistic time when core flushing is needed
P4	12 hrs to 1 day (24 hrs)	1. Maintain LTC 2. Cooldown and depressurization of reactor containment building
P5	1 day to 30 days	1. Maintain LTC 2. Long-term containment building cooldown

Notes:

1. The time when core flushing for B&W plants or hot leg switchover (HLSO) for CE and Westinghouse plants occurs is a plant-specific parameter that can vary from as little as one to two hours after the LOCA occurs to as long as about 14 hours after the LOCA occurs for most plants. A value of 12 hours was chosen to be representative of the time duration that recirculation from the sump may occur without evolving to core flushing or HLSO. However, it is possible that the core flushing flow may be initiated prior to 12 hours or possibly not at all if the core exit subcooling is reestablished for some plants.

A listing and description of significant events that occur in each phase of the hypothetical DEG CL break are listed in Table 6-2. A similar listing and description of significant events that occur in each phase of the hypothetical DEG HL break are listed in Table 6-3.

Table 6-2 Description of Scenario Phases – DEG CL Break

Phase	Duration	Description
P1	0 sec to 30 sec	• Initially subcooled coolant is exhausted as a two-phase mixture into the containment until the end of this phase. The RCS is fully depressurizes during this phase. • Containment temperature increases to a peak or near-peak level. • Containment pressure increases, approaching its peak level. • Debris is generated by the two-phase jet formed by the initial release of subcooled coolant into the containment (for the initial 10-15 seconds of the event). • Surfaces of systems, structures and components inside containment are wetted by the break coolant. • Liquid coolant begins to collect on the containment floor. • Chemical reactions with debris and materials in contact with the exhausted coolant are initiated.
P2	30 seconds to start of sump recirculation (i.e., Drain Down of the RWST/BWST, plant specific timing – generally between 1200 seconds to 3600 seconds)	• RCS is depressurized. • Containment spray is actuated. • ECCS flow from the RWST/BWST to the RCS is actuated. • ECCS flow fills the RV lower plenum (LP), downcomer (DC), and core: – Once the core is refilled in 3 to 10 minutes, the net inflow to the core matches boil-off due to removal of decay heat from the nuclear core plus any refill needed to account for void fraction decrease in the RV. – Coolant in excess of boil-off and void replenishment flows out the CL break. – Steam from the core flows through the broken-loop HL and SG (W & CE plants) or flows out of the internals reactor vessel vent valves (RVVV) between the RV upper plenum and upper DC (B&W plants) and is released to containment. • Safety-grade containment fan coolers are actuated. • Exhausted coolant and containment spray collect in a pool on the containment building floor. • Containment temperature begins to decrease from its peak level. • Containment pressure begins to decrease from its peak level. • Temperature of coolant pooled on containment floor begins to decrease. • Debris carried about the containment by coolant exhausted through the break continues to be washed down to the liquid pool by containment spray.

Table 6-2 Description of Scenario Phases – DEG CL Break (cont.)

Phase	Duration	Description
P2 (cont.)		• Chemical reactions continue with debris and materials in contact with spray flow and the liquid pool on containment floor. • For plant designs with cold side ECCS injection, boron begins to concentrate in the core region due to the boiling process.
P3	Start of sump recirculation (Recirculation of Coolant in the Pool on the Containment Floor) to 12 hrs (Initiation of Active Boron Dilution is established based on Emergency Operating Procedures (EOP)/ Technical Support Center (TSC))	• ECCS is realigned from the RWST/BWST to recirculate coolant from the reactor containment sump. • Containment spray is terminated for some plants, continues to run for plants that do not have safety-grade fan coolers. • If containment spray continues, the containment spray pumps are realigned from the RWST/BWST to recirculate coolant from the reactor containment sump. • Safety-grade containment fan coolers continue operation. • Coolant in excess of boil-off continues to exhaust from the primary system through the CL break. • Containment temperature continues to decrease from its peak level. • Containment pressure continues to decrease from its peak level. • Debris generated by break flow and washed into the containment floor pool is submerged in escaped coolant and containment spray. • Debris is carried about the containment by coolant exhausted through the break and by containment spray. • Liquid pool on containment floor builds to maximum or near-maximum depth. • Temperature of liquid pool on containment floor continues to decrease. • Pool flow fields are established with flow to the reactor building recirculation sump. • Chemical reactions with debris and materials in contact with containment liquid continue. • Debris and boron continue to concentrate in the core region with only cold side injection. Initiation of boron dilution by the operators may change the debris and boron concentration. • Debris beds on recirculation sump screens and on fuel components begin to form.
P4	12 hrs to 1 day	• ECCS continues to recirculate coolant from the reactor containment sump. • Active boron dilution actions(1) that are initiated by the operators, as directed by the EOP, limiting boron concentration build-up in the core.

Table 6-2 Description of Scenario Phases – DEG CL Break (cont.)

Phase	Duration	Description
P4 (cont.)		• Safety-grade fan coolers continue to run. • Containment spray continues to run for plants that do not have safety-grade fan coolers. • Containment atmosphere temperature continues to decrease. • Containment pressure continues to decrease. • Containment pool temperature continues to decrease. • Pool flow fields to the reactor building recirculation sump are maintained. • Chemical reactions with debris and materials in contact with containment pool coolant continue. • Debris beds on recirculation sump screens and on fuel components continue to form.
P5	1 day to 30 days	• ECCS continues to recirculate coolant from the reactor containment sump. • Active boron dilution actions are continued, as needed (pg. 6-6, footnote 1). • Once initiated, boron concentration build-up is controlled by maintaining the active dilution flows. • Safety-grade fan coolers continue to run. • Containment spray continues to run for plants that do not have safety-grade fan coolers. • Containment atmosphere temperature decreases to minimum levels (approaches ultimate heat sink (UHS) temperatures). • Containment pressure approaches minimum quasi-steady state value. • Containment pool temperature decreases to minimum value (approaches UHS levels). • Pool flow fields to the reactor building recirculation sump are maintained, but the flows may be reduced as ECCS equipment could be throttled or stopped based on EOP/TSC guidance. • Chemical reactions with debris and materials in contact with containment pool coolant continue. • Debris beds on recirculation sump screens and on fuel components continue to form.

Note:

1. For some plants, active boron dilution involves alternating the alignment of the ECCS flow back and forth between the CL and the HL. For these plants, it is possible that one of the alignments will result in an increase in boron concentration while the other alignment results in a decrease in boron concentration.

Table 6-3 Description of Scenario Phases – DEG HL Break

Phase	Duration	Description
P1	0 sec to 30 sec	• Initially subcooled coolant is exhausted as a two-phase mixture into the containment until the end of this phase. The RCS fully depressurizes during this phase. • Containment temperature increases to a peak or near-peak level. • Containment pressure increases, approaching its peak level. • Debris is generated by the two-phase jet formed by the initial release of subcooled coolant into the containment (for the initial 10-15 seconds of the event). • Surfaces of systems, structures and components inside containment are wetted by the break coolant. • Liquid coolant begins to collect on the containment floor. • Chemical reactions with debris and materials in contact the exhausted coolant are initiated.
P2	30 seconds to start of sump recirculation (i.e., Drain Down of the RWST/BWST, plant specific timing – generally between 1200 seconds to 3600 seconds)	• RCS is depressurized. • Containment spray is actuated. • ECCS flow from the RWST/BWST to the RCS is actuated. • ECCS flow through the nuclear core and out the HL break is established • Safety-grade containment fan coolers are actuated. • Coolant supplied by the ECCS flows through the core and the excess continues to exhaust from the RCS through the HL break. • Exhausted coolant and containment spray collect in a pool on the containment building floor. • Containment temperature begins to decrease from its peak level. • Containment pressure begins to decrease from its peak level. • Temperature of coolant pooled on containment floor begins to decrease. • Debris carried about the containment by coolant exhausted through the break continues to be washed down to the liquid pool by containment spray. • Chemical reactions continue with debris and materials in contact with spray flow and the liquid pool on containment floor.

Table 6-3 Description of Scenario Phases – DEG HL Break (cont.)

Phase	Duration	Description
P3	Start of sump recirculation (Recirculation of Coolant in the Pool on the Containment Floor) to 12 hrs (Possible initiation of Active Boron Dilution based on EOP/TSC guidance)	• ECCS is realigned from the RWST/BWST to recirculate coolant from the reactor containment sump. • Containment spray is terminated for some plants, continues to run for plants that do not have safety-grade fan coolers. • If containment spray continues, the containment spray pumps are realigned from the RWST/BWST to recirculate coolant from the reactor containment sump. • Safety-grade containment fan coolers continue operation. • Coolant continues to exhaust from the primary system through the HL break, but at reduced velocities. • Containment temperature continues to decrease. • Containment pressure continues to decrease. • Debris generated by break flow and washed into the containment floor pool is submerged in escaped coolant and containment spray. • Debris is carried about the containment by coolant exhausted through the break and by containment spray. • Liquid pool on containment floor is at its maximum or near-maximum depth. • Temperature of liquid pool on containment floor continues to decrease. • Pool flow fields are established with flow to the reactor building recirculation sump. • Chemical reactions with debris and materials in contact with containment liquid continue. • Debris beds on recirculation sump screens and on fuel components begin to form.
P4	12 hrs to 1 day (24 hrs)	• ECCS continues to recirculate coolant from the reactor containment sump. • Active boron dilution(1) actions are initiated by the operators, as directed by the EOP (some plants always initiate this dilution method while others may not because the core exit is subcooled and the boron is not concentrating so no dilution is needed). • Safety-grade fan coolers continue to run. • Containment spray continues to run for plants that do not have safety-grade fan coolers. • Containment atmosphere temperature continues to decrease. • Containment pressure continues to decrease. • Containment pool temperature continues to decrease.

Table 6-3 Description of Scenario Phases – DEG HL Break (cont.)

Phase	Duration	Description
P4 (cont.)		• Pool flow fields to the reactor building recirculation sump are maintained. • Chemical reactions with debris and materials in contact with containment pool coolant continue. • Debris beds on recirculation sump screens and on fuel components continue to form.
P5	1 day to 30 days	• ECCS continues to recirculate coolant from the reactor containment sump. • Active boron dilution actions are either initiated or continued, as needed. • Safety-grade fan coolers continue to run. • Containment spray continues to run for plants that do not have safety-grade fan coolers. • Containment atmosphere temperature continues to decrease to minimum levels (approaches UHS temperatures). • Containment pressure approaches minimum quasi-steady state value. • Containment pool temperature continues to decrease to a minimum value (approaches UHS levels). • Pool flow fields to the reactor building recirculation sump are maintained, but the flows may be reduced as ECCS equipment could be throttled or stopped based on EOP/TSC guidance. • Chemical reactions with debris and materials in contact with containment pool coolant continue. • Debris beds on recirculation sump screens and on fuel components continue to form.

Note:

1. For some plants, active boron dilution involves alternating the alignment of the ECCS flow back and forth between the CL and the HL. For these plants, it is possible that one of the alignments will result in an increase in boron concentration while the other alignment results in a decrease in boron concentration.

6.3 FIGURE OF MERIT

Discussion of Long-Term Cooling Acceptance Criterion

The relevant acceptance criterion for demonstration of acceptable safety injection capability for post-LOCA, LTC is 10 CFR 50.46(b)(5) which states:

> ***Long-term cooling.*** *After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.*

The acceptance criterion lacks specificity in terms of defining LTC and what is an acceptably low core temperature value. Some insight to the NRC position regarding this criterion can be gained from Reference 10. The response to Question 1 of Reference 10 states that LTC refers to the (sump) recirculation mode of ECCS operation and the second paragraph further states that criterion (b)(5) is considered to be satisfied when the core is quenched, the switch from injection to recirculation phases is complete, and recirculation flow rate is large enough to match the boil-off rate. Therefore, criterion (b)(5) is applicable to the DEG HL and CL break scenarios being evaluated in this PIRT.

With regard to fuel temperature, the same reference defines an acceptable heat-up to be on the order of 100 – 200°C, but allows for heat-ups to be higher if justified. Per Reference 11, after the initial heat-up and quench of the core, maintaining a PCT of 800°F for a duration of up to 30 days has been justified. Again, higher fuel cladding temperatures and time at temperature may be acceptable if justified. To summarize:

- The core is quenched.
- The switch to recirculation is complete.
- Recirculation flow is enough to match boil-off.
- PCT of 800°F can be justified for 30 days (after the initial heat-up and quench).

Figure of Merit

The figure of merit against which the phenomena will be evaluated is:

Maintain LTC with debris (e.g., particulates, fiber and corrosion products) in the recirculating coolant.

That is, phenomena will be ranked based on their assessed ability to interfere with or preclude the maintenance of LTC following a hypothetical DEG CL or HL break.

PIRT Success Criterion

Given the discussion of LTC and the figure of merit, the success criterion for LTC is defined as:

LTC is successful if additional clad oxidization is minimized following core quench.

This success criterion is consistent with the success criterion identified in Revision 2 of WCAP-16793-NP (Reference 6) and has been accepted by the NRC staff in an SE on that topical report.

This success criterion provides for the evaluation of phenomena that increase the resistance to core cooling flow, but stop short of inadequate core cooling. This differentiation was specifically chosen as the successful resolution of GSI-191 requires the maintenance of adequate LTC. Therefore, the condition and consequences of inadequate core cooling were felt to be beyond the scope of GSI-191.

6.4 DEVELOPMENT APPROACH FOR THE PWROG GSI-191 PIRT

The time period of interest for the debris entering the RCS within the PWROG GSI-191 PIRT begins with period P3, the time of switchover from injecting from the RWST/BWST. During Period P3, the recirculation of debris laden coolant from the sump can enter the RCS and flow to the core with the ECCS flow (for UPI plants, this debris-laden flow is also injected directly into the RV UP).

For plants that inject ECCS flow on the cold side of the core, the core coolant flows down the DC and into the bottom of the core. Under these flow conditions, there is a potential for debris to collect and form a debris bed at the core inlet and within the core that would challenge LTC.

The initiation of active boron dilution actions mitigates the build-up of boric acid in the core for postulated CL breaks by either reversing the flow in the core (for CE and Westinghouse plants) or providing another flow path to duct coolant from the core to the sump (HL letdown for B&W plants). Both of these processes provide for the flushing of concentrated boron from the core before boron solubility limits are reached. This flushing will also have the effect of diluting post-accident chemical products that are collected and concentrated in the core during periods P2 and P3 due to the boiling associated with core cooling of a CL break.

At the beginning of period P3 following a DEG CL break, the core power is capable of generating sufficient steam that coolant injected into the HL may not readily reach the core and be effective in matching the core decay heat and initiating a core flushing flow for Westinghouse and CE plant designs. Hence, time periods P1 (i.e., blow down), P2 (i.e., injections from the RWST/BWST) and P3 (i.e., initial recirculation of spilled coolant from the containment recirculation sump until active boron dilution [12 hours is provided as a representative time before active boron dilution is initiated in this PIRT activity]) are critical for debris generation and transport, which are the focus of this PIRT. However, the PIRT panel unanimously agreed that time periods P4 (12 hours to 1 day – cool down of the core and reactor containment building) and P5 (1 day to 30 days – LTC) should also be included in this PIRT activity for completeness because these are the periods during which the effects of chemical products become more important. Hence, the PIRT addresses time periods P1 through and including P5, although periods P1 through P3, and particularly P3, are of primary interest for this PIRT.

The PIRT panel recognized that both chemical effects and TH phenomena have the potential to collectively contribute to the overall consequences of post-accident chemical effects on LTC. Thus, the PIRT panel chose to account for both chemical and TH mixing phenomena in the development of a PIRT for this project.

1. As the PIRT panel considered that similar chemical effects can occur at different locations within the RCS, the decision was made to list and evaluate chemical effects in a single table. However, RCS location-dependent effects are called out in the description of either the phenomenon or the SoK for that phenomenon.

2. To more readily account for the variation of TH effects that would exist about the RCS, the PIRT panel chose to list and evaluate TH phenomena by RCS components. Therefore, there are 11 tables for the TH transport and mixing phenomena.

The chemical effects PIRT is presented in Section 7. The TH PIRT is presented in Section 8. As noted previously, a DEG break in the HL results in both chemical and TH phenomena that have similarities to those that occur for a DEG CL break. Variations in phenomena related to break location (HL versus CL), when they are evaluated to occur, are identified in the PIRT.

7 PIRT FOR CHEMICAL EFFECTS

7.1 PURPOSE AND SCOPE FOR CHEMICAL EFFECTS PIRT

Section 7 describes the purpose and scope of the Chemical Effects PIRT, a background description of earlier chemical effects work affecting this PIRT, the Chemical Effects PIRT itself as well as a summary of the high-ranked chemical effects phenomena and their associated SoK.

7.2 FIGURE OF MERIT: CHEMICAL EFFECTS

Figure Of Merit: Chemical Effects
Maintain LTC with debris (e.g., particulates, fiber and corrosion products) in the recirculating coolant.

The rankings of the phenomena listed in the chemical effects PIRT were assigned with respect to each phenomenon's impact or effect on the Figure of Merit: maintaining LTC with particulates, fiber and corrosion products (chemical effects) in the recirculating coolant.

7.3 BACKGROUND FOR CHEMICAL EFFECTS PIRT

An initial limited-scope study was performed by LANL to evaluate potential chemical effects occurring following a LOCA (Reference 12). This study assessed the potential for corrosion products to impede ECCS performance. In some of these tests, aluminum (Al), zinc (Zn), or iron (Fe) nitrates were added to the test water to induce chemical precipitation between the metals and other anionic species in order to assess the associated head loss. The tests showed that gel formation with a significant accompanying head loss across a fibrous bed was possible, although the test conditions and evolution of chemical species were not prototypical of a post-LOCA PWR environment.

A more comprehensive ICET program was conducted under the joint sponsorship of the NRC, EPRI and the PWROG (Reference 13). The primary objectives for the ICET test series were to:

1. Determine, characterize, and quantify chemical reaction products that may develop in a simulated containment pool under a representative post-LOCA environment.

2. Determine if amorphous or gelatinous material could be produced and, if so, quantify the amount of such material that could be produced during the simulated post-LOCA recirculation phase.

The ICET program consisted of five 30-day tests. Each of the five tests represented a unique chemical environment. Each environment was intended to represent a portion of the post-LOCA containment pool chemistry for operating PWR. These conditions were selected so as to broadly characterize containment pool materials and conditions applicable to the existing U.S. PWR nuclear plants after a hypothetical LOCA. Representative types and bounding amounts of submerged and unsubmerged materials were evaluated based on plant surveys (Reference 14). The primary variables that changed during each test were the buffering agent (e.g., sodium hydroxide (NaOH), sodium tetraborate (NaTB), or trisodium phosphate (TSP)) and the insulation materials (e.g., 100 percent fiberglass or 80 percent calcium silicate (Cal-Sil) and 20 percent fiberglass).

The ICET results indicate that:

1. Chemical reaction products with varied quantities, consistencies, attributes, and apparent formation mechanisms were found in each unique ICET environment.

2. Containment materials (e.g., metallic, nonmetallic, and insulation debris), hydrogen ion concentration (pH), buffering agent, temperature, and time are all important variables that influence chemical product formation.

3. Changes to one important environmental variable (e.g., a pH adjusting agent or insulation material) can significantly affect the chemical products that form.

Specifically, amorphous aluminum hydroxide ($Al(OH)_3$) (Reference 15) precipitates were observed upon cooling in ICET Tests 1 and 5. Similar aluminum-based products were observed in the fiberglass insulation of Tests 1, 4, and 5, along with other particulate deposits on the outside of the insulation bundles. Calcium phosphate ($Ca_3(PO_4)_2$) was observed within the test solution within 1 hour of initiating ICET Test 3, and similar products were apparent in fiberglass insulation in Tests 2 and 3 along with other particulate deposits on the outside of the insulation bundles.

The ICET program provided insights to, and an initial understanding of, the solution chemistry and of the types and amounts of chemical reaction products that could form in the ECCS containment pool. However, while the ICET program demonstrated that plant-specific differences in important variables could significantly alter the observed chemical effects, it was difficult to extrapolate the results to other conditions based on the limited testing that was performed, the bounding pH values used to buffer the boric acid solution and the bounding values of representative materials used in the ICET program.

Subsequently, the NRC sponsored follow-up work at LANL to more fully understand the formation of the amorphous $Al(OH)_3$ precipitate in NaOH and NaTB environments (ICET Tests 1, 4, and 5). In addition, this work evaluated the behavior of aluminum over a broader range of conditions (e.g., pH, temperature, and solution age) that might exist throughout the PWR following a LOCA (Reference 15).

The PWROG also sponsored a study to provide input to plant licensees on the type and amounts of chemical precipitates that may form post-LOCA for testing of replacement sump screens. The study evaluated leaching and corrosion data of various containment materials over a wider range of pH and temperature conditions than those tested in the ICET program (Reference 5). The materials, pH, and temperature conditions were determined via plant surveys. The study partitioned containment materials into 15 material classes based on their chemical composition and tested 1 material from each of the 10 classes presumed to have the potential for causing chemical effects in the containment sump: Al, aluminum silicate, Cal-Sil, carbon steel, concrete, electrical grade glass (i.e., E-glass), amorphous silica, Interam E class insulation, mineral wool, and Zn.

Single-material, single-effect dissolution testing was conducted and the dissolved elements found at the highest concentrations were aluminum, silicon, and calcium. Based on this, it was assumed that these elements would be the most likely to form precipitates. Subsequent room temperature single-material (and a few dual-material) precipitation and filterability tests of materials containing these elements were conducted and precipitates from the following materials were observed for certain pH values: Al, Fiber

Frax insulation, galvanized steel, fiberglass insulation, concrete, mineral wool, and Cal-Sil (when TSP buffering was used). The NaTB-buffered tests did not induce any additional precipitates. The three principal precipitates were assumed to be $AlO(OH)$, $AlNa_{12}SiO_5$, and $Ca_3(PO_4)_2$ based on energy dispersive spectroscopy (EDS) analysis. None of the precipitates settled readily. These test observations are generally consistent with the earlier NRC-sponsored studies discussed in References 13, Reference 15, Reference 16 and Reference 17.

The results from these studies have been used for the following two related applications:

1. To develop a tool for predicting the amount of chemical products in specific plant environments.

2. To develop a procedure for generating chemical surrogates for use in large-scale validation testing simulating individual plant configurations.

The predictive tool developed was based on the experimental testing results and enabled the determination of the dissolution rate of species under plant conditions. All dissolved materials that form during each time step were then assumed to precipitate instantaneously to form $Ca_3(PO_4)_2$, $AlO(OH)$, and/or $AlNa_{12}SiO_5$. The particular precipitates depend on the plant materials and type of buffer.

The methods for generating chemical surrogates were largely aimed at ensuring that agglomeration and settling does not occur. These criteria were provided for producing surrogate precipitates that were intended to behave similarly to the above precipitates during strainer testing.

The application of the testing reported in Reference 5 was conservative as the testing used "fresh" or unoxidized samples and evaluated the corrosion rates over short time periods (90 minutes) when the corrosion rate is expected to be at a maximum. These maximum corrosion rates were then used in the predictive tool to extrapolate corrosion rates for 30 days.

The NRC issued an SE (Reference 18) on the PWROG testing and predictive tool of Reference 5. To support this SE, the NRC sponsored research to confirm certain aspects of the work in Reference 5 and the intended applications of the results (Reference 19). In general, the NRC-sponsored research did not contradict, and generally confirmed the test results of Reference 5. Differences in dissolution results between NRC's confirmatory testing and that reported in Reference 5 were attributed to either differences in actual materials, age or storage conditions, or the greater agitation of samples used in the testing documented in Reference 5.

NRC also sponsored research at Argonne National Laboratory (ANL) (Reference 17) to evaluate the physical characteristics and head-loss performance of the surrogate aluminum precipitates recommended by Reference 5 relative to the precipitates generated during earlier NRC-sponsored tests. The ANL study determined that surrogate preparation procedures given in Reference 5 do produce fine precipitates, and the addition of a small amount of precipitate equivalent to 5 ppm ($2x10^{-4}$ M) of dissolved Al resulted in immediate, significant head loss across a fiberglass debris bed.

The NRC found that various research programs, summarized above, significantly advanced the understanding of chemical effects with the post-LOCA containment environment. The NRC also held that these programs collectively demonstrated that, under certain conditions, chemical products can form and significantly affect head loss across fibrous debris beds. However, the NRC also held that there were several fundamental issues that were not addressed by these research activities. For example, the effect of several materials that were expected to exist in containment (e.g., coatings, organics, activated species, etc.) and the influence of certain post-LOCA conditions (e.g., realistic post-LOCA containment temperature profiles, flow through sediment, galvanic effects, radiolytic effects, and the ratio of the containment air to pool volume) on chemical effects were not addressed by ICET or other research programs. Also, ICET and other programs held important variables constant in a given test, and a complete range of plant-specific conditions for important variables had not been studied. It was also not possible to quantify either the mass of various chemical precipitates or the exact conditions leading to precipitation of these species under representative post-LOCA conditions in order to more readily assess plant-specific implications.

To address these concerns, the NRC convened a panel of five experts spanning a range of relevant technical disciplines. The panel had two objectives:

1. Review the NRC-sponsored research conducted through the end of 2005. The review findings are summarized in Reference 20.

2. Identify additional chemical phenomena and issues that have not been considered in the original NRC-sponsored research and that formed the basis for many of the concerns identified earlier in this section.

To accomplish the second objective, the NRC sponsored a PIRT exercise to fully explore the possible chemical effects that may affect ECCS performance during a hypothetical LOCA scenario. The results of the NRC-sponsored PIRT exercise are documented in Reference 21.

In parallel to these activities, the various U.S. PWR utilities (as well as international organizations) conducted chemical effects testing in support of new strainer installations. These activities generated a significant amount of test data, some public and some proprietary, which greatly improved the knowledge base on chemical effects.

The NRC PIRT was issued in 2009. To take advantage of advances in knowledge and understanding of post-accident chemistry, and to inform its comprehensive test and analysis program to bring closure to GSI-191, the PWROG sponsored a PIRT exercise to identify and evaluate the chemical effects associated with coolant recirculating from the reactor containment building sump. This PWROG PIRT was intended to inform both the testing and the analysis performed to support closure of GSI-191.

The PWROG PIRT took into account and used the NRC chemical effects PIRT as a starting point for chemical effects. No attempt was made to partition chemical effects by region or location within the reactor containment building. Spatial considerations for chemical effects are called out in the rationale tables.

However, a unique aspect of the PWROG PIRT was that it also addresses TH transport phenomena that affect chemical phenomena. Furthermore, the PIRT tables associated with TH transport were portioned by components or regions within the RCS. This was done to more clearly focus on the local TH transport phenomena that could affect chemical processes and phenomena.

7.4 CHEMICAL EFFECTS RANKING AND RATIONALE

Table 7-1 Chemical Effects – LBLOCA Ranking

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
Source Terms						
1. Break location variation could result in different debris mixes and p:f ratios.	H	H	H	H	H	M
2. Crud Release. Fe and Ni corrosion oxides from the RCS piping and fuel are released due to hydraulic shock of the break initiation.	L	L	L	L	L	H
3. Submerged source terms: RCP (Reactor Coolant Pump) oil tank failure. Overflow, failure, or leakage occurs due to either the LOCA or a preexisting condition. Oils and other organics are released into containment pool. Tank volume may be as much as ~250 gallon per pump, but the tank may just contain a small amount of leakage.	N/A	N/A	L	L	L	H
4. Washdown of organic materials, such as oils, from containment walls.	L	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
5. Break proximity to secondary systems. A break near cooling systems could result in failure of lines containing solvents (e.g., Freon) into containment environment.	N/A	N/A	N/A	N/A	N/A	H
6. Contamination from secondary side. Contamination from rupture of one or more SG tubes allows secondary side chemicals to be added to containment pool.	N/A	N/A	N/A	N/A	N/A	H
7. Failure of an auxiliary component cooling line. The LOCA causes attached or nearby component cooling line failure which could release a number of chemicals into the containment pool such as chromates, molybdates, nitrites, tolytriazole, benzotriazole and hydrazine.	N/A	N/A	N/A	N/A	N/A	H
8. Heat exchanger: secondary contaminants. Leaks in heat exchanger tubes allow secondary-side water additives to migrate over to the containment pool.	N/A	N/A	N/A	N/A	N/A	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
9. Corrosion due to containment spray containing NaOH. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, lithium hydroxide (LiOH), hydrogen, and for some plants NaOH.	N/A	H	H	H/L	H/L	M
10. Corrosion due to containment spray containing TSP. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, H, and TSP.	N/A	N/A	M	L	L	M
11. Corrosion due to containment spray containing NaTB. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, H, and NaTB.	N/A	N/A	M	L	L	M
12. TSP inhibits the corrosion of aluminum.	N/A	L	M	M	H	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
13. Corrosion of submerged source terms: inhibition due to fiberglass. Leaching of fiberglass inhibits corrosion of certain metals (e.g., aluminum).	N/A	L	M	M	H	M
14. Boric acid corrosion of exposed concrete. Boric acid solutions in contact with exposed concrete begin reacting.	L	L	N/A	N/A	N/A	H
15. Injection of concentrated boric acid storage tank (BAST) fluid from charging or high pressure injection pumps causing boric acid corrosion of exposed concrete.	L	L	L	N/A	N/A	H
16. Radiological reaction of Fe and Ni. Initial iron and nickel oxide breaks off due to the blowdown transient. Reduced Fe and Ni are dissolved in the RCS coolant, combines with air, oxidizes and forms iron hydroxides, and over the long term, hematite, maghemite, and magnetite, etc.	L	L	L	L	L	H
17. Galvanic Corrosion. Electrical contact between metals results in the increased corrosion of the less noble metal.	L	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
18. Cable degradation. The insulation surrounding electrical cables located throughout containment is affected by radiolysis, releasing chlorides.	N/A	L	L	L	M	M
19. Fiberglass leaching. Fiberglass-based insulation products begin leaching constituents (e.g., silicon, aluminum, magnesium, calcium, etc.)	L	M	H	H	H	H
20. Seal abrasion of ECCS pumps. Abrasive wearing of pump seals (e.g., magnetite - high volume/concentration of mild abrasive) may create additional materials that contribute to sump pool chemistry or particle loading.	N/A	N/A	L	L	L	H
21. Dissolution of exposed, uncoated concrete. Dissolution can result in locally high pH (depending on surface area) relatively quickly.	L	M	M	M	M	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
22. Dissolution of protective coatings. Dissolution and leaching of epoxy, alkyd, or zinc-based coatings and primers may occur. Submerged source terms: protective coatings. Leaching of submerged coatings may contribute species to the containment pool. Possible sources include lead-based paints (in older containment buildings), phenolics and polyvinyl chloride (PVC).	N/A	L	L	M	M	M
23. Corrosion due to boric acid. Boric acid pooled on unsubmerged portions of large ferritic steel components (e.g., piping RPV, pressurizer, and steam generator) continues to cause corrosion of these materials.	L	L	L	L	L	H
24. Corrosion source terms from unsubmerged materials. Corrosion of various materials (Al, Fe, concrete, Copper (Cu), Zn) due to condensation and transport into containment pool. Condensation is expected due to non-uniform containment environment temperatures.	L	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
25. Corrosion from submerged source terms, lead shielding. Acetates present in containment pool may dissolve lead, which could lead to formation of lead carbonate particulate. Lead blanketing to shield hot spots and covered with plastic coating, but coating likely destroyed. There may be several hundred pounds of lead in flat sheets. Some plants still use lead wool.	N/A	N/A	L	L	L	M
26. Corrosion from submerged source terms: copper. The concern is not with copper compounds, but the effects that copper may have on other corrosion processes. Copper concentrations evaluated in ICET program. Cu comes from containment air coolers, motor windings and grounding straps. (Fan coolers and motors are typically not submerged.)	N/A	L	L	L	L	H
27. Corrosion from submerged source terms: iron. Boron inhibits pitting corrosion on the surface of steel structures. Iron concentrations evaluated in the ICET program.	N/A	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
28. Corrosion from submerged source terms: aluminum. Less dissolved aluminum than was observed in ICET #1 affects the type and quantity of chemical byproducts that form at high pH values.	N/A	H	H	H	H	H
29. Corrosion from submerged source terms: zinc corrosion products. Zinc oxide, hydroxide, phosphate or silicate are potential precipitates.	N/A	L	L	L	M	M
30. Corrosion of submerged source terms: zinc coprecipitation. Zinc may coprecipitate with other species such as iron and aluminum. The reactor vessel is a possible site for coprecipitation.	N/A	L	L	L	L	M
31. Zinc hydroxide dissolution (zincate). The coolant in the buffered pH containment pool may dissolve zinc hydroxide so that other species, particularly silicates, may precipitate.	N/A	N/A	N/A	N/A	N/A	N/A
32. Corrosion of submerged source terms: zinc passivation. Zinc passivation decreases corrosion of iron.	N/A	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

Phenomenon/Process Description	Initial Depressurization P1 (0-30s) Rank	ECCS Injection P2 (30s-20m) Rank	CL Recirculation P3 (20m-12h) Rank	Cooldown and Depressurization of Containment Building P4 (12h-1d) Rank	Long-term Cooldown of Containment Building P5 (1d-30d) Rank	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.* SoK
33. Corrosion from submerged source terms: zinc-based coatings. Leaching of elemental zinc-based primers may result in additional dissolved zinc in solution.	N/A	L	L	L	L	H
34. Additional source term: bottom mounted instrumentation corrosion. Multiple materials in equipment related to bottom mounted instrumentation (e.g., stainless steel, plastics, organics) may lead to formation of dissolved species. Portions of the bottom mounted instrumentation equipment (mainly instrument/guide tubes, depending on plant design) are located at an elevation below the bottom of the core. At this elevation, the instrument/guide tubes penetrate the lower vessel head and support the instrumentation from the core to the pressure isolation location. Any bottom mounted instrumentation components located below the vessel or containment pool or those which can be exposed to spray may act as a corrosion source term.	N/A	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
35. Additional submerged source terms: fire barriers. Silicone-based seals (bisco seals) are used at many structural penetration points as fire barriers. These may leach in post-LOCA environment.	N/A	L	L	L	L	M
36. Submerged source terms: organic buoyancy. Organics coat materials (e.g., aluminum, calcium silicate, fiberglass, etc.) and increase the buoyancy of particulates so that they are more likely to float.	N/A	L	L	L	L	H
37. Submerged source terms: formation of biofilm. Biofilms form which protect against metallic corrosion (by forming passive layer) or lead to production of acids which increase metallic corrosion. Some biofilms may be preexisting in containment from outages.	N/A	N/A	L	L	L	M
38. Submerged source terms: biological growth in debris beds. Bacteria may grow in preexisting debris beds located on the sump strainer screen or elsewhere within the ECCS system.	N/A	N/A	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
39. Submerged source terms: biologically enhanced corrosion. General corrosion is enhanced due to biological agents. Examples include polysaccharides and sulfate reducing bacteria which may enhance iron corrosion. Sulfur or carbon sources contribute to bacteria formation.	N/A	N/A	L	L	L	M
40. ECCS Pumps: erosion/corrosion. Chemical byproducts cause erosion or corrosion of pump internals, especially tight tolerance components (bearings, wear rings, impellers, etc.).	N/A	N/A	L	L	L	H
41. ECCS Pumps: seal degradation. Chemical environment causes leaching/degradation of pump seal materials.	N/A	N/A	L	L	L	H
42. Transport phenomena associated with metallic scouring. Turbulent flow causes chemical films and products to be scoured off the surface of metallic components so that they enter the containment pool.	L	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
43. Mass transport of the dissolution products away from the surface, creating a concentration gradient that promotes dissolution (flow accelerated corrosion).	H	H	H	H	H	H
44. Jet impingement. Water jet & fine debris within the jet may impact surfaces and chip coatings. This will increase the surface area available for chemical reactions.	L	L	L	L	L	H
45. Straining removes materials at the strainers, preventing full loading of debris in the core.	N/A	N/A	H	H	M	H
46. If surface deposition dominates bulk precipitation, large fiber debris sources scavenge inventory	N/A	N/A	H	H	H	M
<u>**Coolant Chemistry**</u>						
47. RCS coolant boron concentration at the time of the break. The RCS coolant chemistry varies over the fuel cycle with boron concentrations ranging from about 2000 ppm at the beginning of the fuel cycle to near 0 ppm at the end of the fuel cycle.	H	M	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
48. RCS coolant lithium concentration at the time of the break. The RCS coolant chemistry varies over the fuel cycle.	L	L	L	L	L	H
49. RCS coolant pH variability. pH of the coolant at 60°C at beginning of fuel cycle is acidic (pH ≅ 6) and is alkaline (pH ≅ 9) at end of the fuel cycle. The pH variation is less at higher temperatures.	H	M	L	L	L	H
50. Coolant TH conditions of the coolant expelled from the break. Localized boron concentration in break flow jet. Droplet evaporation within the high temperature jet emanating from the pipe break may form a concentrated boron aerosol solution. As boron concentrates at high temperatures (250°C – 300°C), a polymerization appears to occur that releases protons and causes the system to become more acidic as it discharges from the break.	L	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
51. ECCS injection of boron. After the break and as the RCS depressurizes, boron is injected in coolant from accumulators and the RWST/BWST. There is some variability from plant to plant (2400-2700 but could be up to 4500). High local concentrations could exist.	L	M	M	L	L	H
52. RCS fluid shifts towards an oxidizing environment. If the coolant is released as a super heated spray through the break, hydrogen (25 -35 cc/kg of H_2 injected as gas) is released as a gas. Oxygen from the containment atmosphere is absorbed into the coolant.	M	M	M	M	M	M
53. Radiolytic environment exists inside the containment. Radiolysis reactions change the coolant's redox potential.	L	M	M	M	M	M
54. Radiolysis of CO_2 and carbonates could lead to the formation of organic acid ligands (e.g., acetate, butyrate, and oxalate).	L	L	L	L	L	H
55. Radiolysis promotes formation of carbonates.	N/A	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
56. Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.	N/A	N/A	M	H	H	L
57. Hydrogen peroxide effects. Hydrogen peroxide (H_2O_2) will behave much the same as H_2O. Most of it will remain in the liquid phase. Some hydrogen peroxide may evaporate into the containment vapor space and may then cause additional corrosion. If it condenses on cooler surfaces, hydrogen peroxide may accelerate corrosion.	L	L	L	L	L	M
58. Radiological effects: corrosion rate changes. Radiolysis of Chlorine (Cl)-bearing water leads to formation of hypochlorite. This could increase corrosion rates (especially pitting corrosion) of aluminum, stainless steel and iron.	N/A	N/A	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
59. Hydrogen sources within containment. Hydrogen concentrations in vapor and containment pool include the RCS inventory, Schikorr reaction and release from corrosion of metallic materials.	L	L	L	L	L	M
60. Rate of release of NaTB pH control agent. Released to pool on containment floor with melting of ice beds or dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	L	M	H	N/A	N/A	H
61. Rate of dissolution of TSP for pH control. Released to pool on containment floor due to dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	L	M	H	N/A	N/A	H
62. Dilution of TSP or NaTB within the sump pool. Locally high concentration and high pH may exist initially, but sump mixing over time dilutes the locally elevated concentrations.	N/A	L	M	N/A	N/A	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
63. TSP limits the concentration of alkaline earth elements in solution by precipitation in the sump. This precipitation may be collected on the sump screen debris bed, reducing the amount available to transport to and precipitate in the core.	N/A	L	L	M	M	H
64. Localized high concentrations of chemicals at the sump screen. High localized concentrations of certain species may drive the reaction efficiency at the sump screen.	N/A	N/A	L	L	L	L
65. Localized chemistry alters the fiberglass contribution to the chemical environment at the sump screen.	N/A	N/A	L	L	M	L
66. Scavenging of carbon dioxide (CO_2), oxygen (O_2) and nitrogen (N_2) by containment sprays and within the containment pool has the potential to affect containment pool chemistry.	N/A	M	M	M	L	M
67. Nickel oxide becomes catalyst for producing elemental hydrogen from radiolysis.	L	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
68. Organic compounds with two hydroxy groups will coordinate with boric acid to increase acidity.	N/A	L	L	L	L	H
69. Decrease in pH of containment pool. The pH of the containment pool decreases due to evolving containment pool chemistry and affects the reaction rate and the solubility of some species.	N/A	L	M	L	L	H
70. Temperature of containment pool affects the reaction rate and the solubility of some chemical species.	N/A	H	H	H	H	H
71. Chemical products change coolant viscosity in the sump.	N/A	L	L	L	L	H
72. Chemical products change coolant surface tension in the sump.	N/A	L	L	L	L	H
73. For a cold-leg break, the boiling process in the core increases the concentration of chemicals in the reactor, increasing or decreasing the risk of precipitation.	N/A	M	H	M	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
74. For a hot-leg break, the boiling process in the core increases the concentration of chemicals in the reactor, changing the boiling point and increasing or decreasing the risk of precipitation.	L	M	L	L	L	H
75. For a cold-leg break, the boiling process in the core concentrates coolant chemicals affecting the ionic strength, and influencing precipitation.	N/A	L	M	L	L	H
76. For a hot-leg break, the boiling process in the core concentrates coolant chemicals affecting the ionic strength, and influencing precipitation.	L	L	L	L	L	H
77. For a cold-leg break, fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	H	H	H	L
78. For a cold-leg break, chemical products collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
79. For a cold-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	H	H	H	L
80. For a hot-leg break, fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	M	M	M	L
81. For a hot-leg break, chemical products collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	L	L	L	H
82. For a hot-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	N/A	N/A	H	H	M	L

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
83. Chemical reactions producing gas bubbles induce froth flotation processes in the containment pool.	N/A	L	L	L	L	M
Precipitation/Deposition Processes						
84. Containment pool mixing. High velocity, turbulent water flow exists underneath the pipe break location, remainder of the pool relatively quiescent. Containment sprays and sprays draining to lower containment promote mixing. The degree of mixing will affect concentrations altering both debris dissolution rates and precipitation.	N/A	M	M	L	L	M
85. Turbulent mixing. Turbulence in the containment pool (such as directly under the break) either inhibits or promotes precipitate formation and growth.	N/A	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
86. Boundary layer precipitation. As dissolution occurs, concentrations are highest in the boundary layer at the surface of the solid, due to normal phenomena of mass transfer. Since concentrations are highest in the boundary layer, it also suggests that precipitation might also be most likely to occur at the solid surfaces.	N/A	H	H	H	H	H
87. Organic adsorption. Organic species adsorbed on surfaces of solids, altering growth rates or the crystalline habit of precipitates.	N/A	L	L	L	L	M
88. Inorganic adsorption. Inorganic species adsorb on surfaces of solids, altering growth rates or the crystalline habit of precipitates.	N/A	L	H	H	H	H
89. Organic sequestration. Organic electron-rich atoms combine with soluble metal compounds changing the solubility of dissolved metals.	N/A	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
90. Co-precipitation. This is a method of precipitation/ separation. Examples include: Ni/Fe/Chromium (Cr), Al/Silicon (Si)/ Boron (B), Cobalt (Co)/Fe systems. Precipitation of one species leads to precipitation of other species.	N/A	M	M	M	M	M
91. Inorganic Flocculation. Formation of larger clumps of smaller particulates: Depends on PZC (point of zero charge) of the particles and ionic strength of the solution (the higher the strength the smaller the distance for agglomeration).	N/A	H	H	H	H	H
92. Formation of a coagulant. Inorganic chemical species attach to or coat particulate debris, which leads to agglomeration.	N/A	H	H	H	H	H
93. Organic Flocculation. The formation of larger clumps of smaller inorganic particulates due to the adsorption of an organic material	N/A	L	L	L	L	M
94. Organic Stabilization. The formation of larger clumps of smaller inorganic particulates is inhibited due to the adsorption of an organic material	N/A	L	L	L	L	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	**ECCS Injection**	**CL Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
95. Radiological effects: agglomeration. Radiolysis enhances agglomeration of chemical species.	N/A	L	L	L	L	L
96. Change in debris bed properties due to changes in surface charge by adsorption of inorganic species.	N/A	N/A	H	H	H	M
97. Electrochemical precipitation. An electrochemical reaction results in solid phase formation.	N/A	L	L	L	L	H
98. Nuclei formation. Rapid cooling and evaporation of water droplets from the initial break flow may result in precipitation. Concentrations of these species increase as the temperature rapidly decreases.	L	N/A	N/A	N/A	N/A	H
99. Particulate nucleation sites. Particles within containment create nucleation sites for chemical precipitation where examples include: dirt particles, coating debris, insulation debris, biological debris, colloids, etc.	N/A	H	H	H	H	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	**Overall SoK Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
100. Particulate nucleation sites. Particles within containment create nucleation sites for chemical precipitation: an example is radiation tracks.	N/A	L	L	L	L	M
101. Agglomeration of debris on flow-induced bubbles generated from cavitation, deareation, air entrainment and turbulence (opportunity for materials to attach).	N/A	L	L	L	L	M
102. Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.	L	H	H	H	H	L
103. Settling of debris and chemical products in the containment pool. Chemical products formed during this time period may settle within containment pools.	N/A	L	H	H	H	M
104. Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for cold leg injection for cold leg breaks) within reactor.	N/A	N/A	H	H	H	L/M
105. Deposition. Chemical products formed may deposit on other surfaces.	N/A	H	H	H	H	L/M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
106. Deposition on the reactor core. Coolant temperature increase in the core (~60°F to ~80°F from sump pool) and retrograde solubility of some species (e.g., calcium silicate, calcium carbonate, zeolite, sodium calcium aluminate and calcium phosphate) causes scale, build-up on the reactor core.	N/A	N/A	M	M	M	M
107. Homogeneous precipitation in ECCS heat exchangers. Species that are soluble at the containment pool temperature may precipitate at the lower (ΔT ≅ 30°F to 40°F) heat exchanger outlet temperature.	N/A	N/A	M	M	M	M
108. Heterogeneous precipitation on ECCS heat exchanger tubes. Precipitation on heat exchanger surfaces and subsequent debris deposition within close-packed heat exchanger tubes (5/8" diam.) while at the same time reducing the concentration of chemical available for precipitation downstream.	N/A	N/A	H	H	H	M

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
109. Diminished heat transfer in the reactor core. Insulation debris and chemical products mixed within water cause a reduction in the effective heat transfer capabilities (i.e., C_P) of the coolant mixture. *Considering only the affect of chemicals and debris on the thermo-physical properties of coolant.*	N/A	N/A	L	L	L	H
110. Radiological effects: radiation effects on biofilms. Irradiation inhibits the formation and growth of bio-films. (This is one manner in which bio-films are not formed.)	N/A	L	L	L	L	M
111. For a cold-leg break, the boiling process in the core concentrates coolant chemicals affecting the pH, influencing precipitation.	N/A	M	H	M	L	H
112. For a hot leg break, the boiling process in the core concentrates coolant chemicals affecting the pH, influencing precipitation.	N/A	L	L	L	L	H

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

	Initial Depressurization	ECCS Injection	CL Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
113. For a cold-leg break, the boiling process in the core concentrates coolant chemicals, changing the coolant boiling point due to increased concentrations of chemicals.	N/A	L	M	L	L	H
114. For a hot-leg break, the boiling process in the core concentrates coolant chemicals, changing the coolant boiling point due to increased concentrations of chemicals.	N/A	L	L	L	L	H
115. For a cold-leg break, dissolved chemicals in steam moisture carryover deposit on hot surfaces such as the steam generator tubing.	N/A	H	H	M	L	M
116. For a cold-leg break, in regions where dryout/rewetting occurs, the presence of chemical products may create a different deposit structure which does not readily re-dissolve.	N/A	N/A	M	M	L	M
117. Thermal cycling of circulation through residual heat removal (RHR) creates opportunity for the change of colloid properties that can filter on debris.	N/A	N/A	L	L	L	L

Table 7-1 Chemical Effects – LBLOCA Ranking (cont.)

Phenomenon/Process Description	Initial Depressurization P1 (0-30s) Rank	ECCS Injection P2 (30s-20m) Rank	CL Recirculation P3 (20m-12h) Rank	Cooldown and Depressurization of Containment Building P4 (12h-1d) Rank	Long-term Cooldown of Containment Building P5 (1d-30d) Rank	Overall SoK Ranking *If SoK changes by period, multiple entries (separated by '/') are used.* SoK
Additional Items						
118. Perikinetic Flocculation: In perikinetic flocculation, Brownian motion and diffusion bring particles and flocculating agents together. With orthokinetic flocculation, motion of the fluid and velocity gradients help bring particles and flocculating agents together. This enhances the flocculation rate.	N/A	L	L	L	L	H
119. Streaming Potential – Electric field develops across a fixed bed due to conductive fluid flow. This in turn can drive electrophoresis and electrophoretic deposition.	N/A	N/A	L	L	L	M
120. Particle Stickiness.	N/A	L	H	H	H	H
121. Magnetic Attachment – Magnetic particles can agglomerate by a magnetic field.	N/A	L	L	L	L	H
122. Sintering – Solid particles near their melting point consolidate to form more ridged, less porous structures	N/A	L	L	L	L	H

Table 7-2 Chemical Effects – Large Break LOCA Rationale

Phenomenon/Process Description	Rationale for Ranking
Source Terms	
1. Break location variation could result in different debris mixes and p:f ratios.	The p:f was found to be influential in the pressure drops that developed across debris beds formed at the entrance to fuel assemblies in WCAP-16793 (Reference 6) testing. It follows that the debris generation, and hence the p:f ratio, is dependent upon the break location and the plant material around the break, debris inside containment, as well as the debris capture characteristics of the sump screens. Thus, although debris is not introduced into the ECCS until the ECCS is drawing suction from the sump, the debris generation and mix of debris is rated as "H" in all time periods. The SoK of "M" was selected because although the p:f ratio and specific debris mixes are known to be important in determining debris bed head loss, the following are not well understood: • Importance of p:f ratio as a function of particle size and fiber length distribution • Particle and fiber shape effects • Specific material interactions • Effect of flow on importance of debris mix • The particle and fiber sizes generated during different types of breaks • The time sequence when the particulate or fiber reach the core
2. Crud Release. Fe and Ni corrosion oxides from the RCS piping and fuel are released due to hydraulic shock of the break initiation.	There are only a few kg of crud in a normal RCS. This is considered a small amount relative to other LOCA debris sources, and even to latent containment debris. Furthermore, this crud is not easily removed. Even ultrasonic cleaning has removed only approximately 45% of fuel crud in the past. Iron oxides are very insoluble and would not dissolve to any significant extent to contribute to the solution chemistry. Nickel oxides should not affect the precipitation of other compounds. Thus, the release of crud is rated as "L" for all time periods. The SoK was rated "H" because crud has been extensively monitored by utilities and studied by EPRI and others in efforts to control dose rates and its properties are well understood.

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Submerged source terms: RCP oil tank failure. Overflow, failure, or leakage occurs due to either the LOCA or a preexisting condition. Oils and other organics are released into containment pool. Tank volume may be as much as ~250 gallon per pump, but the tank may just contain a small amount of leakage.	Oils used for RCP lubrication are stable and are unlikely to react. Even if they are released into the sump, they will slowly degrade by radiolysis. Oil tanks are designed to be LOCA resistant with vents above the containment flood-up elevation. If oils are present, they could coat other forms of debris and cause debris to stick to surfaces or agglomerate differently than if the oil was not present. The oil and agglomerate could form an oil slick that could reduce the transport to the sump screens. However, presence of oil requires a simultaneous or consequential failure of another system along with the LOCA. The probability of such failures is considered to be small. Therefore until recirculation from the containment pool begins, this phenomenon is considered "N/A." After initiation of recirculation from the containment pool, this phenomenon is ranked as "L." Based on knowledge of the design of oil tanks in plants and the behavior of RCP oils, the SoK is rated as "H."
4. Washdown of organic materials, such as oils, from containment walls.	Organic sources such as oils are expected to be present in very small quantities. This phenomenon is rated as "L" for time periods P1 through and including P5 (the amount of organic materials inside containment both pre- and post-LOCA is expected to be small).. Based on knowledge of organic materials inside containment, the SoK for this phenomenon is rated as "M."
5. Break proximity to secondary systems. A break near cooling systems could result in failure of lines containing solvents (e.g., Freon) into containment environment.	Secondary systems are engineered to withstand LOCA forces. Furthermore, the use of fluorides and chlorides inside containment is controlled. Therefore this phenomenon is considered "N/A" for all time periods. Based on knowledge of plant design and limitations of materials used inside containment, the SoK is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
6. Contamination from secondary side. Contamination from rupture of one or more SG tubes allows secondary side chemicals to be added to containment pool.	Significant secondary to primary leakage is not permitted by regulation and considered unlikely by design. If a secondary-to-primary leak were to occur, the leakage is expected to be small and the small concentration of additives in the secondary side would be diluted into solution in the containment building when discharged out the break or diluted into the core mixture inventory. Leak volume is small compared to volume of water in containment building and would be presumably small compared to volume of water in the core leading to significant dilution of the leakage. Therefore, the impact of additives would be small or negligible. Therefore this phenomenon is considered "N/A" for all time periods. Based on knowledge of plant design and limitations of materials used inside containment, the SoK is rated as "H."
7. Failure of an auxiliary component cooling line. The LOCA causes attached or nearby component cooling line failure which could release a number of chemicals into the containment pool such as chromates, molybdates, nitrites, tolytriazole, benzotriazole and hydrazine.	Auxiliary component cooling systems and lines are engineered to withstand LOCA forces. Furthermore, the use of fluorides and chlorides inside containment is controlled so SCC of component cooling lines leading to failure is unlikely. Therefore this phenomenon is considered "N/A" for all time periods. Based on knowledge of plant design and limitations of materials used inside containment, the SoK is rated as "H."
8. Heat exchanger: secondary contaminants. Leaks in heat exchanger tubes allow secondary-side water additives to migrate over to the containment pool.	SG are engineered to withstand LOCA forces. Should a leak occur, the concentration of secondary system chemicals such as ammonia, hydrazine and morpholine are in the ppb to low ppm concentration range so the total mass of secondary chemicals added to the sump would be small. The impact of additives would be small or negligible. Therefore, this phenomenon is considered "N/A" for all time periods. Based on knowledge of plant design and limitations of materials used inside containment, the SoK is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
9. Corrosion due to containment spray containing NaOH. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, hydrogen, and for some plants NaOH.	The containment spray pH will be high and materials susceptible to corrosion at high pH such as aluminum will be attacked. The pH will be highest in NaOH plants when the NaOH is being added via the spray addition tank. Spray conditions will be less corrosive at later times when the pH and temperatures are lower due to mixing of the borated solution with NaOH. Experience from the ICET tests was that corrosion during spray was small or negligible compared to corrosion of submerged components (e.g., almost no weight change for unsubmerged coupons). Also, for short spray durations (between 30 sec and 4 h), the ICET data show that when coupons subjected to simulated spray are corroded, there is little release of the corrosion products into the spray run-off. At much longer spray durations there could be significant release of corrosion products into the runoff. However, long term, the temperature drops reducing the potential for corrosion. Therefore, this phenomenon is considered "N/A" for the time period P1 (containment spray has not actuated), "H" for time periods P2 and P3 (release of NaOH from its storage tank to the containment spray flow), and either "H" or "L" for time periods P4 and P5, depending upon termination of containment spray. The SoK was rated "M" because the amount of corrosion is dependent on the initial condition of the materials (i.e. existing protective oxides) and most studies have not used realistic plant materials.

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
10. Corrosion due to containment spray containing TSP. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, H, and TSP.	For TSP plants, the buffer is stored in "baskets" that facilitate the dissolution of the TSP when spilled coolant reaches the elevation inside containment to wet the TSP. The dissolution time is typically less than 1 hour after the LOCA. Thus, the initial containment spray will be slightly acidic, which will not aggressively corrode aluminum. When dissolved, the containment spray pH for TSP plants will be relatively benign (pH = 7-8) so corrosion is expected to be low. Also, TSP is known to inhibit corrosion of aluminum in this pH range. Data from the ICET tests demonstrated that corrosion during spray with a TSP buffer was small or negligible compared to corrosion of submerged components. Therefore this phenomenon is considered "N/A" for time period P1 and P2 (containment spray has not actuated and containment spray drawing from the RWST/BWST), "M" for time period P3 (release of dissolution of TSP in the spilled coolant), and "L" for time periods P4 and P5. The SoK was rated "M" because the amount of corrosion is dependent on the initial condition of the materials (i.e. existing protective oxides) and most studies have not used realistic plant materials.
11. Corrosion due to containment spray containing NaTB. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, H, and NaTB.	The containment spray pH for NaTB plants will be relatively benign (pH = 7-8.3) so aluminum corrosion is expected to be low. Experience from ICET tests was that corrosion during spray was small or negligible compared to corrosion of submerged components (i.e., almost no weight change for unsubmerged coupons). Therefore, this phenomenon is considered "N/A" for time period P1 and P2 (containment spray has not actuated and containment spray drawing from the RWST/BWST), "M" for time period P3 (release of dissolution of TSP in the spilled coolant), and "L" for time periods P4 and P5. The SoK was rated "M" because the amount of corrosion is dependent on the initial condition of the materials (i.e., existing protective oxides) and most studies have not used realistic plant materials.

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
12. TSP inhibits the corrosion of aluminum.	The inhibition of aluminum corrosion by phosphate and other species has been well studied. Internal work at Westinghouse, WCAP-16785 (Reference 29), showed significant inhibition of Al corrosion by phosphate. Other studies at higher temperatures have shown that at high pH solutions of TSP will corrode aluminum. Over the long term, TSP inhibition of corrosion of aluminum may significantly reduce aluminum as a source of chemical debris. Therefore this phenomenon is considered "N/A" for time period P1 (containment spray has not actuated and containment spray drawing from the RWST/BWST), "L" for time period P2 (filling the pool on the containment floor), "M" for time periods P3 and P4 (dissolution of TSP in the spilled coolant and for the first day of recirculation from the containment pool), and "H" for time period P5 (inhibiting aluminum corrosion over the long term). The SoK was rated "M" because the amount of corrosion is dependent on the initial condition of the materials (i.e., existing protective oxides) and most studies have not used realistic plant materials. The effect of pH on the extent of inhibition has also not been well characterized.
13. Corrosion of submerged source terms: inhibition due to fiberglass. Leaching of fiberglass inhibits corrosion of certain metals (e.g., aluminum).	The inhibition of aluminum corrosion by silicates is well known from previous testing and literature. The magnitude of the effect will depend on the concentration of silicate species in solution, which will increase gradually over the 30 day period. Quantification of the effect (i.e., the threshold concentration of silicate needed to cause inhibition) and better understanding of the rate at which fiberglass releases the necessary components into solution is needed. Internal work at Westinghouse, WCAP-16785 (Reference 29), shows significant inhibition of Al corrosion by silicate. Therefore this phenomenon is considered "N/A" for time period P1 (too short a time period for silicate inhibition to occur), "L" for time period P2 (time period is still short), "M" for time periods P3 and P4 (inhibition likely to begin within the first day of recirculation from the containment pool), and "H" for time period P5 (time for silicate inhibition to occur long term). A SoK of "M" was assigned because silicate chemistry is complex and more integrated effects tests are needed to get a better understanding of silicate inhibition.

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
14. Boric acid corrosion of exposed concrete. Boric acid solutions in contact with exposed concrete begin reacting.	This phenomenon is well understood and requires high concentrations of un-buffered boric acid. However, boric acid is not likely to be very corrosive to concrete since it is a relatively weak acid. Leaching from concrete does not appear to be a significant source term for chemicals in water compared to other sources (e.g., metal corrosion, leaching from fiberglass). This phenomenon may be more important before boric acid is buffered (when the solution is at lower pH), which only occurs for short times during time periods P1 and P2. Concrete corrosion rates were low in ICET testing and the WCAP-16530-NP-A (Reference 5) testing showed that concrete corrosion is low. The corrosion occurs at low pH values, so ranking was only done in the early part of the accident when low pH values are possible. The area of exposed concrete at most plants and under most LOCA scenarios will be small. Therefore this phenomenon is considered "L" for time periods P1 and P2 (sump pool is un-buffered) and "N/A" for time periods P3, P4 and P5 (sump pool is buffered). A SoK of "H" was assigned because of the availability of applicable industry data.
15. Injection of concentrated BAST fluid from charging or high pressure injection pumps causing boric acid corrosion of exposed concrete.	Phenomenon of interaction of boric acid with concrete is well understood. The proposed process requires direct discharge of un-buffered boric acid solution onto concrete. Even if this occurs, the area of exposed concrete is expected to be small. The amounts of materials released from the concrete are expected to be small compared to other inorganic sources in containment (e.g., fiberglass, etc). The boric acid is neutralized by buffers rapidly during a LOCA (generally within 1 hour) so this could only have an impact for a short time. See item 14. This phenomenon is rated as "L" for time periods P1 through and including P3 (until the buffer is fully dissolved in the containment pool) and "N/A" for time periods P4 and P5 (buffer is dissolved in the coolant pool). Based on knowledge of dissolution of buffer agents in the post-LOCA containment pool, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
16. Radiological reaction of Fe and Ni. Initial iron and nickel oxide breaks off due to the blowdown transient. Reduced Fe and Ni are dissolved in the RCS coolant, combines with air, oxidizes and forms iron hydroxides, and over the long term, hematite, maghemite, and magnetite, etc.	As noted in item 2, the amount of mobile iron oxide and nickel oxide in the RCS is limited to a few kg, so any secondary reaction that dissolves and then precipitates the iron and nickel oxides will have little effect. The dissolution and precipitation processes listed are very dependent on the surface area of the oxides, pH, temperature and redox conditions, and the sequence of changes described would likely evolve over days. Also, iron oxides are very insoluble and would not dissolve to any significant extent to contribute to solution chemistry. Therefore, while these processes are possible, the low amount of materials and the slow kinetics make them unimportant. Due to the very low concentrations and the slow kinetics for this phenomenon, it is rated as "L" for all five time periods. The power industry understands crud reactions well. Thus the SoK for this phenomenon is rated as "H."
17. Galvanic Corrosion. Electrical contact between metals results in the increased corrosion of the less noble metal.	Galvanic corrosion effects are well understood, and depend on factors such as the relative surface areas of the materials, their physical separation, and the nature of the contacts (e.g., resistance of any surface oxides between the two materials). As galvanic couples are avoided in the design of piping systems, this phenomenon will only occur accidentally, (e.g., two dissimilar metals in electrical contact become immersed in the sump pool, two pieces of metal fall into contact, except as identified below). Factors such as physical separation and contact resistance will likely make this effect of only minimal significance. As noted above, galvanic couples are avoided in containment, except for the intentional couple in galvanized steel and zinc-based coatings. Galvanized steel corrosion in post-LOCA chemical environments was studied in WCAP-16530 (Reference 5) and found to be insignificant. Based on the discussion above, this phenomenon is rates as "L" for all five time periods. Based on knowledge of galvanic cells and the discussion above, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
18. Cable degradation. The insulation surrounding electrical cables located throughout containment is affected by radiolysis, releasing chlorides.	Polyvinyl chloride insulation degradation will release hydrochloric acid (HCl), which will depress the pH of the coolant pool and increase corrosion. If the pH of the recirculating coolant solution decreases, the potential for precipitation after corrosion has occurred may also increase. If the pH was to become very acidic, additional corrosion reactions may become important. However, cable degradation occurs at relatively high dose rates. Rates of HCl release have been predicted in previous modeling and the quantities appear to have little effect on the pH because of the presence of buffers in the sump fluid. Thus, this phenomenon is rated as "N/A" for time period P1 (too short a time to have an effect), "L" for time periods P2, P3 and P4 (again, short time periods) and "M" for time period P5 (long-term exposure). An SoK of "M" reflects uncertainty in the amount of radiation that will be present post-LOCA.
19. Fiberglass leaching. Fiberglass-based insulation products begin leaching constituents (e.g., silicon, aluminum, magnesium, calcium, etc.)	The leaching of the constituents of glasses is well understood. Fiberglass dissolution will be significant due to the high surface area available, particularly at high pH. Fiberglass dissolution releases various silicate species that can lead to inhibition of aluminum corrosion. Other products (e.g., calcium, etc) can lead to precipitate formation in the presence of TSP. Fiberglass dissolution is fairly well understood and rate equations as a function of temperature and pH are available from previous testing. Its importance will increase with the time that the fibers are exposed to the ECCS water. This phenomenon is rated as "L" for time period P1 (short exposure time), "M" for time period P2 (again, short exposure time), and "H" for time periods P3, P4 and P5 (long-term exposure). There is a very large knowledge base on dissolution of glasses due to the extensive use in a large number of industries and the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
20. Seal abrasion of ECCS pumps. Abrasive wearing of pump seals (e.g., magnetite - high volume/concentration of mild abrasive) may create additional materials that contribute to sump pool chemistry or particle loading.	Phenomenon well understood and evaluated using the methods of WCAP-16406-P-A (Reference 4). Seals are typically constructed from wear-resistant materials. The amount of additional material that could be released is small. This phenomenon is rated as "N/A" for time periods P1 and P2 (no debris in the coolant pumped from the Refueling/Borated Water Storage Tank) and "L" for time periods P3, P4 and P5 (accounts for material properties of the seals and the amount of seal material in pumps). Based on knowledge of pump design and materials used for seals, the SoK for this phenomenon is rated as "H."
21. Dissolution of exposed, uncoated concrete. Dissolution can result in locally high pH (depending on surface area) relatively quickly.	Release of materials due to dissolution of concrete is well understood and is low compared to other materials that contribute to solution chemistry (i.e., fiberglass). The increase in pH associated with concrete dissolution is a well-known phenomenon. However, there is not much exposed concrete in most PWR. This phenomenon is rated as "L" for time period P1 (due to the short duration of this time period) and "M" for time periods P2, P3, P4 and P5 (due to the longer time duration allowed for possible dissolution of concrete). Based on the available data on concrete dissolution, the SoK for this phenomenon is rated as "M."
22. Dissolution of protective coatings. Dissolution and leaching of epoxy, alkyd, or zinc-based coatings and primers may occur. Submerged source terms: protective coatings. Leaching of submerged coatings may contribute species to the containment pool. Possible sources include lead-based paints (in older containment buildings), phenolics and PVC.	Most protective coatings are qualified and degradation studies have been conducted. Leaching of epoxies was evaluated and demonstrated to be negligible in WCAP-16530-NP-A (Reference 5). The bulk of the polymers used in containment will not decompose rapidly at temperatures expected after a LOCA. However, not much is known about the slow leaching of containment polymers over long periods per Reference 30. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period), "L" for time periods P2 and P3 (again, due to the relatively short duration of these time periods) and "M" for time periods P4 and P5 (due to the longer time duration of these periods that could allow slow dissolution of coatings). Based on the available data for coating dissolution, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
23. Corrosion due to boric acid. Boric acid pooled on unsubmerged portions of large ferritic steel components (e.g., piping RPV, pressurizer, and steam generator) continues to cause corrosion of these materials.	Boric acid corrosion has been studied extensively and EPRI has issued a guidebook addressing the issue. In the case of post-LOCA corrosion of unsubmerged portions of large ferritic steel components, the most likely corrosion period is when the pH is low. This is prior to buffering of the coolant pool on the containment floor. Regardless of whether the buffering is accomplished by NaOH addition to containment spray or by passive dissolution of a buffer agent, the time for active corrosion is limited. Once the coolant is buffered, corrosion rates will be low. At later time periods, particularly if containment sprays are terminated, it is unlikely that there is an active transport mechanism to move corrosion products to the coolant pool on the containment floor. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to either short time durations or the coolant pool being buffered). Based on the available data for boric acid corrosion of unsubmerged ferritic steel components, the SoK for this phenomenon is rated as "H."
24. Corrosion source terms from unsubmerged materials. Corrosion of various materials (Al, Fe, concrete, Cu, Zn) due to condensation and transport into containment pool. Condensation is expected due to non-uniform containment environment temperatures.	Condensed water (having been distilled) will be relatively benign toward materials as it will be near neutral pH and therefore will not have the corrosive properties of the pool solution. It is not expected to contribute much as a source term. Transport of existing corrosion products due to condensation might be significant if condensation continues for long time periods. Containment spray, when operating, will dominate wetting of un-submerged surfaces. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the near-neutral pH of the condensate). Based on available data on the benign behavior of condensate (distilled water) on corrosion in general, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
25. Corrosion from submerged source terms and lead shielding. Acetates present in containment pool may dissolve lead, which could lead to formation of lead carbonate particulate. Lead blanketing to shield hot spots and covered with plastic coating, but coating likely destroyed. There may be several hundred pounds of lead in flat sheets. Some plants still use lead wool.	Lead corrosion is well understood. The source term for acetate in the pool is not well identified and the development of significant concentrations of acetates post-LOCA is unlikely. Lead carbonates are fairly insoluble, so precipitates could form if enough lead were to be dissolved. However, the lead blankets are protected by robust plastic coatings that are unlikely to be damaged unless directly hit by a jet flow in close proximity to the break. The PWROG jet impingement testing of lead blankets has demonstrated the robustness of the plastic coating of lead blankets. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short duration of these time periods), and "L" for time periods P3, P4 and P5 (due to the unlikely existence of acetates in the post accident pool and the robustness of the plastic cover of the lead blankets). Based on the available data for corrosion of lead and the construction of the lead blankets, the SoK for this phenomenon is rated as "M."
26. Corrosion from submerged source terms: copper. The concern is not with copper compounds, but the effects that copper may have on other corrosion processes. Copper concentrations evaluated in ICET program. Cu comes from containment air coolers, motor windings and grounding straps. (Fan coolers and motors are typically not submerged.)	The effects of copper on corrosion of other materials are well understood. It is not expected that there will be significant concentrations of copper in the pool water. Copper corrosion rates in ICET testing were quite low, and ICET tests did not indicate much release of copper into solution. Therefore, copper corrosion is expected to be small or negligible (a second order effect). If copper corrosion products were in the coolant pool, it is possible that there would be a reduction of corrosion rates of other materials, which might lead to a beneficial effect for the concentrations of materials that might precipitate in the core during boiling (i.e., aluminum, etc). This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period), and "L" for time periods P2 through and including P5 (due to the low likelihood of corrosion of copper by the post-LOCA sump fluid). Based on the available data for corrosion of copper, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
27. Corrosion from submerged source terms: iron. Boron inhibits pitting corrosion on the surface of steel structures. Iron concentrations evaluated in the ICET program.	Corrosion of iron and steels is well understood. Iron release/precipitation was evaluated in the ICET program. Uncoated steel only lost significant weight in ICET Test #1 (high pH, NaOH with fiberglass insulation). In the other four (4) tests, corrosion of uncoated steel was found to be insignificant (iron was never measured in solution and steel coupons that were either galvanized or coated with IOZ coating never exhibited a weight loss - galvanized steel coupons exhibited a weight gain when TSP was present, possibly due to the formation of zinc phosphate, as identified in recent tests). Therefore, corrosion of submerged iron is considered a second order effect and is not an important contributor to post-LOCA pool chemistry. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period), and "L" for time periods P2 through and including P5 (due to the very low corrosion rates of submerged iron in the post-LOCA sump fluid). Based on the available data for corrosion of submerged iron in post-LOCA coolant, the SoK for this phenomenon is rated as "H."
28. Corrosion from submerged source terms: aluminum. Less dissolved aluminum than was observed in ICET #1 affects the type and quantity of chemical byproducts that form at high pH values.	Aluminum corrosion and precipitation is well understood. Aluminum corrosion is a key contributor to the formation of precipitates in the core (aluminum hydroxide and aluminum oxy-hydroxide) and, when captured on a fiber bed through which water is attempting to flow, can cause high head loss. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period), and "H" for time periods P2 through and including P5 (due to the effect of aluminum corrosion products on head loss across a fiber bed). Based on the available data on the effects of aluminum corrosion on head loss across fiber beds, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
29. Corrosion from submerged source terms: zinc corrosion products. Zinc oxide, hydroxide, phosphate or silicate is potential precipitates.	Phenomenon well understood. Zinc is not considered important for chemical effects since zinc corrosion was not observed to be a significant issue in ICET tests. Galvanized steel has shown some corrosion in laboratory testing, but even when it occurs, the corrosion product release rate has been low. Current tests (CHLE tests) indicate that zinc precipitates form on corroding surfaces and are not released into solution or transported to a significant degree. Halogens accelerate the process, but halogens will not be released (due to degradation of electrical cable insulation) until late in the LTC period. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of these time periods), "L" for time periods P2, P3 and P4 (due to the low corrosion rates and low release rates) and "M" for time period P5 (due to the long-term release of halogens). Based on the available data on the effects of zinc corrosion and the ongoing CHLE tests, the SoK for this phenomenon is rated as "M."
30. Corrosion of submerged source terms: zinc coprecipitation. Zinc may coprecipitate with other species such as iron and aluminum. The reactor vessel is a possible site for coprecipitation.	Phenomenon well understood. Zinc is not considered important for chemical effects. Zinc compounds with aluminum and iron such as Franklinite are not common in nature and are not found at high concentrations in PWR sludge or crud. Zinc oxides and carbonates and silicates would form preferentially under most circumstances. If zinc is coprecipitating, the amount of material involved with zinc coprecipitation is likely to be small relative to precipitation of other compounds (e.g., aluminum) is likely to have the most significant impact. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time periods), "L" for time periods P2, through and including P5 (due to the unlikely formation of compounds combining zinc with aluminum and iron). Based on the available data on the effects of zinc coprecipitating with other metals, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
31. Zinc hydroxide dissolution (zincate). The coolant in the buffered pH containment pool may dissolve zinc hydroxide so that other species, particularly silicates, may precipitate.	Zinc hydroxide is not found in significant amounts in containment. Zinc hydroxide is fairly insoluble. It is unlikely that the dissolution of zinc hydroxide could lead to the formation of other precipitates. This phenomenon is rated as "N/A" for time periods P1 through and including P5 (due to the small amount of zinc hydroxide inside the containment and the unlikely dissolution of zinc hydroxide). Based on the small amount of zinc hydroxide inside containment and the available data on the effects of zinc hydroxide dissolution, the SoK for this phenomenon is rated as "N/A."
32. Corrosion of submerged source terms: zinc passivation. Zinc passivation decreases corrosion of iron.	Passivation phenomena are well understood. Zinc is used to inhibit corrosion of other materials (i.e. galvanizing), so the presence of zinc could have the beneficial effect of reducing concentrations of other materials that are released into solution. Unlikely to be of any importance for materials other than galvanized steels with a damaged coating. However, iron corrosion rates are expected to be low under post-LOCA pH conditions, so this is a second order effect and is not considered important. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time periods), "L" for time periods P2 through and including P5 (due to the second order effect of zinc passivation in the post-LOCA environment). Based on the available data on the effects of zinc passivation, the SoK for this phenomenon is rated as "H."
33. Corrosion from submerged source terms: zinc-based coatings. Leaching of elemental zinc-based primers may result in additional dissolved zinc in solution.	Zinc in solution may inhibit corrosion of other materials due to passivation (see item 30). This would be a beneficial effect. However, post LOCA laboratory corrosion testing has not shown elevated zinc concentrations. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time periods), "L" for time periods P2 through and including P5 (due to the second order effect of zinc passivation in the post-LOCA environment). Based on the available data on the effects of zinc passivation, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
34. Additional source term: bottom mounted instrumentation corrosion. Multiple materials in equipment related to bottom mounted instrumentation (e.g., stainless steel, plastics, organics) may lead to formation of dissolved species. Portions of the bottom mounted instrumentation equipment (mainly instrument/guide tubes, depending on plant design) are located at an elevation below the bottom of the core. At this elevation, the instrument/guide tubes penetrate the lower vessel head and support the instrumentation from the core to the pressure isolation location. Any bottom mounted instrumentation components located below the vessel or containment pool or those which can be exposed to spray may act as a corrosion source term.	Surface areas are small. Seal table materials are corrosion resistant, so corrosion releases from these materials should be small. Dissolution/corrosion rates of relevant materials well understood. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time periods), "L" for time periods P2, through and including P5 (due to the small amount of corrosion-resistant nature of the materials used in the seal table). Based on the available data on the seal table materials, the SoK for this phenomenon is rated as "M."
35. Additional submerged source terms: fire barriers. Silicone-based seals (bisco seals) are used at many structural penetration points as fire barriers. These may leach in post-LOCA environment.	Surface areas are small, and fire barrier materials are fairly resistant to chemical attack. Silicones used for this purpose are resistant to hydrolysis up to 400°F and are radiation resistant. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time periods), "L" for time periods P2 through and including P5 (due to the small surface areas and inert behavior of fire barrier and silicon materials). Based on the available data on the fire barrier and silicone materials, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
36. Submerged source terms: organic buoyancy. Organics coat materials (e.g., aluminum, calcium silicate, fiberglass, etc.) and increase the buoyancy of particulates so that they are more likely to float.	The concentrations of organics are expected to be low, while the surface area of the debris will be high. Floating could cause particles to stay in the containment pool and not enter the ECCS pump suction because they would remain above the strainers. This behavior, if it were to occur, would reduce the supply of particles that could clog the strainers or the core. However, the quantity of organics is expected to be low. Also, the average binder content of fiberglass (<10%) is so low that the particulates will still have a specific gravity greater than 1. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period), "L" for time periods P2, through and including P5 (due to the small source of organic materials inside containment). The SoK for this phenomenon is rated as "H" because enhanced buoyancy of particulates due to organic coatings is well understood.
37. Submerged source terms: formation of biofilm. Biofilms form which protect against metallic corrosion (by forming passive layer) or lead to production of acids which increase metallic corrosion. Some biofilms may be preexisting in containment from outages.	Corrosion effects due to biofilms are well understood. It will take some time for biofilms to form and the post-LOCA sump conditions are not likely conducive to biofilm formation. Thus, the quantity of biofilm expected inside containment post-LOCA is very low or negligible. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short duration of these time periods), "L" for time periods P3 through and including P5 (due to the unlikely formation of biofilms inside containment post-LOCA). Based on the available data on the formation of biofilms inside containment post-LOCA, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
38. Submerged source terms: biological growth in debris beds. Bacteria may grow in preexisting debris beds located on the sump strainer screen or elsewhere within the ECCS system.	The quantity of biofilm that is expected to form post-LOCA in debris beds inside containment early in the accident is very low or negligible Temperatures do not favor biofilm growth early in an accident. At later times, biofilm of low permeability may develop within fibrous debris beds (Biotechnology and Bioengineering 109, p1013 (2012)). This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short duration of these time periods), and "L" for time periods P3 through and including P5 (due to the unlikely formation of biofilms inside containment post-LOCA due to the low nutrient environment in the sump and the elevated radiation levels). Based on the available data regarding the formation of biofilms inside containment post-LOCA, the SoK for this phenomenon is rated as "M."
39. Submerged source terms: biologically enhanced corrosion. General corrosion is enhanced due to biological agents. Examples include polysaccharides and sulfate reducing bacteria which may enhance iron corrosion. Sulfur or carbon sources contribute to bacteria formation.	The quantity of biofilm formed inside containment post-LOCA is expected to be very low or negligible. Biologically enhanced corrosion is usually a slow process and containment conditions favor sterilization early in an accident. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short duration of these time periods), and "L" for time periods P3 through and including P5 (due to the unlikely formation of biofilms inside containment post-LOCA). Based on the available data regarding the formation of biofilms inside containment post-LOCA, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
40. ECCS Pumps: erosion/corrosion. Chemical byproducts cause erosion or corrosion of pump internals, especially tight tolerance components (bearings, wear rings, impellers, etc.).	The chemical environments leading to pump seal degradation are well understood. This is only an issue when significant concentrations of chemicals are present and the pumps have started. Excluding sodium hydroxide, most of the chemicals in the sump pool are not corrosive at the concentrations present in the pool. The chemical precipitates predicted to be formed will be amorphous and too soft to cause erosion. Also, the concentration of chemical precipitates is expected to be very low compared to other types of particulate debris. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to ECCS suction being taken from the RWST/BWST during these time periods), and "L" for time periods P3, through and including P5 (due to the unlikely contribution of chemical byproducts to erosion/corrosion of pump internals). Based on knowledge or available data regarding the design of ECCS pumps and erosion/corrosion of pump internals, the SoK for this phenomenon is rated as "H."
41. ECCS Pumps: seal degradation. Chemical environment causes leaching/degradation of pump seal materials.	The chemical environments leading to pump seal degradation are well understood. This is only an issue when significant concentrations of chemicals are present and the pumps have started. Most of the chemicals in the sump pool are not corrosive. Chemicals in pool solution would not be expected to cause degradation of elastomeric materials. The volume/area of pump seals is small so the potential contribution of this phenomenon, if it were to occur, is insignificant relative to other debris source terms. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to ECCS suction being taken from the RWST/BWST during of these time periods), and "L" for time periods P3 through and including P5 (due to the post-LOCA sump fluid not being likely to cause chemical degradation of pump seal materials). Based on knowledge or available data regarding the design of ECCS pumps and pump seal degradation, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
42. Transport phenomena associated with metallic scouring. Turbulent flow causes chemical films and products to be scoured off the surface of metallic components so that they enter the containment pool.	The phenomenon is relatively well understood and can be modeled. Unless there is an impinging turbulent jet, shear rates will not be high enough to remove films either in the containment pool or within the ECCS. This phenomenon is likely to occur only if weakly adherent films are subjected to turbulent flow. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the relatively low flow rates in the containment pool). Based on the available data on the nature of flows and fluid velocities within the pool and within the ECCS system, the SoK for this phenomenon is rated as "M."
43. Mass transport of the dissolution products away from the surface, creating a concentration gradient that promotes dissolution (flow accelerated corrosion).	This phenomenon is well understood. Convective mass transport moves corrosion products away from the surface, thereby enhancing their dissolution rate and promoting further corrosion. Models exist to predict this behavior, although the velocity across the surface must be estimated to use the models. In regions where there is limited convective mass transport, high local concentrations of corrosion products could limit their dissolution (and hence further corrosion) by reaching the solubility limit. Flow accelerated corrosion is not expected to be important in the normal sense because either flows are weak or materials are resistant to flow accelerated corrosion (e.g. stainless piping). However, maintaining some mass transport away from corroding surfaces is an integral feature of corrosion product release and chemical product formation. This phenomenon is rated as "H" for time periods P1 through and including P5 (due to the importance of this phenomenon in generating corrosion products in sufficient quantity to be of concern). Based on the current understanding of mass transport of the dissolution products away from a corroding surface, the SoK for this phenomenon is rated as "H."
44. Jet impingement. Water jet & fine debris within the jet may impact surfaces and chip coatings. This will increase the surface area available for chemical reactions.	This phenomenon can create particulate matter only during time period P1. However, jet impingement testing has not shown much damage to coating materials, and the area of direct jet impingement is small compared to the area inside containment. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the lack of damage to coatings materials arising from jet impingement). Based on the available data on jet impingement damage to coatings, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
45. Straining removes materials at the strainers, preventing full loading of debris in the core.	This phenomenon is well understood. Once the ECCS is aligned to operate to recirculate coolant from the containment sump, debris removed from the ECCS flow by the strainers is not available to deposit in the core. As the debris bed ages, some trapped material could penetrate the screen and be ducted to the core. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to ECCS suction being taken from the RWST/BWST during these time periods), "H" for time period P3 and P4 (during which the debris bed is expected to form) and "M" for time period P5 (when the debris bed is fully formed and only "shedding" of debris from the formed bed is expected). Based on the available data on the performance of sump screens with debris loads, the SoK for this phenomenon is rated as "H."
46. If surface deposition dominates bulk precipitation, large fiber debris sources scavenge inventory	This phenomenon will be very important once the fiber bed forms, as it provides a mechanism for removal of chemical precipitants from water before they reach the core. The large surface area of the fibers means that heterogeneous precipitation on the fibers (and particles) will dominate homogeneous precipitation in solution. Location for precipitation is very important and dictates whether a particular precipitate has the potential to interfere with core cooling. If precipitation occurs in the pool, it can be captured at the strainer (item 43), which prevents it from getting to the core. If it occurs on surfaces, such as within heat exchangers, it may not be available to be transported to the core. The formation of precipitate on surfaces will be the dominant precipitation mechanism if the level of super-saturation is low. This is expected to be the case except for locations within and after heat exchangers where super-saturation may be high and fiber debris sources will not be present in large quantities. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to ECCS suction being taken from the RWST/BWST during these time periods), and "H" for time periods P3 through and including P5 (during the recirculation of coolant from the containment pool by the ECCS). Based on the available data regarding surface deposition, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	**Rationale for Ranking**
Coolant Chemistry	
47. RCS coolant boron concentration at the time of the break. The RCS coolant chemistry varies over the fuel cycle with boron concentrations ranging from about 2000 ppm at the beginning of the fuel cycle to near 0 ppm at the end of the fuel cycle.	This is only important during time period P1 when no other source of boron exists. Corrosion of some materials depends strongly on the boron concentration. This phenomenon is well understood and rate equations have been developed from previous testing for material corrosion due to the presence of boron. This original RCS boron concentration will eventually be swamped by contributions from other sources. This phenomenon is rated as "H" for time period P1 (due to the RCS inventory being the only source of boron during this time period), "M" during time period P2 (when boron is being added to the containment pool by the accumulators and the Refueling/Borated Water Storage Tank) and "L" for time periods P3 through and including P5 (when there is no boron addition). Boron concentrations are measured and well controlled, so the SoK for this phenomenon is rated as "H."
48. RCS coolant lithium concentration at the time of the break. The RCS coolant chemistry varies over the fuel cycle.	The expected lithium concentrations are well understood. Lithium will be a minor component of the post-LOCA coolant since it is typically present during normal operation at concentrations between 0.1 and 3.2 ppm. It will have an initial influence only during the short period between blow down of the RCS and a few minutes later when coolant from safety injection and the pH buffer set the pH. Lithium has almost no effect on precipitation (it is not a component of the precipitates of interest), its concentrations are generally low, and can lead to an increase in pH during the periods when the boron and other chemical concentrations are near zero. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the low concentration of lithium expected post-LOCA). Based on the knowledge or available data regarding lithium content and behavior in the coolant post-LOCA, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
49. RCS coolant pH variability. pH of the coolant at 60°C at beginning of fuel cycle is acidic (pH ≅ 6) and is alkaline (pH ≅ 9) at end of the fuel cycle. The pH variation is less at higher temperatures.	pH is an important factor in determining corrosion rates. The expected pH variation is well understood and controlled. pH can be calculated from the solution chemistry. The period of post-LOCA pH variability due to RCS operating chemistry will be very short. Once the safety injection system contributes significantly to the sump volume, the influence of the operating RCS chemistry will be swamped out. This phenomenon is rated as "H" for time period P1 (due to the pH of the RCS break flow being determined by the pH of the RCS inventory during this time period), "M" during time period P2 (since pH of the RCS inventory is mitigated by the pH of the accumulators and the RWST/BWST) and "L" for time periods P3 through and including P5 (when no additional inventory is being added to the sump pool). The pH of the coolant sources are measured and controlled, so the SoK for this phenomenon is rated as "H."
50. Coolant TH conditions of the coolant expelled from the break. Localized boron concentration in break flow jet. Droplet evaporation within the high temperature jet emanating from the pipe break may form a concentrated boron aerosol solution. As boron concentrates at high temperatures (250°C – 300°C), a polymerization appears to occur that releases protons and causes the system to become more acidic as it discharges from the break.	The average boron concentration increase will be small enough that the pH drop due to polymerization will be at most a few tenths of a pH unit, not enough to cause a large change in corrosion rates. The area directly impacted by the portion of the break flow jet having a high concentration of boron will be small. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the small change in pH associated with the break flow thermal hydraulic conditions). Based on the knowledge or available data regarding the thermal hydraulic conditions of the break flow, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
51. ECCS injection of boron. After the break and as the RCS depressurizes, boron is injected in coolant from accumulators and the RWST/BWST. There is some variability from plant to plant (2400-2700 but could be up to 4500). High local concentrations could exist.	This phenomenon is of some importance before the pH buffering agent has been fully added to the coolant pool. The presence of boron in the pool water has a significant effect on aluminum corrosion. It also increases the ionic strength of the water. There may be a small effect of boron concentration that is independent of pH. Boil-off in the core will lead to locally high boron concentrations that can lead to local blocking. This phenomenon is rated as "L" for period P1 because the injection is just beginning and "M" for time periods P2 and P3 (due to dissolution and/or mixing of buffer with the pool inventory) and "L" for time periods P4 and P5 (when addition of borated water and the dissolution and/or mixing of buffer is complete). Based on knowledge or available data regarding the thermal hydraulic conditions of the break flow, the SoK for this phenomenon is rated as "H."
52. RCS fluid shifts towards an oxidizing environment. If the coolant is released as a super heated spray through the break, hydrogen (25 –35 cc/kg of H2 injected as gas) is released as a gas. Oxygen from the containment atmosphere is absorbed into the coolant.	The oxidizing power of the coolant will affect corrosion rates of some materials (e.g., alloys containing Ni, Fe and Cr), and will affect the solubility of some precipitates. Iron is not a major concern in a coolant pool post-LOCA. Some important containment materials such as aluminum will react with water over a wide range of reduction/oxidation (i.e., redox) potentials and the effect of dissolved hydrogen and oxygen on such materials will be small. Dissolution of non-metallic insulation materials and concrete will also not be influenced by dissolved gasses. This phenomenon is rated as "M" for time periods P1 through and including P5 (due to the small effect of redox potential over all time periods on aluminum corrosion). Based on the knowledge or available data associated with redox conditions, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
53. Radiolytic environment exists inside the containment. Radiolysis reactions change the coolant's redox potential.	As noted in Item 50, the redox potential of the coolant will only affect some materials such as iron and nickel-based alloys. However, iron and nickel reactions are not a concern post-LOCA. The reactions of interest are aluminum corrosion and glass dissolution, and they do not have strong dependencies on redox conditions of the coolant pool. Thus, radiolysis has a secondary effect on corrosion and dissolution of interest post-LOCA. This phenomenon is rated as "L" for time period P1 (short duration) and "M" for time periods P2 through and including P5 (due to the small effect of radiolysis on corrosion and dissolution over these time periods). Based on the knowledge or available data associated with radiolysis effects, the SoK for this phenomenon is rated as "M."
54. Radiolysis of CO2 and carbonates could lead to the formation of organic acid ligands (e.g., acetate, butyrate, and oxalate).	In the presence of oxygen, formation of oxalate is possible, but this is not considered significant. The relatively low concentrations of carbon dioxide and carbonates preclude reduction reactions to form significant amounts of more complex organics. Formic acid may be generated. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to small effect of radiolysis over all time periods on aluminum corrosion). Based on the knowledge or available data associated with radiolysis of CO_2 and carbonates, the SoK for this phenomenon is rated as "H."
55. Radiolysis promotes formation of carbonates.	This phenomenon is well understood. Over time most organics will be decomposed into CO_2. In an unbuffered system this will lower the pH. In a buffered system this will lead to increased concentrations of carbonate and or bicarbonate ions that could form precipitates. Carbonates can lead to buffering and affect the pH of the solution. This phenomenon is rated as "N/A" for time period P1 (short duration), "L" for time period P2 through and including P5 (organics in coolant likely small fraction of total debris). Based on the knowledge or available data associated with radiolysis effects, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
56. Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.	The significance of this phenomenon will depend strongly on the extent of release of fission products, actinides and activation products and their transport to the debris bed. Could become important in P4 and P5. High local production of oxidants could damage the debris bed, as could direct radiation damage to the debris. If the conditions in a debris bed are different from the bulk coolant, precipitation within the bed might be promoted. This could have a large effect at the core inlet or at a sump screen where flow through a debris bed is needed for core cooling. This phenomenon is rated as "N/A" for time periods P1 and P2 (recirculation through the containment sump has not begun), "M" for time period P3 (relatively short time period) and "H" for P4 and P5 (longer time for collection of radioactive materials and development of radiation fields). Based on the knowledge or available data associated with radiation-induced reactions with post-LOCA coolant and debris, the SoK for this phenomenon is rated as "L."
57. Hydrogen peroxide (H2O2) effects. H2O2 will behave much the same as H2O. Most of it will remain in the liquid phase. Some hydrogen peroxide may evaporate into the containment vapor space and may then cause additional corrosion. If it condenses on cooler surfaces hydrogen peroxide may accelerate corrosion.	Hydrogen peroxide is produced by water radiolysis and it does not travel far from the core. Concentration released into the vapor phase will be low. Hydrogen peroxide could lead to increased corrosion, but at high temperatures H_2O_2 would be expected to degrade to H_2O fairly rapidly. The greatest influence of hydrogen peroxide would likely be an increase of the corrosion rate of copper alloys. However, the boiling point for hydrogen peroxide is near 150°C, which is not greatly different from that for water. Thus, highly concentrated solutions would not be expected to form on cool copper surfaces. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the expected degradation of H_2O_2 into H_2O). Based on the knowledge or available data associated with the behavior of H_2O_2, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
58. Radiological effects: corrosion rate changes. Radiolysis of Cl-bearing water leads to formation of hypochlorite. This could increase corrosion rates (especially pitting corrosion) of aluminum, stainless steel and iron.	Typically the concern with chlorine species and corrosion is localized corrosion phenomena such as pitting or cracking, and these can be initiated at low concentrations. Hypochlorite could lead to increased corrosion, but it would depend on the amount of hypochlorite that was formed. While these degradation mechanisms will have an effect on the ability of a plant to be restarted in the future, they will have little effect (compared to the effects of pH and temperature) on general corrosion/dissolution processes unless the concentration becomes quite high. While concentrated hypochlorite can attack many containment materials (even stainless steels), only low concentrations of hypochlorite are expected to form in the post-LOCA containment environment. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short duration of these time periods), and "L" for time periods P3 through and including P5 (due to expected low concentrations of chlorine species inside containment post-LOCA). Based on the knowledge or available data associated with availability of chlorine species inside containment post-LOCA and the behavior of hypochlorite, the SoK for this phenomenon is rated as "M."
59. Hydrogen sources within containment. Hydrogen concentrations in vapor and containment pool include the RCS inventory, Schikorr reaction and release from corrosion of metallic materials.	Hydrogen sources in containment are well understood. Hydrogen may alter the redox potential of the pool water. Most of the important containment materials and the reactions of interest are not strongly sensitive to redox conditions. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the weak expected influence of hydrogen on the reactions of interest). Based on knowledge or available data associated with the behavior of H_2 on reactions of interest, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
60. Rate of release of NaTB pH control agent. Released to pool on containment floor with melting of ice beds or dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	The rate at which NaTB is released determines the evolution of the pool pH and borate concentration. The pool pH, in turn, affects most corrosion/dissolution and precipitation reactions. All of the NaTB will be dissolved within the first hour of an accident, so the release rate will drop to zero. This behavior of NaTB is well understood. This phenomenon is rated as "L" for time period P1 (since NaTB is not yet dissolving), "M" for time period P2 (when NaTB is beginning to dissolve), "H" for time period P3 (when NaTB is completely dissolved) and "N/A" for time periods P4 and P5 (when NaTB has been completely dissolved and the phenomenon associated with the release rate of NaTB has been terminated). Based on the knowledge or available data associated with the dissolution of NaTB, the SoK for this phenomenon is rated as "H."
61. Rate of dissolution of TSP for pH control. Released to pool on containment floor due to dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	Release rate of TSP determines the evolution of the pool pH, which affects most corrosion, dissolution and precipitation reactions. The rate of TSP dissolution and subsequent mixing within the sump is particularly important for situations where calcium-rich debris such as Cal-Sil is present. If TSP dissolves quickly and is thoroughly mixed with the sump pool, further dissolution of calcium containing debris will be inhibited. However, if TSP dissolves slowly, then calcium concentrations would increase more rapidly, and calcium phosphate precipitation in solution would occur to a greater extent when the sump was mixed. The dissolution of TSP is well understood. This phenomenon is rated as "L" for time period P1 (since TSP is not yet dissolving), "M" for time period P2 (when TSP is beginning to dissolve), "H" for time period P3 (when TSP is completely dissolved) and "N/A" for time periods P4 and P5 (after TSP has been completely dissolved and the phenomenon associated with the release rate of TSP has been terminated). Based on the knowledge or available data associated with the dissolution of TSP, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
62. Dilution of TSP or NaTB within the sump pool. Locally high concentration and high pH may exist initially, but sump mixing over time dilutes the locally elevated concentrations.	Locally high concentrations (or regions that are unbuffered) may exist until pool mixing is complete. pH variations will lead to difference in corrosion/dissolution and precipitation rates. Duration of effects due to unmixed conditions would be relatively short. Debris in the immediate vicinity of buffer baskets will be subjected to a brief period of elevated pH as the basket contents dissolve. The elevated pH solution will also be denser than the bulk solution, so it will tend to remain deep in the pool, along with denser debris that has entered the pool. The effect will be more pronounced with TSP, since it is the stronger base. The effect will still be only of moderate importance because of the limited volume which will be affected, and because recirculation will quickly erase this phenomenon. This phenomenon is rated as "N/A" for time period P1 (since the buffer is not yet dissolving), "L" for time period P2 (when the buffer is beginning to dissolve), "M" for time period P3 (when the buffer is completely dissolved) and "N/A" for time periods P4 and P5 (after the buffer has been completely dissolved and has been mixed with the containment pool inventory). Based on the knowledge or available data associated with the dissolution of the buffer and turn-over of the containment pool, the SoK for this phenomenon is rated as "M."
63. TSP limits the concentration of alkaline earth elements in solution by precipitation in the sump. This precipitation may be collected on the sump screen debris bed, reducing the amount available to transport to and precipitate in the core.	Phenomenon is relatively well understood as are the precipitates, although the precipitation kinetics may not be. Important at later stages (P4 and P5) when significant dissolution of alkaline earths has occurred. TSP is commonly used in fossil boilers to control precipitation on surfaces. Adding TSP encourages homogeneous precipitation. Suspended alkaline earth phosphate solids can then be removed by blow down. In the post-LOCA environment where TSP is used, it is likely that most of the alkaline earth precipitation will occur in the sump, and will settle or be removed by the sump screen. This phenomenon is rated as "N/A" for time period P1 (when TSP is not yet dissolving), "L" for time periods P2 and P3 (when the buffer is dissolving and mixing with the pool), "M" for time periods P4 and P5 (when the buffer is completely dissolved and mixed with the containment pool inventory and has had time to form alkaline earth precipitates). Based on the knowledge or available data associated with the behavior of TSP and its interaction with alkaline earths, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
64. Localized high concentrations of chemicals at the sump screen. High localized concentrations of certain species may drive the reaction efficiency at the sump screen.	Where there is flow through the debris bed, localized chemistry variations will be small or will not exist. Solids that have collected at the sump screen will react with the coolant just as the case with debris elsewhere in containment. The fluid within the sump screen debris bed may contain somewhat higher than average concentrations of certain reaction products than average, but flow through the debris bed will tend to limit the concentration process. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short time available for chemical reactions to occur) and "L" for time periods P3 through and including P5 (when debris bed on the sump screen is built and flow through is established). Based on the knowledge or available data associated with the behavior of debris beds and the flow that will be maintained through the bed, the SoK for this phenomenon is rated as "L."
65. Localized chemistry alters the fiberglass contribution to the chemical environment at the sump screen.	Where there is flow through the debris bed during periods P3 through P5, localized chemistry variations will be small or will not exist. Leaching of materials from the fiberglass at the sump screen (e.g., calcium) could cause precipitation of materials (e.g., calcium phosphate) within the debris bed instead of elsewhere. However, this is a second order effect. This phenomenon is rated as "N/A" for time periods P1 and P2 (due to the short time available for chemical reactions to occur) and "L" for time periods P3 and P4 (when the debris bed has been established and chemical reactions are taking place but producing corrosion products at low concentrations) and "M" for P5 (when long-term chemical effects may influence the fibrous debris on the sump screen). Based on the knowledge or available data associated with the long-term chemical behavior of fiberglass, the SoK for this phenomenon is rated as "L."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
66. Scavenging of CO_2, O_2 and N_2 by containment sprays and within the containment pool has the potential to affect containment pool chemistry.	Scavenging of CO_2 will generate carbonate and depress the pH in the absence of a buffer. The formation of nitric acid from N_2 will similarly depress the pH in the absence of a buffer (TSP or NaTB). Scavenging of O_2 can change the redox potential of the pool solution. The concentration of gases in the containment atmosphere is known so the equilibrium concentration in solution can be calculated. Carbonates may also be involved directly in the formation of precipitates and corrosion films. Overall, these processes are of moderate importance, but are not nearly as important as aluminum corrosion and Cal-Sil dissolution. This phenomenon is rated as "N/A" for time period P1 (due to the short time available for chemical reactions to occur), "M" for time periods P2 through and including P4 (when long-term chemical effects may result in scavenging of CO_2, O_2 and N_2, depending upon the termination of containment sprays) and "L" for period P5 (once pool and air solutions are in equilibrium, the sprays will not scavenge any more gases). Based on the knowledge or available data associated with phase equilibria and the influence of carbonates on precipitation, the SoK for this phenomenon is rated as "M."
67. Nickel oxide becomes catalyst for producing elemental hydrogen from radiolysis.	The catalytic effect of nickel oxide is well known. Surfaces composed of nickel oxide will comprise an extremely small fraction of the total surface area after a LOCA, so any catalytic action will be minimal and this phenomenon has been given a low ranking. This phenomenon is rated as "L" for time periods P1 through and including P5 (due to the small amount of nickel oxide surface area available post-LOCA). Based on the knowledge or available data associated with the amount of nickel oxide available post-LOCA and the chemical behavior of nickel oxide in a post-LOCA environment, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
68. Organic compounds with two hydroxyl groups will coordinate with boric acid to increase acidity.	The effect of certain specific organic compounds that contain two hydroxyl groups on boric acid acidity is well understood. The concentration of organics in the sump water will be low, and it is unlikely that these specific organic compounds will form at concentrations sufficient to affect the pH significantly. With time, radiolysis will decompose the organics to CO_2 – the rate of organic loss will depend on whether fission products are released into the pool. Ethylene glycol and other similar compounds could coordinate with boric acid to greatly increase its acidity. However, the concentration of such species is expected to be low in post-LOCA coolant. This phenomenon is rated as "N/A" for time period P1 (due to the short duration of this time period) and "L" for time periods P2 through and including P5 (due to lack of compounds with two hydroxyl groups in the containment pool post-LOCA). Based on the knowledge or available data associated with the amount of organic compounds with two hydroxyl groups in the containment pool post-LOCA, the SoK for this phenomenon is rated as "H."
69. Decrease in pH of containment pool. The pH of the containment pool decreases due to evolving containment pool chemistry and affects the reaction rate and the solubility of some species.	The rates of many chemical reactions depend on pH. Therefore the corrosion/leaching rates of materials may change as the sump pH changes with time. The solubilities of relevant precipitates also depend on pH, and so the possibility of formation of precipitates (or their dissolution) will also change with time. These phenomena are well understood. Aluminum corrosion products are least soluble at pH values near neutral. Since aluminum corrosion products can cause high head loss in a fibrous debris bed, this effect could be very important, especially at long times when the sump temperature is low. This phenomenon is rated as "N/A" for time period P1 (due to the short time available for chemical reactions to occur), "L" for time period P2 (when the pool pH will be changing due to buffer addition/dissolution as well as initial chemical reactions), "M" for time period P3 (after buffer has been added/dissolved and chemical reactions are beginning to affect the pH of the containment pool) and "L" for time periods P4 and P5 (due to the long-term effects of chemical reactions on containment pool pH). Based on the knowledge or available data associated with the long-term chemical behavior of post-LOCA chemical reactions, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
70. Temperature of containment pool affects the reaction rate and the solubility of some chemical species.	The rates of chemical reactions increase with increasing temperature. Therefore the corrosion/leaching rates of materials will change as the sump temperature changes with time. The solubilities of relevant precipitates can change with temperature, and so the possibility of formation of precipitates will also change with time. These phenomena are well understood. This phenomenon is rated as "N/A" for time period P1 (due to the short time available for chemical reactions to occur) and "H" for time periods P2 through and including P5 (to allow for temperature effects on chemical reactions throughout the 30 day period of interest). Based on the knowledge or available data associated with the influence of temperature on post-LOCA chemical reactions, the SoK for this phenomenon is rated as "H."
71. Chemical products change coolant viscosity in the sump.	This phenomenon is relatively well understood. The concentration of chemicals is too low to have a major effect on viscosity. This was demonstrated in the ICET tests. Effects on viscosity were very small. As viscosity will not be affected until concentrations become quite high, it seems unlikely that the change in viscosity would have a significant effect on core cooling. This phenomenon is rated as "N/A" for time period P1 (due to the short time available for chemical reactions to occur) and "L" for time periods P2 through and including P5 (since concentration of corrosion products will remain dilute in the sump). Based on the available data for the dependency of viscosity on corrosion product concentrations, the SoK for this phenomenon is rated as "H."
72. Chemical products change coolant surface tension in the sump.	Surface tension changes could affect debris flotation, gas bubble retention on debris beds, and many other interfacial processes. Most of the chemical products formed in the sump are not surface active, and so the effect on surface tension will be small at the concentrations of interest. This phenomenon is considered a second order effect. This phenomenon is rated as "N/A" for time period P1 (due to the short time available for chemical reactions to occur) and "L" for time periods P2 through and including P5 (since corrosion products are not surface active). Based on the knowledge or available data for the dependence of surface tension on corrosion products, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
73. For a cold-leg break, the boiling process in the core increases the concentration of chemicals in the reactor, increasing or decreasing the risk of precipitation.	The concentration of chemicals due to boiling in the core can increase the concentrations of non-volatile chemical by as much as a factor of 20 before boron dilution measures are taken. This greatly increases the chances of precipitation. This phenomenon is well understood and is most important when there is substantial boiling in the core. Precipitation of products in the core could have a direct impact on core cooling. This phenomenon is rated as "N/A" for time period P1 (when the system is blowing down), "M" for time period P2 (when the core is flooded and removal of decay heat is initiated), "H" for time period P3 (when ECCS is recirculating coolant from the sump and is matching boil-off), "M" for time period P4 (after active boron dilution measures have been taken and decay heat is dropping) and "L" for time period P5 (since decay heat continues to be reduced). Based on the knowledge or available data associated with the concentration of corrosion products in the core and its effect on core cooling, the SoK for this phenomenon is rated as "H."
74. For a hot-leg break, the boiling process in the core increases the concentration of chemicals in the reactor, changing the boiling point and increasing or decreasing the risk of precipitation.	There will be much less boiling for a hot-leg break than a cold leg break and there is direct core throughput without core inlet blockage that restricts the concentration buildup. However, the phenomenon of a change in boiling point with increased concentration of chemicals is well understood. This could have a minor effect on precipitation limit depending on the solubility gradient. The impact of a change in boiling point is small or negligible compared to the impact of the increase of concentration of the chemicals during boiling. The increase in chemical concentrations could have a slight impact on increasing the time that boiling is occurring (boiling continues until ECCS can remove decay heat without boiling). This would only have an effect in a narrow temperature range, however. This phenomenon is rated as "L" for time period P1 (the RCS is in blow down and initial ECCS flow is from the Refueling/Borated Water Storage Tank), "M" for time period P2 (there is likely to be some boiling during this time period due to high level of decay heat) and "L" for time periods P3 through and including P5 (when still boiling due to drop in decay heat at later times). The effect becomes "N/A" after boiling is halted by the ECCS heat removal. Based on knowledge and availably of data for and analyses of the hot-leg LOCA, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
75. For a cold-leg break, the boiling process in the core concentrates coolant chemicals affecting the ionic strength, and influencing precipitation.	The effect of ionic strength on precipitation is well understood. Activity coefficients reach a minimum between about 0.2 and 2 M ionic strength. Solubility is a maximum at this point. As the ionic strength increases above 2 M, activity coefficients increase. This decreases solubility and causes precipitation. The influence of ionic strength on solubility is important, but is secondary compared to the concentration of the precipitating species. This phenomenon is rated as "N/A" for time period P1 (when the system is blowing down), "L" for time period P2 (when the core is flooded but has not had sufficient time to concentrate chemical in the core), "M" for time period P3 (when the core is boiling and active boron dilution actions have not been taken yet), and "L" for time periods P4 and P5 (when the core is boiling by active boron dilution actions are being taken, resulting in flushing the core). Based on the available data for the concentration of corrosion products in the core and the known relation between ionic strength and solubility from solution thermodynamics, the SoK for this phenomenon is rated as "H."
76. For a hot-leg break, the boiling process in the core concentrates coolant chemicals affecting the ionic strength, and influencing precipitation.	This phenomenon is well understood and is important only if there is significant boiling in the core. If the core is not blocked, there will be little if any boiling. The effect of ionic strength is also well understood and its effect on precipitation can be modeled. The impact is small compared to the increase in concentration of the chemicals causing precipitation during boiling. This phenomenon is rated as "L" for time period P1 (the RCS is in blow down) and "L" for time periods P2 through and including P5 (drop in decay heat at later times). The effect becomes "N/A" when the core throughput precludes boiling. Based on knowledge and availably of data for and analyses of the hot-leg LOCA, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
77. For a cold-leg break, fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	This process is important once debris enters the core. The underlying chemistry is understood but there is little ability to predict the changes in flow patterns and mixing volumes due to collection of fibrous debris on fuel debris filters or spacer grids within the fuel elements. Flow patterns in the core will be very important during the boiling process and are related to the power distributions that are not easily characterized. Mixing with the lower plenum will have a large influence on core chemical concentrations, and the effect of debris on such mixing patterns is controlled by the amount of debris and locations where it may collect near the core inlet. Since the location of these blockages is not easily characterized, the effect on both the quantity and quality of precipitate is also difficult to predict. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it) and "H" for time periods P3 through and including P5 (recirculating coolant supplied to the core potentially has fibrous debris in it). Based on the lack of knowledge and lack of data regarding flow patterns in the core under cold-leg break conditions, the SoK for this phenomenon is rated as "L."
78. For a cold-leg break, chemical products collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	Flow patterns in the core will be very important during the boiling process but are not well understood because the location of blockages cannot be easily characterized. The amount of precipitation expected to take place directly on the fuel cladding will not significantly alter the flow patterns or mixing volumes. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it) and "L" for time periods P3 through and including P5 (recirculating coolant supplied to the core potentially has chemical products in it but the deposition does not significantly alter flow channel dimensions in the core). Based on LOCADM calculations that show deposition of chemical products on fuel elements is only a few mils for cold-leg break conditions, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
79. For a cold-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	This process is important once debris and chemicals enter the core. There is little ability to predict the chemical/fibrous debris interactions or the changes in flow patterns and mixing volumes in the core. Flow patterns in the core will be very important during the boiling process and are not easily characterized. The combination of fiber and chemical products in a debris bed will cause the greatest pressure drops. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it) and "H" for time periods P3 through and including P5 (recirculating coolant supplied to the core potentially has both fibrous debris and chemical products in that may collect on fuel elements an affect flow patterns in the core). Based on the lack of both knowledge regarding this phenomenon and either data or calculations of mixing and flow patterns in the core, the SoK for this phenomenon is rated as "L."
80. For a hot-leg break, fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	This process is important once debris enters the core. The underlying chemistry is understood but there is little ability to predict the changes in flow patterns and mixing volumes due to the collection of fibrous debris on fuel elements. The presence of fibers can affect both the quantity and quality of precipitate generated if boiling were to occur. Flow patterns in the core will be very important during a boiling process and are not easily characterized. However, significant boiling in the core is not expected for a hot leg break except for the case of hot leg injection, in which case the debris will be injected into the top of the core where boiling would inhibit the formation of debris beds. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it) and "M" for time periods P3 through and including P5 (recirculating coolant supplied to the core potentially has both fibrous debris and chemical products in that may collect on fuel elements an affect flow patterns in the core but flushing flow is expected to be maintained). Based on the lack of both knowledge regarding this phenomenon and either data or calculations of mixing and flow patterns in the core, the SoK for this phenomenon is rated as "L."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
81. For a hot-leg break, chemical products collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	Flow patterns in the core will be very important during the boiling process but are not easy to characterize. The amount of precipitation forming scale on the fuel cladding is not expected to significantly alter the flow patterns or mixing volumes. Significant boiling is not expected for a hot leg break except for the case of hot leg injection, in which case the debris will be injected into the top of the core where boiling would inhibit the formation of debris beds debris beds. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it) and "L" for time periods P3 through and including P5 (recirculating coolant supplied to the core potentially has chemical products in it but the deposition does not significantly alter flow channel dimensions in the core and flushing flow through the core is maintained). Based on maintaining flushing flow through the core and Loss-of-Coolant Accident Deposition Model (LOCADM) calculations that show deposition of chemical products on fuel elements is only a few mils for hot-leg break conditions, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
82. For a hot-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	This process is important once debris and chemicals enter the core. There is little ability to predict the chemical/fibrous debris interactions or the changes in flow patterns and mixing volumes in the core. Flow patterns in the core will be very important during the boiling process and are not easy to characterize. The combination of fiber and chemical products in a debris bed will cause the greatest pressure drops. However, significant boiling is not expected for a hot leg break except for the case of hot leg injection, in which case the debris will be injected into the top of the core where boiling would inhibit the formation of debris beds. Boiling could also occur if flow into the core is restricted by debris This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and the ECCS suction is from the Refueling/Borated Water Storage Tank which has no debris associated with it), "H" for time periods P3 and P4 (recirculating coolant supplied to the core potentially has both fibrous debris and chemical products in it and decay heat is high during these time periods) and "M" during time period P5 (recirculating coolant supplied to the core potentially has both fibrous debris and chemical products in it that may collect on fuel elements an affect flow patterns in the core but decay heat is low). Based on the lack of both knowledge regarding this phenomenon and either data or calculations of mixing and flow patterns in the core, the SoK for this phenomenon is rated as "L."
83. Chemical reactions producing gas bubbles induce froth flotation processes in the containment pool.	Corrosion reactions could produce hydrogen gas. Not all materials will attach to gas bubbles on their own. Industrial flotation processes often add flotation agents to promote attachment. Froth flotation may influence debris transport, but won't have a significant influence on chemical product formation. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (not considered to be a significant phenomenon that affects corrosion). Based on the knowledge or available data associated with the corrosion rates and consequential hydrogen generation inside a PWR containment post-LOCA, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
Precipitation/Deposition Processes	
84. Containment pool mixing. High velocity, turbulent water flow exists underneath the pipe break location, remainder of the pool relatively quiescent. Containment sprays and sprays draining to lower containment promote mixing. The degree of mixing will affect concentrations altering both debris dissolution rates and precipitation.	Concentrations of chemicals can affect corrosion and precipitation. The actual velocity patterns in the containment pool are determined by plant design and are therefore plant-specific. Fluid velocities in the containment pool can be modeled using CFD. However, the previous rationale regarding mixing of buffer agents also applies here. The phenomenon will persist until the sump has "turned over" several times. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor), "M" for time periods P2 and P3 (building the sump pool and initial turning over (recirculation) of the sump pool) and "L" for time periods P4 and P5 (sump pool has turned over several times and significant gradients of chemical including corrosion products in the sump pool are not expected). Based on the available data associated with the velocities in the sump pool, the rate of sump pool inventory turn-over and mixing processes in general, the SoK for this phenomenon is rated as "M."
85. Turbulent mixing. Turbulence in the containment pool (such as directly under the break) either inhibits or promotes precipitate formation and growth.	The phenomenon of turbulence-enhanced precipitation is reasonably well understood but is only relevant to PWR containments in limited areas where turbulence exists. Local velocities associated with water falling from the break location into the containment pool are considered to have little or no effect on accelerating corrosion. With large sump screen areas, it is expected that most of the sump pool will be nearly quiescent. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (only velocities directly under the break are higher than those in the containment pool as a whole). Based on knowledge or available CFD calculations of post-LOCA sump pool velocities with the ECCS aligned to recirculate coolant from the containment pool, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
86. Boundary layer precipitation. As dissolution occurs, concentrations are highest in the boundary layer at the surface of the solid, due to normal phenomena of mass transfer. Since concentrations are highest in the boundary layer, it also suggests that precipitation might also be most likely to occur at the solid surfaces.	The mass transfer mechanism for surface deposition is well understood. For example, it has been shown to occur for concrete in the presence of TSP. Precipitation that occurs on fixed surfaces is less likely to transport to the strainer or core where it could have an impact on core cooling. Boundary layer phenomena are well understood and can be modeled. Also, heterogeneous precipitation is typically favored over homogeneous processes, especially when the specific surface areas for such processes are large. This is very important, since it will affect the location and transport of chemical products. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "H" for time periods P2 through and including P5 (once the pool has formed, where precipitates form is important to what corrosion products are delivered to the recirculation screen and eventually to the core). Based on existing literature on boundary layer precipitation, the SoK for this phenomenon is rated as "H."
87. Organic adsorption. Organic species adsorbed on surfaces of solids, altering growth rates or the crystalline habit of precipitates.	This phenomenon is well understood and is likely to occur. However, the concentration of organics will be low, and not all organics will adsorb on all solids. With time, radiolysis will decompose the organics to CO_2 – the rate of organic loss will depend on whether fission products are released into the pool. Also, if precipitation is heterogeneous, particle size and shape will not be particularly important. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (due to small amount of organic materials inside PWR containments). Based on the knowledge or available information regarding organic adsorption, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
88. Inorganic adsorption. Inorganic species adsorb on surfaces of solids, altering growth rates or the crystalline habit of precipitates.	There are many inorganic species in the pool (pH buffers, boric acid, dissolution products, etc.) that could affect the crystallization of precipitates. Factors that inhibit precipitation will reduce the impact of precipitation of inorganic materials on core cooling. Heterogeneous nucleation is in most locations expected to be the dominant mechanism for precipitation. It is known that borates and phosphates strongly influence the nature of precipitates, and these species will be present at high concentrations in the coolant recirculating from the containment pool. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions to occur), "L" for time period P2 (still very little time for the formation of corrosion products relative to saturation limits) and "H" for time periods P3 through and including P5 (sufficient time has lapsed to allow for adsorption of inorganic species on surfaces of solids inside PWR containments). Based on the knowledge or available information regarding inorganic adsorption, the SoK for this phenomenon is rated as "H."
89. Organic sequestration. Organic electron-rich atoms combine with soluble metal compounds changing the solubility of dissolved metals.	This phenomenon is well understood. Complexation could increase solubility of corrosion products and reduce precipitation, but the concentration of organics that would be able to undergo complexation is likely to be low, as only organic compounds with specific structures will interact with dissolved metals in this way. Therefore, this phenomenon is not expected to have a significant effect on corrosion or precipitation. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (because of the small amount of organic materials inside PWR containments). Based on the knowledge or available information regarding organic sequestration, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
90. Co-precipitation. This is a method of precipitation/separation. Examples include: Ni/Fe/Cr, Al/Si/B, Co/Fe systems. Precipitation of one species leads to precipitation of other species.	This is a well-known phenomenon, and will occur to some extent in the containment pool. Co-precipitation could increase or decrease the amount of solids that are formed by precipitation. It is difficult to assess the impact of this phenomenon, aside from a possible reduction in the concentrations of some species that might otherwise not precipitate. However, the overall impact of this phenomenon is less significant than primary precipitation. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "M" for time periods P2 through and including P5 (due to likelihood of this phenomenon occurring inside PWR containments). Based on the existing knowledgebase for co-precipitation, the SoK for this phenomenon is rated as "M."
91. Inorganic Flocculation. Formation of larger clumps of smaller particulates: Depends on PZC (point of zero charge) of the particles and ionic strength of the solution (the higher the strength the smaller the distance for agglomeration).	This phenomenon can be very important once the concentration of chemicals is high enough for precipitation. Flocculation (agglomeration) to form larger particles could result in particles that are easier to trap in the debris bed either on the strainers or in the core. If it occurs in the containment pool, it could have the important effect of reducing the amount of solids that passes through the strainer. The extent of flocculation will have a large influence on the pressure drop induced across a debris bed by a chemical product. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "H" for time periods P2 through and including P5 (due to likelihood of this phenomenon occurring inside PWR containments post-LOCA). Based on the available information regarding flocculation of inorganic materials from testing such as the ICET program and WCAP-16530-NP-A (Reference 5), the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
92. Formation of a coagulant. Inorganic chemical species attach to or coat particulate debris which leads to settling.	The use of inorganic coagulants is a well understood and established technology. Alum is a commonly used coagulant, forming aluminum hydroxides. Larger particles formed in the containment pool by flocculation are more easily trapped by the sump screen. They can also settle out in the containment pool or in the lower plenum of the reactor vessel and therefore not be available to block the core. The ability of corroded aluminum to precipitate as aluminum hydroxide and act as a coagulant can lead to agglomeration which is discussed in Item 89. The ranking and SoK associated with aluminum corrosion (21) and agglomeration (81) apply.
93. Organic Flocculation. The formation of larger clumps of smaller inorganic particulates due to the adsorption of an organic material	This phenomenon is well understood. Flocculation (agglomeration) of inorganic materials to form larger particles could result in particles that are easier to settle either in the containment pool or in the reactor vessel lower plenum, or to trap in debris bed at either the recirculation strainers or at the core. The concentration of organics inside containment post-LOCA is expected to be low. As only a subset of organic compounds can participate in this process, the concentration of relevant organics will be even lower. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (because of the small amount of organic material inside PWR containments post-LOCA). Based on the available information regarding flocculation and agglomeration of organic materials from open literature, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
94. Organic Stabilization. The formation of larger clumps of smaller inorganic particulates is inhibited due to the adsorption of an organic material	This phenomenon is well understood. Inhibition of the agglomeration of inorganic particulates via surface adsorption of organic materials is not likely to be important because of the low concentration of organics expected to be present in the containment post-LOCA. Also, as only a subset of organic compounds can participate in this process, the concentration of relevant organics will be even lower. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (because of the small amount of organic material inside PWR containments post-LOCA). Based on the available information regarding organic stabilization and the small amount of organic materials inside containment post-LOCA, the SoK for this phenomenon is rated as "M."
95. Radiological effects: agglomeration. Radiolysis enhances agglomeration of chemical species.	No specific mechanism by which this could occur was specified. It is possible that radiolysis could change the surface charge of metal ions with two easily accessible oxidation states. While such a phenomenon has been reported for some systems, it is not expected to be important for aluminum and calcium, the two species of primary importance in the post-LOCA environment, as these do not have two easily accessible and stable redox states. It could also have a second order effect by producing organics that could promote or prevent agglomeration. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (due to the low likelihood of this phenomenon affecting chemical species of interest). Based on the limited knowledge or available information regarding radiolysis effects on agglomeration of aluminum and calcium materials inside containment post-LOCA, the SoK for this phenomenon is rated as "L."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
96. Change in debris bed properties due to changes in surface charge by adsorption of inorganic species.	The underlying science associated with this phenomenon is well understood but the effect and application of these principles to a debris bed inside containment post-LOCA is not well understood and is hard to predict. Reproducible effects of water type on debris bed head loss have been reported and attributed to this phenomenon. This phenomenon may be overshadowed by heterogeneous precipitation. This phenomenon is rated as "N/A" for time periods P1 and P2 (recirculation of containment pool coolant through the recirculation screen has not been initiated) and "H" for time periods P3 through and including P5 (due to the possible effects of this phenomenon to significantly alter debris bed properties). Based on the available information regarding changes in surface charge of debris beds by absorption of inorganic species inside containment post-LOCA, the SoK for this phenomenon is rated as "M."
97. Electrochemical precipitation. An electrochemical reaction results in solid phase formation.	This phenomenon is well understood. Electrochemical precipitation could affect the corrosion rate of the base material. This phenomenon will occur, especially within the iron, nickel, and copper systems. However, the most important species in the post-LOCA environment (calcium, aluminum, silicon and buffer components) are in a stable valence states and will not be subject to electrochemical precipitation. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (due to low likelihood of this phenomenon affecting chemical species of interest (e.g., aluminum, calcium and silicone)). Based on the available information regarding electrochemical precipitation, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
98. Nuclei formation. Rapid cooling and evaporation of water droplets from the initial break flow may result in precipitation. Concentrations of these species increase as the temperature rapidly decreases.	Nucleation is important for precipitation formation but abundant nucleation sites exist throughout the containment pool. Boron/lithium solids may form, but they will be entrained by the spray and dissolved again, so this phenomenon is of little importance. This phenomenon is rated as "L" for time period P1 (the only time period during which there are subcooled jets issuing from the break) and "N/A" for time periods P2 through and including P5 (blowdown has ended and there is no rapid cooling and evaporation of water droplets from the break). Based on the available information on expansion of subcooled jets, the SoK for this phenomenon is rated as "H."
99. Particulate nucleation sites. Particles within containment create nucleation sites for chemical precipitation: examples include: dirt particles, coating debris, insulation debris, biological debris, colloids, etc.	Nucleation phenomena are well understood. Once both debris and precipitants are present in the pool water, there are abundant nucleation sites throughout the containment pool and this phenomenon becomes very important. Heterogeneous nucleation is the dominant mechanism for precipitation. This phenomenon will have a strong influence on where chemical products form and their transport. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "H" for time periods P2 through and including P5 (due to the existence of both particulates and corrosion products in solution in the containment pool). Based on the knowledge or available information regarding effects of nucleation, the SoK for this phenomenon is rated as "H."
100. Particulate nucleation sites. Particles within containment create nucleation sites for chemical precipitation: an example is radiation tracks.	Nucleation is an important step in the formation of precipitations, but abundant nucleation sites will be available in the containment pool. The importance of heterogeneous precipitation has been discussed earlier. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "L" for time periods P2 through and including P5 (main interaction of radiation will be with water not the chemicals). Based on knowledge of heterogeneous precipitation, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
101. Agglomeration of debris on flow-induced bubbles generated from cavitation, deaereation, air entrainment and turbulence (opportunity for materials to attach).	Not all materials will attach to gas bubbles on their own. Industrial flotation processes often add floatation agents to promote attachment. Flotation is a well understood process but bubble generation from these processes is not expected to be a dominant event and therefore the phenomenon should not be very significant. The paper industry carefully controls bubbles during the application of coatings and pigments because of the effects produced by small bubbles on agglomeration. The same phenomenon could occur within the ECCS, but if a large fraction of precipitation takes place on system surfaces and debris, entrained bubbles will not be able to exert a large influence. Debris will be the dominant source of nucleation sites. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "L" for time periods P2 through and including P5 (due to low likelihood of agglomeration of debris on flow-induced bubbles). Based on the available information regarding formation of flow-induced bubbles in the recirculating ECCS flow, the SoK for this phenomenon is rated as "M."
102. Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.	The kinetics of precipitation for slightly supersaturated solutions is very important, as these systems are metastable and can persist for long periods. Precipitation of some species may never occur over the relevant time scales. Kinetics of precipitation affects particle size and separation. The time it takes for precipitates to form will influence the impact of precipitation on core cooling. Solutions can be slightly supersaturated for long periods of time without precipitation occurring. The relationship between multiple effects (kinetics, supersaturation, presence and type of nucleation sites, etc) is difficult to predict. Slow kinetics of precipitation reduces impact on core cooling, which is a beneficial effect. The conservative approach is to assume precipitation occurs as soon as a solution is supersaturated (instantaneous, no effect of kinetics). This phenomenon is common in boric acid systems and must be accounted for in laboratory studies of solubility. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor) and "H" for time periods P2 through and including P5 (due to the possible role of kinetic effects in the sump pool). Based on the limited knowledge or available information regarding chemical kinetics in the containment pool, the SoK for this phenomenon is rated as "L."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
103. Settling of debris and chemical products in the containment pool. Chemical products formed during this time period may settle within containment pools.	This is an important sink term for debris and precipitates. If settling in the containment pool occurs, fewer particles will be available to be captured on the sump strainer or reach the core so there will be less of an impact on core cooling. Flow rates within the containment pool are so low that suspended chemical product particles larger than a few microns will tend to settle. This phenomenon is rated as "N/A" for time period P1 (little time for chemical reactions and no pool on the containment floor), "L" for time period P2 (containment pool is building, velocities are higher) and "H" for time periods P3 through and including P5 (pool is established, flows are established and settling is possible based on the hydrodynamic behavior of particles). Based on the available information regarding settling of particulates and chemical products in the containment pool, the SoK for this phenomenon is rated as "M."
104. Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for cold leg injection for cold leg breaks) within reactor.	The lower plenum may be relatively quiescent after a cold leg break. This will be especially true after the lower plenum has had a chance to cool below the temperature of the fluid entering from the downcomer. The warmer, lower density water from the downcomer will turn and enter the core, and any particles that separate from the flow will sink to the bottom of the reactor. If settling in the lower plenum occurs, fewer particles will be available to be captured in the core and so there will be less of an impact on core cooling. However, the extent to which this phenomenon occurs is difficult to predict because it is difficult to predict because the particle size distribution in the lower plenum cannot be characterized. This phenomenon is rated as "N/A" for time periods P1 and P2 (the ECCS flow is drawn from the RWST/BWST and contains no debris) and "H" for time periods P2 through and including P5. The ECCS flow is recirculated from the containment pool. For cold leg breaks, the core flow matches boil-off and continually decreased later in time. Settling is possible based on particle hydrodynamics. Based on the available information regarding settling of particulates and chemical products in the reactor vessel lower plenum, the SoK for this phenomenon is rated as "L" or "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
105. Deposition. Chemical products formed may deposit on other surfaces.	This is an important sink term for both particulate debris and precipitates. The underlying phenomena are well understood but the extent to which this will occur cannot be predicted at this time. If deposition occurs outside of the strainer and core inlet debris beds, fewer particles will be available to be captured on the debris bed at the strainer or the core. Thus, there will be less of an impact on core cooling. This is an important phenomenon but difficult to predict. The specific surface area for chemical product deposition is large (heat exchangers, sprayed walls, debris surfaces) so deposition on surfaces other than the core inlet and the sump screen is likely. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down and time for chemical reactions is short) and "H" for time periods P2 through and including P5 (deposition of chemical products is possible throughout the final four time periods of the scenario). Based on the available information regarding deposition of chemical products during coolant recirculation from the containment pool, the SoK for this phenomenon is rated as "L" or "M."
106. Deposition on the reactor core. Coolant temperature increase in the core (~60°F to ~80°F from sump pool) and retrograde solubility of some species (e.g., calcium silicate, calcium carbonate, zeolites, sodium calcium aluminate and calcium phosphate) causes scale, build-up on the reactor core.	Solubility data for many of these species as a function of temperature may not exist. Calculations using various software packages (e.g., OLI) may not be reliable depending on the input data used. These software packages do not model kinetic effects. Evolutions of the concentrations of relevant species, pH, and ionic strength need to be known for calculations. Scale buildup on the core can affect heat transfer and deposition in the core will have a negative impact on core cooling. Scaling due to species with retrograde solubility is well known in heat exchangers, boilers, and hot water heaters. Deposition will occur, but LOCADM analyses have shown that such deposits will not cause excessive fuel temperatures or significant flow restriction. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the Refueling/Borated Water Storage Tank) and "M" for time periods P3 through and including P5 (deposition of chemical products in the core, particularly due to boiling in the core for a cold-leg break). Based on the available data for deposition of chemical products under boiling conditions, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
107. Homogeneous precipitation in ECCS heat exchangers. Species that are soluble at the containment pool temperature may precipitate at the lower (ΔT ≅ 30°F to 40°F) heat exchanger outlet temperature.	Kinetics of precipitation are important to this precipitation process. In addition, homogeneous precipitation is less likely than heterogeneous precipitation when abundant nucleation sites are available and there is good mass transport to the nucleation sites. For example, homogeneous precipitation in ECCS heat exchangers is less likely than heterogeneous precipitation as the HX walls provide a much higher density of nucleation sites than the bulk solution. The process is well understood. The major gap is in the kinetics – the residence time in the HX may not be long enough compared to the kinetic time scale for precipitation to occur. Also, precipitation will depend on the degree of super saturation of the coolant as it passes through the HX. Aluminum-based chemical products become less soluble at lower temperatures, and since these compounds can cause large head losses across debris beds, this phenomenon is ranked of medium importance, particularly at longer times. Whether or not the precipitation is homogeneous or heterogeneous is probably not of crucial importance, since high flow rates within the ECCS heat exchangers can generate sufficiently large wall stresses to dislodge precipitates forming on the walls. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the RWST/BWST) and "M" for time periods P3 through and including P5 (the ECCS is aligned to operate in the recirculation mode and coolant from the containment pool is recirculated through the ECCS and CSS heat exchangers). Based on the available information regarding homogeneous precipitation of chemical products in heat exchangers, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
108. Heterogeneous precipitation on ECCS heat exchanger tubes. Precipitation on heat exchanger surfaces and subsequent debris deposition within close-packed heat exchanger tubes (5/8" diam.) while at the same time reducing the concentration of chemical available for precipitation downstream.	Fouling of heat exchangers by precipitation from solution is well understood. The HX walls provide a large surface area for precipitation. This is an important mechanism for precipitant removal from solution. The major knowledge gap is in understanding the kinetics. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the RWST/BWST) and "H" for time periods P3 through and including P5 (The ECCS is aligned to operate in the recirculation mode and coolant from the containment pool is recirculated through the ECCS and CSS heat exchangers. Heterogeneous precipitation expected to be the dominant precipitation mechanism). Based on the available information regarding heterogeneous precipitation of chemical products in heat exchangers, the SoK for this phenomenon is rated as "M."
109. Diminished heat transfer in the reactor core. Insulation debris and chemical products mixed within water cause a reduction in the effective heat transfer capabilities (CP) of the coolant mixture. Considering only the affect of chemicals and debris on the thermo-physical properties of coolant.	The particle and solute concentrations expected in the containment pool are too low for any appreciable effect on thermo-physical properties, including heat capacity of the fluid. This phenomenon was explored in earlier PWROG testing. The presence of debris and chemical products over the range tested did not cause a significant increase in simulated fuel rod temperatures. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the Refueling/Borated Water Storage Tank) and "L" for time periods P3 through and including P5 (the ECCS is aligned to operate in the recirculation mode and coolant from the containment pool is recirculated through the ECCS and CSS heat exchangers with concentration of corrosion products and debris in the recirculating coolant increasing over time). Based on the available data from testing of fluid properties in the presence of dissolved solids, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
110. Radiological effects: radiation effects on biofilms. Irradiation inhibits the formation and growth of bio-films. (This is one manner in which bio-films are not formed.)	The significance of this phenomenon will depend strongly on the extent of release of fission products, actinides and activation products into the pool. Biofilms are not expected to have a significant presence in containment during a LOCA, thus the effect of radiation will likely not be very important. High local production of oxidants and direct radiation damage will likely slow or stop biofilm growth. However, at Three Mile Island (TMI), biological growth was observed in the presence of radiation and post-LOCA radiation fields may not be high enough for sterilization. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down) and "L" for time periods P2 through and including P5 (long-term opportunity for the development of biofilms). Based on knowledge or available information about formation of biofilms in the presence of radiation, the SoK for this phenomenon is rated as "M."
111. For a cold-leg break, the boiling process in the core concentrates coolant chemicals affecting the pH, influencing precipitation.	This phenomenon is well understood and may be important when there is significant boiling in the core. Boiling increases the concentration of solutes and can directly lead to precipitation that can clog the core and lead to reduced core cooling. The increase in concentration due to boiling is well understood and easy to model. Before active boron dilution actions, core concentrations of boric acid and buffer components will become very high. The pH of the coolant in the core will likely drop for anticipated Na/B ratios. Precipitation in the core will likely not be of any consequence because of the violent mixing and strong secondary flows within the core will destroy any debris beds there. However, once the precipitates exit the core and enter the lower plenum, they may have an opportunity to contribute to core inlet blockage. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "M" for time period P2 (boiling of ECCS water from the Refueling/Borated Water Storage Tank), "H" for time period P3 (prior to initiation of active boron dilution actions) and "M" for time period P4 (decay heat remains high) and P5 (long-term cooling at low decay heat with active boron dilution actions being taken). Based on the available analytical and experimental information about concentration of boric acid in a boiling core for a cold leg break prior to active boron dilution actions being taken, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
112. For a hot leg break, the boiling process in the core concentrates coolant chemicals affecting the pH, influencing precipitation.	Significant boiling is not expected for a hot leg break except for the case of hot leg injection, in which case the debris will be injected into the top of the core where boiling would inhibit the formation of debris beds. The effect of pH on solubility is well understood. This effect is very important and the change in pH as chemicals are concentrated during the boiling process can be modeled. However, this phenomenon is important only if there is significant boiling in the core, and may either increase or decrease precipitation. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down) and "L" for time periods P2 through and including P5 (particulates in the recirculating coolant provide nucleation sites to initiate precipitation of corrosion products from solution). Based on maintaining a flushing flow through the core for a hot-leg break, the SoK for this phenomenon is rated as "H."
113. For a cold-leg break, the boiling process in the core concentrates coolant chemicals, changing the coolant boiling point due to increased concentrations of chemicals.	This phenomenon is well understood and could have a large effect on precipitation depending on the solubility gradient. Boiling increases the concentration of solutes and can directly lead to precipitation that can clog the core and lead to reduced core cooling. The increase in fluid saturation temperature will be only a few degrees, but this can be important since the solubilities of boric acid and sodium borates are strongly dependant on temperature. The increase in concentration due to boiling is well understood and easy to model. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "L" for time period P2 (small time period with limited concentration increases), "M" for time period P3 (prior to initiation of active boron dilution actions) and "L" for time periods P4 and P5 (long-term cooling after active boron dilution actions have been taken). Based on the available analytical and experimental information about concentration of chemicals in a boiling core for a cold leg break prior to active boron dilution actions being taken, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
114. For a hot-leg break, the boiling process in the core concentrates coolant chemicals, changing the coolant boiling point due to increased concentrations of chemicals.	For a hot-leg break, little boiling is expected except for during hot leg injection. In that case, there will be enough mixing at the top of the core so that the process of concentrating chemicals and debris is limited. The impact of changing the boiling point is small or negligible compared to the impact of the increase of concentration of the chemicals during boiling. This process could have a slight impact on increasing the time that boiling is occurring (boiling continues due to a decrease in boiling point whereas otherwise boiling would have stopped at the original boiling point). This would only have an effect in a narrow temperature range, however. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down) and "L" for time periods P2 through and including P5 (maintaining flushing flow precludes boiling). Based on maintaining a flushing flow through the core for a hot-leg break, the SoK for this phenomenon is rated as "H."
115. For a cold-leg break, dissolved chemicals in steam moisture carryover deposit on hot surfaces such as the steam generator tubing.	Deposition of dissolved chemicals in steam moisture carryover on hot surfaces such as the steam generator tubing will restrict heat transfer through those surfaces. This is important during time periods when the SG contributes to core cooling as important sites of heat rejection from the core. Also an increase in pressure drop through the steam generator due to deposition of chemicals will influence the core liquid level after a cold leg break. Deposition on the steam generator tubing may occur until the steam generator is cooled. Boiling of coolant backing into the steam generator after a cold leg break will also take place with possible deposition. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "H" for time periods P2 and P3 (steam generator expected to be hot due to reverse heat transfer from isolated secondary side), "M" for time period P4 (boiling decreases due to lower decay heat and the secondary side of the steam generator begins to cool) and "L" for time period P5 (low decay heat and stored energy of steam generators secondary side is dissipated). Based on the available information from moisture carry over measurements from heated bundle testing, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
116. For a cold-leg break, in regions where dryout/rewetting occurs, the presence of chemical products may create a different deposit structure which does not readily re-dissolve.	Phenomena such as dehydration can change the deposit structure or composition, as can sintering. While the basic phenomena are well understood in general, the state of knowledge of the deposited species in the core is not well understood. This phenomenon may be particularly important in the presence of debris which can become incorporated in the deposited solid. The ability of materials to redissolve could help improve core cooling if these materials have clogged the core, but it is difficult to predict how the morphology of the deposits might change due to dryout/rewetting. This effect was observed in laboratory testing. Temporary uncovering of the core is unlikely after debris could enter the core for a DEG cold leg break. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the Refueling/Borated Water Storage Tank), "M" for time periods P3 and P4 (considerable boiling occurs for the first day following the postulated LOCA, active boron dilution actions may provide opportunities for dryout and rewetting), and "L" for the time period P5 (low decay heat rate results in reduce boiling and active boron dilution actions result in less opportunities for dryout/rewetting). Based on the available data from bundle heat transfer testing, the SoK for this phenomenon is rated as "M."
117. Thermal cycling of circulation through RHR creates opportunity for the change of colloid properties that can filter on debris.	Repeated heating and cooling of precipitates will age the particles. It is difficult to predict what impact this would have. Most particles will be removed by settling or filtering by the debris bed before they recirculate many times. It is expected that all precipitates will age with time. With aluminum-based chemical products, the species initially formed have been shown to be quite capable of affecting head loss across a debris bed without any ripening. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and initial ECCS flow is from the Refueling/Borated Water Storage Tank) and "L" for time periods P3 through and including P5 (allows for changes in colloid properties due to thermal cycling of materials through the RHR heat exchanger can occur over the full 30 day time period, but changes in properties in the RHR are considered a secondary effect compared to the presence and concentration of colloids). Based on limited knowledge and availably of information, the SoK for this phenomenon is rated as "L."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
Additional Items	
118. Perikinetic Flocculation: In perikinetic flocculation, Brownian motion and diffusion bring particles and flocculating agents together. With orthokinetic flocculation, motion of the fluid and velocity gradients help bring particles and flocculating agents together. This enhances the flocculation rate.	Perikinetic flocculation phenomenon is well understood. Both forms of flocculation (orthokinetic and perikinetic) are important for causing aggregation that can lead to larger particles, but orthokinetic flocculation is more important in a flowing system. Agglomeration to larger particle sizes could result in particles that are easier to settle or to trap in the debris bed either on the strainers or in the core. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down) and "L" for time periods P2 through and including P5 (there will be fluid motion in the containment pool, in the ECCS due to pumped flow, and in the core for either a cold-leg or hot-leg break). Based on maintaining fluid movement about the containment and within both the ECCS and the core, the SoK for this phenomenon is rated as "H."
119. Streaming Potential – Electric field develops across a fixed bed due to conductive fluid flow. This in turn can drive electrophoresis and electrophoretic deposition.	This phenomenon is well understood. The high conductivity of the coolant will limit electrokinetic effects. The electric field due to conductive fluid flow is expected to be very low so this phenomenon should not be very important. This phenomenon is rated as "N/A" for time periods P1 and P2 (the RCS is in blow down and "clean" coolant is being pumped from the RWST/BWST) and "L" for time periods P3 through and including P5 (the fluid motion in the containment pool, in the ECCS due to pumped flow, and in the core dominate electrokinetic effects). Based on maintaining fluid movement about the containment and within both the ECCS and the core, the SoK for this phenomenon is rated as "M."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
120. Particle Stickiness.	The underlying basis for "particle stickiness" is well understood and is an important phenomenon. In this context, "stickiness" is a non-technical word for the attractive/repulsive forces that contribute to aggregation, which can lead to larger particles. These forces are important in determining bed formation and agglomeration. Sticky particles can bridge gaps much larger than the particle diameter (like a basketball net filling with snow). Agglomeration to larger particle sizes could result in particles that are easier to settle in the containment pool or the reactor vessel lower head, or to trap in the debris bed on either the recirculation strainers or in the core. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "L" for the time period P2 ("clean" coolant is being pumped from the RWST/BWST) and "H" for time periods P3 through and including P5 (the recirculating coolant carries particulate and fibrous debris as well as an increasing concentration of corrosion products, giving rise to the opportunity for particles to "stick" together). Based on maintaining fluid movement about the containment with both particulate and fibrous debris and an increasing concentration of corrosion products, and with an understanding of how particulates agglomerate, the SoK for this phenomenon is rated as "H."
121. Magnetic Attachment – Magnetic particles can agglomerate by a magnetic field.	There is a large amount of information available on this topic. The mass of magnetic particles (e.g., magnetite/nickel ferrite from RCS piping and fuel) is small. Therefore the magnetic particle concentrations will be low and consequently magnetic effects are also expected to be low. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "L" for the time periods P2 through and including P5 (small source of magnetic particles yielding a low concentration of magnetic particles in the recirculating coolant pool on the containment floor). Based on the knowledge of the agglomeration behavior of magnetic particles and the low concentration of such particles in the coolant pool on the containment floor, the SoK for this phenomenon is rated as "H."

Table 7-2 Chemical Effects – Large Break LOCA Rationale (cont.)

Phenomenon/Process Description	Rationale for Ranking
122. Sintering - Solid particles near their melting point consolidate to form more ridged, less porous structures	This phenomenon is well understood and its impact can easily be assessed from available data on solids expected to be present on heated surfaces and their melting points. If sintering occurs, the resultant solids could be much more effective at restricting flow and presumably reducing heat transfer. However, the particles in the containment pool during a LOCA are expected to be inorganic particles, which have a high melting point and are therefore not expected to partially melt. This phenomenon is rated as "N/A" for time period P1 (the RCS is in blow down), "L" for the time periods P2 through and including P5 (inorganic materials do not have low melting temperatures that would favor sintering). Based on the knowledge of the properties of inorganic particles resulting from chemical effects that occur in the post-LOCA coolant pool in the containment, the SoK for this phenomenon is rated as "H."

8 PIRT FOR THERMAL-HYDRAULICS AND TRANSPORT

8.1 PURPOSE AND SCOPE OF THERMAL-HYDRAULICS AND TRANSPORT PIRT

This section of the PIRT identifies and ranks TH and transport phenomena in the RCS that impact LTC and may be influenced by the presence of solutes and solid debris in the coolant.

8.2 FIGURE OF MERIT: THERMAL-HYDRAULICS AND TRANSPORT

Figure of Merit: Thermal-Hydraulics and Transport
Maintain LTC with debris (particulates, fiber and corrosion products) in the recirculating coolant.

PIRT rankings reflect relative importance of TH and transport phenomena with respect to their impact on the Figure of Merit. That being maintain LTC with debris in the recirculating coolant.

8.3 BACKGROUND FOR THERMAL-HYADRAULICS AND TRANSPORT PIRT

The mixing/transport tables in the Reference 28 PIRT were developed for a narrowly focused objective and scenario. The present PIRT relates to decay heat removal with debris-laden coolant recirculating from the reactor containment building sump. To do this, the mixing/transport PIRT documented in WCAP-17047-NP (Reference 28) served as a 'strawman' that was expanded to include both hot leg and cold leg breaks for a mission time of 30 days and, most significantly, debris in the form of fiber, particulates, and chemical precipitates all of which are typically referred to as "solids" in the tables. Other primary sources of information provided to the PIRT review team were the USNRC GSI-191 chemical effects PIRT documented in NUREG-1918 (Reference 21) and PWROG sponsored topical reports for sump debris chemical effects related to in-vessel precipitation evaluation models documented in WCAP-17211-P/NP (Reference 24), thermo-physical properties of un-buffered and buffered coolant documented in WCAP-17021-NP (Reference 25), single-rod nucleate boiling heat transfer tests documented in WCAP-17040-P/NP (Reference 26), and rod bundle nucleate boiling heat transfer tests documented in WCAP-17360-P/NP (Reference 27).

8.4 THERMAL-HYDRAULICS AND TRANSPORT RANKING AND RATIONALE

Table 8-1 Core – Boiling Region (DEG CL & HL Break)

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Bulk accumulation of solutes and solids in liquid mixing volume due to decay heat boil-off of liquid mixing volume.	L	M	H	M	L	M
2. Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor phase) motion and power distribution within core boiling region.	L	M	H	M	L	M
3. Transport due to circulation/communication between core and upper plenum regions of liquid mixing volume.	L	M	H	M	L	M
4. Molecular diffusion transport between liquid and vapor phases.	L	L	L	L	L	H
5. Transport/mixing of solutes and solids between core boiling region and other reactor vessel regions due to double diffusive convection.	L	L	L	L	L	M
6. Molecular diffusion transport within liquid mixing volume of core boiling region.	L	L	L	L	L	H
7. Molecular diffusion transport from core boiling region to barrel/baffle region.	L	L	L	L	L	H

Table 8-1 Core – Boiling Region (All break sizes, all break locations) (cont.)

Phenomenon/Process Description	Initial Depressurization P1 (0-30s) Rank	ECCS Injection P2 (30s-20m) Rank	Cold Leg Recirculation P3 (20m-12h) Rank	Cooldown and Depressurization of Containment Building P4 (12h-1d) Rank	Long-term Cooldown of Containment Building P5 (1d-30d) Rank	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.* SoK
8. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by density gradient in reactor vessel analogous to Rayleigh-Bénard convection).	L	M	H	L	L	M
9. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	L	L	L	L	L	H
10. Accumulation of solutes and solids due to boiling from metal heat and stored thermal energy in the fuel.	L	L	L	L	L	H
11. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	H	L	L	M
12. Transport/mixing due to unsteady or oscillatory flow resulting from thermal-hydraulic instabilities such as flow excursion (Ledinegg) instability, flow regime transition instability, and geysering/chugging instability.	L	L	M	L	L	M

Table 8-1 Core – Boiling Region (All break sizes, all break locations) (cont.)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
13. Transport/mixing due to unsteady or oscillatory flow resulting from dynamic thermal-hydraulic instabilities such as density-wave oscillations, pressure drop oscillations, flow regime induced instabilities, and acoustic instabilities.	L	M	M	L	L	M
14. Secondary circulation due to two-phase flow regime transition from homogeneous (uniform) to heterogeneous (non-uniform) void distribution (analogous to thermally driven Rayleigh-Bénard convection).	L	H	M	L	L	M
15. Reduction of solutes due to plate-out on heater rods resulting in the plate-out collecting in the heated core such that there are changes in resistances and flow patterns	N/A	N/A	M	M	M	M
16. Dissolved gasses produce bubbles at debris beds due to pressure drop across debris bed.	N/A	N/A	L	L	L	M
17. Chemical reactions producing gas bubbles induce froth flotation processes.	N/A	N/A	L	L	L	M
18. Capture within bed/filter or entrapment by bed/filter.	N/A	N/A	H	H	H	M

Table 8-2 Rationale for Core – Boiling Region (DEG CL & HL Break)

Phenomenon/Process Description	Rationale for Ranking
1. Bulk accumulation of solutes and solids in liquid mixing volume due to decay heat boil-off of liquid mixing volume.	All the RCS liquid is discharged from the core and RCS during the P1 phase by the break discharge and liquid carryout from boiling and flashing in the reactor vessel. The core is refilled with low concentration boric acid fluid during phase P2 by the accumulators or pumped ECCS injection. The injection is clean liquid with boric acid concentrations entering from the accumulators, RWST/BWST pumped injection, and possibly higher concentrations from concentrated boric acid storage tanks. The boric acid concentration can increase from core boiling in phases P2 and P3 if there is an insufficient core flushing flow established. The core flushing is passive for a hot leg break with cold side injection that exceeds the core boiloff rate. Initiation of core flushing flows via a form of hot leg injection or dump-to-sump can dilute the boric acid plus the solids, boric acid, and sump pH additives that are introduced to the RCS at the time of sump switchover at the beginning of phase P3. If there is no substantial resistance increase due to fiber and other particulate deposition at the core inlet or on spacer grids, there is no appreciable change to the core heat removal or core flow patterns and the solutes and solids are well distributed in the core mixing region during phases P3 and P4. During phase P5, the fibrous debris plugs which may have started to form in P3 and P4 could create local resistances and potentially change the core flow distribution. In extreme cases the blockages influence the distribution of solutes and solids in the core mixing region. While adequate flow for decay heat removal is maintained, the ever changing flow patterns with fibrous beds can capture chemical products that reach the core. Previous conservative testing of a single fuel assembly showed that formed blockages can become nearly impervious to fluid flow for hot leg breaks with specific particulate to fiber ratio. In this extreme case the decay heat removal flows can be adversely impacted by nearly complete core plane blockage from debris plugs, however, this condition is unacceptable and limits were placed on the fiber content to ensure the complete core blockage would not exist. This condition is acceptable with alternate flow paths through the baffle or via hot leg injection to provide adequate flow to the core. The core solutes and solids concentrate due to the decay heat boiling for a CLPD break for plants with cold side injection in phase P3. Core flushing flows from hot leg injection change the net core flow direction and debris introduction locations in Phase P3. Initiation of dump-to-sump flows through the hot leg decay heat dropline for some plants provides core flushing but with flow is from the cold side injection. In either case the flushing flows dilute the concentrations of solutes and solids in the core. The flushing flows will be adequate

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	provided a complete core blockage is not developed in plants without alternate flow paths. If a plant design has alternate flow paths, additional core blockage may be acceptable. In either case, an adequate flow to remove core decay heat and flush the core concentrations is provided. The rankings were listed as "L" for P1 because of the blowdown effects and short duration. The ranking increased to "M" for P2 as the core boiloff needed to remove the decay heat and stored energy in the metal and fuel concentrates the boric acid in the core region as the ECCS refills and quenches the fuel rods. This process continues during the longer P3 phase that is ranked "H" following ECCS sump recirculation initiation that introduces additional boric acid, debris, and sump pH buffers from the sump. These solids and solutes enter the RV and flow to the core with the fluid needed to replace core boiloff for a cold leg break. Once an active core flushing flow is introduced for a CLPD break, the core concentrations decline so the rankings are reduced to "M" for P4 and "L" for the longer term P5. The SoK of "M" was selected as a compromise between the well-known key phenomena for the first three phases, contrasted with the uncertainty of the potential debris collections in the later phases of the transient event.
2. Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor phase) motion and power distribution within core boiling region.	Core boiling occurs for all breaks locations during phases P1 and P2. Core boiling continues for a cold leg break for most plants during phases P3 and P4 unless the core flushing flow can remove the core decay heat without boiling. The core flushing flows are plant specific and some plants may suppress boiling during phase P5 and others may not. The ECCS flow rates are important for the hot leg break. If cold side injection continues there is a passive flushing flow maintained that could suppress boiling in phase P3, P4, or P5 for a hot leg break. The non-uniform fuel bundle and fuel pin powers create a variable heating rate with non-uniform boiling in the core region. This non-uniform boiling produces static head differences that drives cross flow in the core region and the bubble rise induces a turbulent mixing in the core and upper plenum region that mixes the boric acid, solids, and sump pH additives. Both cold and hot leg breaks produces turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor) motion during some of the phases in the core. When the core is actively boiling, it is the primary phenomena responsible for transport/mixing of solutes and solids within the core boiling region. The flow patterns created by two-phase flow regimes such as bubbly, slug, or churn turbulent, are directly related to the void motion that

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	is controlled by the radial and axial power distributions in the core. Key considerations are the ECCS flow rates, initiation of active flushing flows, the decay heat rates and core inlet temperatures. The presence of boric acid, solids, or sump pH additives is not expected to significantly affect solution properties relative to pure water because flushing flows will be initiated to maintain these concentrations at moderate to low levels. The rankings were listed as "L" for P1 because of the blowdown effects and short duration. The ranking increased to "M" for P2 as the assembly power distributions influence the local void distributions created by core boiloff needed to remove the decay heat in each region as the ECCS refills and quenches the fuel rods. This process continues during the longer P3 phase that is ranked "H" following ECCS sump recirculation initiation that introduces additional boric acid, debris, and sump pH buffers from the sump. These solids and solutes enter the RV and flow to the core with the fluid needed to replace core boiloff for a cold leg break. Once an active core flushing flow is introduced for a CLPD break, the core concentrations decline and the turbulent mixing contributions are less important so they are reduced to "M" for P4 and "L" for the longer term P5. The SoK of "M" was selected as a compromise between the well-known key phenomena for the first three phases, contrasted with the cycle to cycle power differences and uncertainty of the potential debris collections in the later phases of the transient event.
3. Transport due to circulation/communication between core and upper plenum regions of liquid mixing volume.	Transport of boric acid due to circulation/communication between core and upper plenum regions of liquid mixing volume is provided by the circulation patterns created by the void motion and/or core flushing flows. The upward circulation for high power regions and downward circulation to lower power regions is the primary phenomenon by which higher concentration boric acid, solids, and sump pH additives are mixed with fluid from the core exit into the upper plenum regions. The B&W plants have an additional mixing mechanism created by the plenum cylinder and the holes within it. The upper holes allow the phases to separate and the liquid recirculates downward in the outlet annulus region and back into the upper plenum region through holes adjacent to the hot leg flow paths. The rankings were listed as "L" for P1 because of the blowdown effects and short duration. The ranking increased to "M" for P2 as the liquid droplets initially carry some boric acid upward and later the pool mixture level refills

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	into the upper plenum with flows created by the local power level and void distributions created by core boiloff needed to remove the decay heat as the ECCS refills and quenches the fuel rods. This process continues during the longer P3 phase that is ranked "H" following ECCS sump recirculation initiation that introduces additional boric acid, debris, and sump pH buffers from the sump. These solids and solutes enter the RV and flow to the core and into the upper plenum as the void with the fluid needed to replace core boiloff for a cold leg break. Once an active core flushing flow is introduced for a CLPD break, the core concentrations decline and the turbulent mixing contributions are less important so they are reduced to "M" for P4 and "L" for the longer term P5. The SoK of "M" was selected as a compromise between the well-known key phenomena for the first three phases, contrasted with the cycle to cycle power differences and uncertainty of the potential debris collections in the later phases of the transient event.
4. Molecular diffusion transport between liquid and vapor phases.	Molecular diffusion between the liquid and steam is small in all phases relative to the turbulent transport that is occurring in the core mixing region. Therefore it was ranked as "L" for all phases and the SoK of "H" was assigned because molecular diffusion is well understood.
5. Transport/mixing of solutes and solids between core boiling region and other reactor vessel regions due to double diffusive convection.	Temperature related density changes and concentration changes allow for mixing in low flow scenarios. This phenomena is of low importance because it is much weaker than the transport/mixing mechanism created by the Rayleigh-Bénard type density-driven convection mechanisms. Therefore it was ranked as "L" for all phases and the SoK of "M" was assigned because of the wide variation in temperatures and concentrations that can be developed in periods P4 and P5.
6. Molecular diffusion transport within liquid mixing volume of core boiling region.	Molecular diffusion between the liquid region in the core is of "L" importance to in all phases because the transport/mixing mechanism of boiling/bubble motion, turbulence, entrainment, and density-driven convection mechanisms occurring in the core mixing region overwhelms it. An "H" SoK was assigned because molecular diffusion is well understood.

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
7. Molecular diffusion transport from core boiling region to barrel/baffle region.	Molecular diffusion between the liquid region in the core and the baffle region has little area for any communication and it is several orders of magnitude less than the transport/mixing mechanism due to the manometric pressure gradient that exists between the boiling region of the core and the predominate liquid filled region in the baffle. Therefore it was ranked as "L" for all phases and the SoK of "H" was assigned because molecular diffusion is well understood.
8. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by density gradient in reactor vessel analogous to Rayleigh-Bénard convection).	Natural convection driven by boric acid and other solids concentration (analogous to Rayleigh-Bénard convection) influences the convection flow patterns and the transport and mixing in reactor vessel and the lower plenum if there is no increased hydraulic resistance from debris accumulation between the core and lower plenum regions. During phase P3 but prior to initiation of a flushing flow for the cold leg break, the concentration gradient between the core and lower plenum can be more significant than the temperature gradients between these two regions. The rankings were listed as "L" for P1 because of the blowdown effects and short duration. The ranking increases to "M" for P2 as the boiloff begins concentrating the boric acid. This process continues during the longer P3 phase that is ranked "H" following ECCS sump recirculation initiation that introduces additional boric acid, debris, and sump pH buffers from the sump. These solids and solutes enter the RV and they concentrate due to boiloff for a cold leg break. Once an active core flushing flow is introduced for a CLPD break, the core concentrations decline and the natural convection is less important and reduced to "L" for P4 and P5 as the flushing flow in more dominate. The SoK of "M" was selected as a compromise between the well-known key phenomena for the first three phases, contrasted with the cycle to cycle power differences and uncertainty of the potential debris collections in the later phases of the transient event.
9. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	Secondary flow patterns are limited to localized regions and they are not as effective as the larger circulation patterns from the turbulent flows in providing mixing in the core region. Therefore it was ranked as "L" for all phases and the SoK of "M" was assigned because of the wide variation in flows and concentrations that can be developed in periods P4 and P5.

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
10. Accumulation of solutes and solids due to boiling from metal heat and stored thermal energy in the fuel.	The decay heat production is the dominate heat source in the core during all phases. The stored energy in the metal structures and the fuel pin cause the localized boiling to be slightly higher during the P2 phase, but nearly all of it is dissipated prior to the P3 to P5 phases. A ranking of "L" is assigned for all phases with a SoK of "H."
11. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	The hot leg break locations establish a direct venting path for the cold side ECCS injection to pass through the core, absorb the core decay heat, and pass out of the break. These break locations will not have unsteady or oscillatory flows. The cold leg break location can result in unsteady or oscillatory flow from loop seal reformation and clearing and/or SG liquid entrainment or level swell. The oscillations can change the core flow patterns cyclically until the hot leg injection can continuously condense all the core steam and suppresses core boiling. Plants that must switch ECCS injection from cold to hot sides to ensure core flushing flow will continue to cycle the core flows indefinitely. Add something about formation of the debris bed and its overall blockage that could be more important if a debris bed is formed
12. Transport/mixing due to unsteady or oscillatory flow resulting from thermal-hydraulic instabilities such as flow excursion (Ledinegg) instability, flow regime transition instability, and geysering/chugging instability.	The thermal-hydraulic instabilities such as flow excursion (Ledinegg) instability, flow regime transition instability, and geysering/chugging instability are phenomena that can occur under certain conditions and geometries. These relatively static instabilities are most prevalent at low pressures and can occur without any external stimulus. (The Ledinegg instability is the most dominate type of static instability. Consider a heated channel with an externally imposed pressure drop. If a small perturbation in the flow occurs, this can lead to a decrease in pressure drop due to the dependence of pressure drop on the two-phase flow characteristics of the heated channel.) These static instabilities can partially influence mixing and debris formulations could enhance these mixing mechanisms. However, these mixing mechanisms are less significant than the global transport and mixing patterns in the core. The rankings were listed as "N/A" for P1 because there is no static condition during the short blowdown duration. The ranking was increased to "L" for P2 as core begins to achieve a static balance after refill and quench with core boiloff needed to remove the decay heat and stored energy in the metal. This process continues during the longer P3 phase that is ranked "M" following ECCS sump recirculation initiation as the flow instabilities can have additional influence on the overall mixing effectiveness for a cold leg break. Once an active core flushing flow is introduced for a CLPD break, the external core throughput

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	is more dominate so the rankings are reduced to "L" for P4 and P5. The SoK of "M" was selected as it is challenging to separate the static contributions from the overall mixing flow from void motion during the transient.
13. Transport/mixing due to unsteady or oscillatory flow resulting from dynamic thermal-hydraulic instabilities such as density-wave oscillations, pressure drop oscillations, flow regime induced instabilities, and acoustic instabilities.	The rankings were listed as "L" for P1 because of the short blowdown duration. The ranking was increased to "M" for P2 and P3 after the core refills and establishes a quasi-steady balance to achieve a balance with oscillatory manometric levels after refill and quench. The condensation in the cold legs and downcomer interact with core boiloff needed to remove the decay heat and stored energy in the metal. This process continues during the longer P3 phase that is ranked "M" following ECCS sump recirculation initiation as the flow instabilities can have additional influence on the overall mixing effectiveness for a cold leg break. Once an active core flushing flow is introduced for a cold-leg pump discharge break, the external core throughput is more dominate so the rankings are reduced to "L" for P4 and P5. The SoK of "M" was selected this phenomenon is understood.
14. Secondary circulation due to two-phase flow regime transition from homogeneous (uniform) to heterogeneous (non-uniform) void distribution (analogous to thermally driven Rayleigh-Bénard convection).	Secondary circulation due to two-phase flow regime transition from homogeneous (uniform) to heterogeneous (non-uniform) void distribution can occur from assembly to assembly in the core. Homogeneous bubbly flows occur in lower boiling/bubbling rates and the liquid circulation rates are fairly stable and can be correlated to the steaming rate. The heterogeneous flows occur in higher boiling/bubbling rates and the bubbles combine and produce an oscillatory rate the influences the liquid circulation. These variations may be observed between assemblies and they can contribute to additional mixing. The rankings were listed as "L" for P1 because of the short blowdown duration with little liquid in the core. The ranking was increased to "H" for P2 after the core refills and establishes a quasi-steady balance with different steaming rates based on the power in each fuel assembly. This process continues during the longer P3 phase that is ranked "M" following ECCS sump recirculation initiation as the decay heat rates and the boiling contributions decrease. Once an active core flushing flow is introduced for a CLPD break, the external core throughput is more dominate so the rankings are reduced to "L" for P4 and P5.

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
15. Reduction of solutes due to plate-out on heater rods resulting in the plate-out collecting in the heated core such that there are changes in resistances and flow patterns	Boiling on the fuel pin surface can result in plateout of solids on cladding. This beneficially reduces the concentrations of the solutes in the solution, but the plateout increases the temperature rise across the fuel pin. As the plateout builds, it can also decrease the flow area in the fuel bundle. In extreme cases the plateout can grow from adjacent fuel pins until it bridges across to the adjacent fuel pins and changes the flow resistance in the HC and the core localized flow patterns. However, debris limits will be established to preclude the bridging from rod to rod. A debris bed cannot form in the first two phases so "N/A" was assigned for them while a ranking of "M" is assigned for the remaining phases with a SoK of "M" given the wide variation is debris sources and flushing flows that may be observed from plant to plant.
16. Dissolved gasses produce bubbles at debris beds due to pressure drop across debris bed.	The quantity of dissolved gasses that produces bubbles at debris beds due to pressure drop across debris bed is of little consequence in the core boiling region because the bubbles produced by boiling overwhelm the quantity of gasses. A debris bed cannot form in the first two phases so "N/A" was assigned for them while a ranking of "L" is assigned for the remaining phases with a SoK of "M" given the uncertainty in the possible debris beds.
17. Chemical reactions producing gas bubbles induce froth flotation processes.	Chemical reactions that produce gas bubbles can induce froth flotation processes in a more quiescent pool, however, this is either a flowing region with throughput for a hot leg break or it is a boiling pot for a cold leg break or a hot leg break with blockage. In either case, the liquid throughput or the bubbles from boiling dominate the mixing such that the effects from chemically produced gas bubbles are small. In addition, the plausible sources of gas bubbles are limited (primarily to radiolysis, chemical reactions and possibly due to spilling of coolant out the break at an elevated position relative to the pool on the containment floor). The chemicals are not introduced to the core during the first two phases so "N/A" was assigned for them while a ranking of "L" is assigned for the remaining phases with a SoK of "M" given the uncertainty in the possible debris beds.

Table 8-2 Rationale for Core – Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
18. Capture within bed/filter or entrapment by bed/filter.	The capture rate of solids increases once a bed/filter begins to form. Entrapment of bubbles can also occur once the bed integrity is such that the bubbles cannot dislodge the material in the filter bed and the openings in the bed/filter are smaller than the bubble size. A debris bed cannot form in the first two phases so "N/A" was assigned for them while a ranking of "H" is assigned for the remaining phases with a SoK of "M" given the uncertainty in the possible debris beds.

Table 8-3 Core – Non-Boiling Region (Mainly hot leg breaks with substantial ECCS flow rate and subcooling)

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Natural circulation transport within core region due to "chimney effect" of hot channel.	N/A	N/A	M	M	M	M
2. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by concentration gradient in reactor vessel analogous to Rayleigh-Bénard convection).	N/A	N/A	L	L	L	M
3. Turbulent transport (dispersion) within core region.	N/A	N/A	L	L	L	M
4. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	N/A	N/A	L	L	L	M
5. Double diffusive convection transport.	N/A	N/A	L	L	L	H
6. Molecular diffusion transport from boiling region of core to non-boiling region.	N/A	N/A	L	L	L	H

Table 8-3 Core – Non-Boiling Region (Mainly hot leg breaks with substantial ECCS flow rate and subcooling) (cont.)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	*If SoK changes by period, multiple entries (separated by '/') are used.*
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
7. Molecular diffusion transport from non-boiling core region to barrel/baffle region.	N/A	N/A	L	L	L	H
8. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	N/A	N/A	M	M	L	M
9. Gas evolution from chemical reaction creates bubbles that increase pressure drop across a debris bed.	N/A	N/A	L	L	L	M
10. Dissolved gasses produce bubbles at debris beds due to pressure drop across debris bed.	N/A	N/A	L	L	L	M
11. Chemical reactions producing gas bubbles induce froth flotation processes.	N/A	N/A	L	L	L	M
12. Capture within bed/filter or entrapment by bed/filter.	N/A	N/A	H	H	H	M

Table 8-4 Rationale for Core – Non-Boiling Region

Phenomenon/Process Description	Rationale for Ranking
1. Natural circulation transport within core region due to "chimney effect" of hot channel.	During period P1, the system is blowing down. This is a highly dynamic condition in which there is no non-boiling region of the core so the phenomenon is therefore ranked as "N/A" for this period. Similarly, for period P2, the system is in a dynamic condition with boiling in the core so it is also ranked as "N/A" for period P2. As the decay heat decreases, regions of the core can subcool in later periods. Higher power fuel bundles have larger fluid temperature increases across the bundle. The high power bundle has lower liquid density that supports an up flow circulation in the high power bundle. While this liquid circulation is not as vigorous as two-phase void motion, it creates bulk circulation to augment mixing. During periods P3, P4 and P5, for both a hot leg and cold leg break, this phenomenon can affect local velocities and mixing patterns and it is ranked as having an importance of "M." This phenomenon is reasonably well understood, has been observed in testing and is predictable using appropriate models. Therefore, it is ranked as having a SoK of "M."
2. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by concentration gradient in reactor vessel analogous to Rayleigh-Bénard convection).	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic and considerable flashing and boiling occur so there is little to no core non-boiling region so it is negligible and is therefore ranked as "N/A" for this period. Boiling concentrates the solids and solutes and the increased concentration increases the density of the solution. Higher density can create downward natural convection transport of the higher concentration solution from core region downward into the lower plenum and to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by concentration gradient in reactor vessel analogous to Rayleigh-Bénard convection). During periods P3, P4 and P5, debris is introduced into the core and there is sufficient time for debris gradients to form. However, the gradients are unlikely to result in the generation of additional chemical effects. Therefore, the importance of this phenomenon is ranked as "L" for periods P3, P4 and P5. Based on available density driven data and analyses from sources in addition to GSI-191, the SoK assigned to this phenomenon is "M."
3. Turbulent transport (dispersion) within core region.	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. During periods P3, P4 and P5, the non-boiling region of the core will be laminar to transition turbulent so

Table 8-4 Rationale for Core – Non-Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	this transport (dispersion) in the non-boiling region of the core is small. This phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon has been observed experimentally and analytically. Therefore a SoK of "M" is assigned to it.
4. Transport/mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation.	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. During periods P3, P4 and P5, the non-boiling region of the core will be laminar to transition turbulent so mixing within core region due to secondary flows induced by non-uniform wall turbulence or flow separation is not significant. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon has been observed experimentally and analytically. Therefore a SoK of "M" is assigned to it.
5. Double diffusive convection transport.	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. During periods P3, P4 and P5, double diffusive convection transport can develop as variations in concentration and temperature gradients develop. Once core flushing flows are initiated, the flushing flows will dilute the concentration gradients and defeat this transport mechanism. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. As plants have procedures that guide the establishment of flushing flows, the SoK for this phenomenon is assigned a "H" ranking.
6. Molecular diffusion transport from boiling region of core to non-boiling region.	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this period. Molecular diffusion during this period is overwhelmed by the dynamics associated with boiling and is therefore also ranked as "N/A" for period P2. Molecular diffusion in the non-boiling region in the core is of "L" importance to periods P3, P4 and P5. For postulated hot-leg breaks, flow is continually flushed through the core. For a cold leg break, molecular diffusion is overwhelmed by the transport/mixing mechanism of boiling/bubble motion, turbulence, entrainment, and density-driven convection mechanisms occurring in the core mixing region.

Table 8-4 Rationale for Core – Non-Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	A "H" SoK is assigned because molecular diffusion is well understood and thermal-hydraulic conditions in the core can be predicted analytically.
7. Molecular diffusion transport from non-boiling core region to barrel/baffle region.	During the blowdown period, P1, and the refill and reflood period, P2, the system and core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this period. For periods P3, P4 and P5, molecular diffusion between the liquid region in the core and the baffle region has little area for any communication and it is much smaller than the natural circulation and convection transport/mixing mechanisms. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. A "H" SoK is assigned because molecular diffusion is well understood and thermal-hydraulic conditions in the core can be predicted analytically.
8. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	During the blowdown period, P1, and the refill and reflood period, P2, the system and the core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. During periods P3, P4 and P5, the hot leg break locations establish a direct venting path for the cold side ECCS injection to pass through the core, absorb the core decay heat, and pass out of the break. These break locations will not have unsteady or oscillatory flows. However, the cold leg break location can result in unsteady or oscillatory flow from loop seal reformation and clearing and/or SG liquid entrainment or level swell. The oscillations can change the core flow patterns cyclically until the hot leg injection can continuously condense all the core steam and suppresses core boiling. Plants that must switch ECCS injection from cold to hot sides to ensure core flushing flow will continue to cycle the core flows indefinitely. This phenomenon is ranked as "M" for periods P3 and P4. As decay heat decreases, the phenomenon can still occur but it is less significant after the core flushing flow has stabilized the system. These oscillations are more prone to occur in breaks other than the scenario for this PIRT (e.g., breaks that are less than DEG breaks). Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. As this phenomenon is understood and there is an ongoing PWR Owners Group program to further study this phenomenon, a SoK of "M: has been assigned to it for the scenarios considered for this PIRT.

Table 8-4 Rationale for Core – Non-Boiling Region (cont.)

Phenomenon/Process Description	**Rationale for Ranking**
9. Gas evolution from chemical reaction creates bubbles that increase pressure drop across a debris bed.	During the blowdown period, P1, and the refill and reflood period, P2, the system and the core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. During periods P3, P4 and P5, the gas evolution from chemical reactions in the non-boiling region of the core can create some bubbles that could get trapped in a debris bed. In the non-boiling region of the core, this resultant bed resistance must remain small otherwise boiling will begin. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon is assigned a SoK of "M" based on available data and predictive models.
10. Dissolved gasses produce bubbles at debris beds due to pressure drop across debris bed.	During the blowdown period, P1, and the refill and reflood period, P2, the system and the core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. For periods P3, P4 and P5, the pressure drop for a debris bed in the non-boiling region of the core must be small, otherwise the flow would decrease and boiling would occur. Therefore, with a small pressure drop, the quantity of dissolved gasses that produces bubbles at debris beds is small and they should not substantially increase the bed resistance in the non boiling region. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon is assigned a SoK of "M" based on available data and predictive models.
11. Chemical reactions producing gas bubbles induce froth flotation processes.	During the blowdown period, P1, and the refill and reflood period, P2, the system and the core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore ranked as "N/A" for this time period. For periods P3, P4 and P5, chemical reactions that produce gas bubbles can induce froth flotation processes in a more quiescent pool; however, this has to be a region with some liquid through flow otherwise boiling would begin. The liquid throughput without boiling should dominate the mixing such that the effects from chemically produced gas bubbles are small. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon is assigned a SoK of "M" based on available data and predictive models.

Table 8-4 Rationale for Core – Non-Boiling Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
12. Capture within bed/filter or entrapment by bed/filter.	During the blowdown period, P1, and the refill and reflood period, P2, the system and the core response is dynamic with considerable flashing and boiling so there is little to no core non-boiling region and is therefore is ranked as "N/A" for this time period. For periods P3, P4 and P5, the capture rate of solids increases once a bed/filter begins to form. Entrapment of bubbles can also occur once the bed integrity is such that the bubbles cannot dislodge the material in the filter bed and the openings in the bed/filter are smaller than the bubble size. However, the flow resistance cannot be too high in this region because there has to be sufficient flow to keep it as a non-boiling region. The effect of capturing or entrapping debris is important to the success criteria for the PIRT. Therefore, this phenomenon is ranked as "H" for periods P3, P4 and P5. Based on available fuel assembly head loss testing, the SoK assigned to this phenomenon is "M."

Table 8-5 Baffle-Former-Barrel Region (Upflow designs: All B&W, all C-E, and some Westinghouse)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Natural convection transport due to density gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	L	M	H	H	H	M
2. Turbulent transport/mixing between former elevations.	L	L	L	L	L	M
3. Molecular diffusion transport within barrel/baffle region or between the core and barrel/baffle regions.	L	L	L	L	L	H
4. Double diffusive convection transport.	L	L	L	L	L	H
5. Accumulation of solutes and solids due to boiling from metal heat.	L	L	L	L	L	H
6. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	M	L	L	M
7. Accumulation of solids and "sticky particulates" on former plates (includes settling) due to inertial separation of solids.	N/A	N/A	L	L	L	M

Table 8-6 Rationale for Baffle-Former-Barrel Region

Phenomenon/Process Description	Rationale for Ranking
1. Natural convection transport due to density gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	For period P1, the reactor system is blowing down and there is little opportunity for natural convection due to a density gradient in the baffle-former-barrel region. Therefore, this phenomenon is ranked as "L" for this period. During periods P2 through and including P5, the core power produces a fluid temperature rise or additional boiling in the bundle. This creates a lower density that supports up flow circulation in the core and downflow in the baffle region that is primarily liquid filled. When boiling is occurring in the core, the liquid circulation within these regions is vigorous and its flow under two-phase conditions is higher than when the core is not boiling. The hot leg break can reestablish core exit subcooling after the decay heat drops. The cold leg break maintains high internal circulation rates while core boiling is active. The initiation of core flushing flow can, with time, suppress core boiling and reduce the core to baffle flow recirculation rates. This phenomenon is ranked as "M" in period P2 due to the short duration of the period and the refilling of the baffle-former-barrel region following period P1. Owing to the longer time periods over which this phenomenon can occur, this phenomenon is assigned a ranking of "H" for periods P3, P4 and P5. This phenomenon is predicted by models and is therefore assigned a SoK of "M."
2. Turbulent transport/mixing between former elevations.	For period P1, the reactor system is blowing down and the baffle region empties as well. Therefore, this phenomenon is ranked as "L" for this period. For periods P2 through and including P5, turbulent transport can occur in or near the holes in the former plates. This jetting from the high flow rates keeps the fluid in the baffle region well mixed at the former plates and in between them. However, this phenomenon has little effect on the long-term core cooling of the core. Therefore, this phenomenon is ranked as "L" for periods P2 through and including P5. Based on the availability of models to predict this behavior, the SoK assigned to this phenomenon is "M."

Table 8-6 Rationale for Baffle-Former-Barrel Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Molecular diffusion transport within barrel/baffle region or between the core and barrel/baffle regions.	For all time periods, molecular diffusion between the liquid region in the core and the baffle region has little area for any communication and it is several orders of magnitude less than the transport/mixing mechanism due to the manometric pressure gradient that exists between the boiling region of the core and the predominate liquid filled region in the baffle. Therefore, this phenomenon is ranked as "L" for all five periods. Based on the knowledge and understanding associated with molecular diffusion, this phenomenon is assigned a SoK of "H."
4. Double diffusive convection transport.	Double diffusive convection transport in the baffle could develop later in the accident if there are holes or slots connecting the core and baffle regions. However, for all time periods, the convection from core decay heat overwhelms this mechanism. Therefore, this phenomenon is ranked as "L" for all five periods. Based on the knowledge and understanding associated with double diffusive convection transport, this phenomenon is assigned a SoK of "H."
5. Accumulation of solutes and solids due to boiling from metal heat.	The stored energy in the relatively thin baffle and former plates dissipates early during the accident before accumulation of solutes and solids becomes significant. Since there is little stored heat available, this mechanism is insignificant. Therefore, this phenomenon is assigned a ranking of "L" for all five time periods. Based on the knowledge of metal mass and the ability of accurately calculate stored energy of the baffle-former-barrel components, the SoK assigned to this phenomenon is "H."

Table 8-6 Rationale for Baffle-Former-Barrel Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
6. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	For period P1, the reactor vessel is blowing down and there is little opportunity for mixing in the baffle-former-barrel region. Therefore, this phenomenon is assigned a rank of "L" for this time period. The hot leg break locations establish a direct venting path for the cold side ECCS injection to pass through the core, absorb the core decay heat, and pass out of the break. These break locations will not have unsteady or oscillatory flows. The cold leg break location can result in unsteady or oscillatory flow from loop seal reformation and clearing and/or SG liquid entrainment or level swell. The oscillations can change the core and baffle flow patterns cyclically until the hot leg injection can continuously condense all the core steam and suppresses core boiling. Plants that must switch ECCS injection from cold to hot sides to ensure core flushing flow will continue to cycle the core flows indefinitely. Thus, the ranking for this phenomenon was increased to "M" for P2 and P3 after the core refills and establishes a quasi-steady balance to achieve a balance with oscillatory manometric levels after refill and quench. Once an active core flushing flow is introduced for a cold-leg break, the external core throughput is more dominate so the rankings are reduced to "L" for P4 and P5. A SoK of "M" was assigned to this phenomenon as it is understood but variable in nature based on different ECCS boundary conditions.
7. Accumulation of solids and "sticky particulates" on former plates (includes settling) due to inertial separation of solids.	For periods P1 and P2, no debris has been introduced to the reactor vessel. Therefore, this phenomenon is assigned a rank of "N/A" for these periods. During periods P3, P4 and P5, solids and "sticky particulates" could accumulate on former plates from settling in the stagnant corners in the baffle region. Collection of solids in regions of the baffle that do not influence flow patterns removes material that could increase the severity of the blockages in the core region. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. Based on knowledge of the design of the baffle-former-barrel region, the SoK assigned to this phenomenon is "M."

Table 8-7 Lower Plenum Region (Top of lower core plate to bottom of reactor vessel)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Molecular diffusion transport between core and lower plenum regions and within the lower plenum.	L	L	L	L	L	H
2. Natural convection (due to concentration driven fluid density instability analogous to Rayleigh-Bénard convection) transport of higher concentration solution between core region and lower plenum region and within lower plenum liquid mixing volume where concentration is lower.	L	M	M	M	L	M
3. Double-diffusive convection transport between core and lower plenum and within lower plenum.	L	L	L	L	L	H
4. Accumulation of solutes and solids due to boiling (metal heat release) from lower plenum structures.	L	L	L	L	L	H
5. Turbulent mixing (dispersion) within lower plenum region associated with convection in reactor vessel below the lower support plate.	L	L	L	L	L	M
6. Transport due to circulation/communication between core and lower plenum regions of liquid mixing volume.	L	M	M	M	M	M

Table 8-7 Lower Plenum Region (Top of lower core plate to bottom of reactor vessel) (cont.)

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
7. Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	M	L	L	M
8. Transport of chemical solids within lower plenum due to secondary flow patterns within the lower head region.	L	L	M	M	M	M

Table 8-8 Rationale for Lower Plenum Region

Phenomenon/Process Description	Rationale for Ranking
1. Molecular diffusion transport between core and lower plenum regions and within the lower plenum.	The rate of molecular diffusion transport from the lower core to non-boiling lower plenum region is small compared to the natural circulation or density driven flows between these two regions. Therefore this phenomenon is ranked as "L" for all phases and the SoK of "H" was assigned because molecular diffusion is well understood.
2. Natural convection (due to concentration driven fluid density instability analogous to Rayleigh-Benard convection) transport of higher concentration solution between core region and lower plenum region and within lower plenum liquid mixing volume where concentration is lower.	Natural convection driven by boric acid and other solids concentration (analogous to Rayleigh-Bénard convection) influences the convection flow patterns and the transport and mixing in reactor vessel and the lower plenum if there is no increased hydraulic resistance from debris accumulation between the core and lower plenum regions. During phase P3 but prior to initiation of a flushing flow for the cold leg break, the concentration gradient between the core and lower plenum can be more significant than the temperature gradients between these two regions. The rankings were listed as "L" for P1 because of the blowdown effects and short duration. The ranking increases to "M" for P2 as the boil-off begins concentrating the boric acid. This process continues during the longer P3 phase that is ranked "H" following ECCS sump recirculation initiation that introduces additional boric acid, debris, and sump pH buffers from the sump. These solids and solutes enter the RV and they concentrate due to boil-off for a cold leg break. Once an active core flushing flow is introduced for a cold-leg pump discharge break, the core concentrations decline and the natural convection is less important and reduced to "M" for P4 and "L" for P5 as the flushing flow are more dominate. The SoK of "M" was selected as a compromise between the well-known key phenomena for the first three phases, contrasted with the cycle to cycle power differences and uncertainty of the potential debris collections in the later phases of the transient event
3. Double-diffusive convection transport between core and lower plenum and within lower plenum.	Double-diffusive convection transport between core and lower plenum and within lower plenum region is small compared to the natural circulation or density driven flows between these two regions. Therefore. This phenomenon is ranked as "L" for all five periods. As double-diffusive convections transport is a well-understood phenomenon, a SoK ranking of "H" was assigned to this phenomenon.

Table 8-8 Rationale for Lower Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
4. Accumulation of solutes and solids due to boiling (metal heat release) from lower plenum structures.	Accumulation of solutes and solids due to boiling (metal heat release) from lower plenum structures is limited in magnitude to the stored energy in the lower plenum heat structures. Therefore, this phenomenon was ranked as "L" for all five periods. The amount of thermal energy stored in the lower plenum structures is readily calculated. Therefore a SoK of "H" was assigned to this phenomenon.
5. Turbulent mixing (dispersion) within lower plenum region associated with convection in reactor vessel below the lower support plate.	The average lower plenum flow rate entering from the bottom of the downcomer is roughly equal to the ECCS flows for a hot leg break. The lower plenum flows are roughly equal to the core boil-off rate up until the time of core flushing for cold leg breaks. The net flows through this region are not significant so the flows are not turbulent once the RV refills with liquid. These flows contribute little (dispersion) within lower plenum region. Therefore, the ranking assigned to this phenomenon is "L" for all five time periods. There are analytical tools available to calculate flow rates into the lower plenum during the various periods of a DEG hot or cold leg break. Therefore, a SoK of "M" was assigned to this phenomenon.
6. Transport due to circulation/communication between core and lower plenum regions of liquid mixing volume.	During period P1, the reactor vessel is blowing down and this phenomenon has no effect on circulation within the lower plenum. Therefore, a ranking of "L" is assigned to this phenomenon for P1. Transport due to circulation/communication between core and lower plenum regions of liquid mixing volume are created by the non-uniform power production in the core fuel assemblies. The transport is accentuated by core baffle flows for an up flow baffle plant without any blockages. Therefore, for periods P2 through and including P5, this phenomenon is ranked as "M." The rankings are held at "M" following flushing flows during periods P4 and P5 because the flow between the core and lower plenum retains an importance for the flushing flow or reduced flows because of the potential debris buildup between those two regions. Based on test data and analytical models, a SoK of "M" is assigned to this phenomenon.

Table 8-8 Rationale for Lower Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
7. Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	For period P1, the reactor vessel is blowing down and there is little opportunity for mixing in the baffle-former-barrel region. Therefore, this phenomenon is assigned a rank of "L" for this time period. Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping) can occur for cold leg breaks up to the time of core flushing. Reverse flows allow higher concentrations of solids and solvents to flow into the lower plenum and possibly into the lower downcomer. During insurges, lower concentrations flow from the DC into the lower plenum. This sloshing can provide passive dilution from the core through the LP if global blockages are not present. The hot leg breaks do not produce the oscillatory flows observed by the cold leg breaks. Thus, this phenomenon is ranked as "M" for periods P2 and P3, and "L" for periods P4 and P5 after core flushing flows are introduced and the decay heat decreases. A SoK of "M" was assigned to this phenomenon as it is understood but variable in nature based on different ECCS boundary conditions.
8. Transport of chemical solids within lower plenum due to secondary flow patterns within the lower head region.	The transport of chemicals and solids within lower plenum due to secondary flow patterns within the lower head region is small relative to the convection flows early in the transient. Therefore, a ranking of "L" is assigned to this phenomenon during periods P1 and P2. Later in the transient, secondary flows may become more important. Therefore, a ranking of "M" is assigned to periods P3, P4 and P5. Based on test data and models to predict flows in the lower plenum, this phenomenon was assigned a SoK of "M."

Table 8-9 Downcomer Region (Includes baffle-former-barrel region in Westinghouse downflow designs)

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Transport of lower concentration solution (in excess of make-up for boil-off) from downcomer to inner reactor vessel liquid mixing volume regions.	L	M	M	M	M	M
2. Accumulation of solutes and solids in liquid phase due to downcomer boiling.	L	L	L	L	L	H
3. Transport and generation of turbulence due to cold leg flow/direct injection to downcomer interaction with core barrel in downcomer region as related to turbulent transport/mixing within lower plenum. In addition, azimuthally asymmetric flow distribution may result due to ECCS headering/spill or RVVV spillover as related to non-uniform flow fields in the lower plenum region.	L	M	M	L	L	M
4. Transport and generation of secondary flow patterns within downcomer as related to mixing in lower plenum.	L	L	L	L	L	M

Table 8-9 (cont.) **Downcomer Region (Includes baffle-former-barrel region in Westinghouse downflow designs)**

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
5. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	M	L	L	M
6. Transport of non-condensable gas, liquid, solutes, and solids to reactor vessel upper plenum (head) via upper head spray nozzles.	L	L	L	L	L	M

Table 8-10 Rationale for Downcomer Region

Phenomenon/Process Description	Rationale for Ranking
1. Transport of lower concentration solution (in excess of make-up for boil-off) from downcomer to inner reactor vessel liquid mixing volume regions.	During period P1, the system is blowing down and all liquid is being discharged to containment. Therefore a ranking of "L" is assigned to this phenomenon during this period. Once the ECCS is initiated, subcooled ECCS condenses steam in the upper downcomer and cold leg and the mixed fluid has a lower concentration solution that is transported from the downcomer to inner reactor vessel LP liquid mixing volume regions. Thus, during periods P2 through and including P5, this phenomenon is assigned a ranking of "M." There are models to predict the thermal hydraulics in the downcomer region. Therefore, this phenomenon is assigned a SoK of "M."
2. Accumulation of solutes and solids in liquid phase due to downcomer boiling.	The thick RV shell can cause boiling on the wall surface early in the transient when a single failure of an ECCS train is postulated. This boiling can partially increase the concentration of solutes and solids in liquid phase due to downcomer boiling. Once the shell cools, then the boiling subsides. During period P1 and P2, debris has not been introduced to the reactor vessel. Therefore, the phenomenon is related only to solutes and it is ranked as "L" for periods P1 and P2. During periods P3, P4 and P5, the reactor vessel has substantially cooled and there is little, if any, boiling. Therefore, the phenomenon with solutes and solids is also ranked as "L" for periods P3, P4 and P5. The stored thermal energy of the reactor vessel is readily calculated as is the thermal response of the reactor vessel to a postulated large break LOCA. Therefore, the SoK assigned to this phenomenon is "H."

Table 8-10 Rationale for Downcomer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Transport and generation of turbulence due to cold leg flow/direct injection to downcomer interaction with core barrel in downcomer region as related to turbulent transport/mixing within lower plenum. In addition, azimuthally asymmetric flow distribution may result due to ECCS headering/spill or RVVV spillover as related to non-uniform flow fields in the lower plenum region.	During period P1, the reactor vessel is blowing down and mixing related to LTC is not important so this phenomenon is ranked as "L" during period P1. During the later portion of period P1 and the beginning of period P2 there is significant turbulence in the downcomer related to the accumulator injection phase. Once the accumulator empties and the gas discharges, the cold leg flow/direct injection to downcomer interaction due to lower pumped ECCS flows in the downcomer region are not highly turbulent. The subcooled liquid condenses steam and there are plumes with temperature or density differences that create circulation and mixing within downcomer region. Therefore, during periods P2 and P3, this phenomenon is ranked as "M." The effects of plumes due to cold leg recirculation are moderated after sump recirculation as the liquid temperature increases and the steaming rate decreases as the decay heat declines. Hot leg injection also reduces the flow rates to the downcomer and therefore, for periods P4 and P5, this phenomenon is ranked as "L." There are thermal hydraulic models to predict downcomer mixing. Therefore, a SoK of "M" is assigned to this phenomenon.
4. Transport and generation of secondary flow patterns within downcomer as related to mixing in lower plenum.	During period P1, the system is blowing down and the downcomer empties and begins to refill so secondary flow patterns are of little importance so it is ranked as "N/A" for this time period. During periods P2 through P5 the downcomer refills and secondary flow patterns can be established that can have some, albeit small, influence secondary flow patterns in the downcomer to lower plenum region. To account for his small influence, this phenomenon is ranked as "L" for periods P3, P4 and P5. This phenomenon has been observed experimentally and analytically. Therefore a SoK of "M" is assigned to it

Table 8-10 Rationale for Downcomer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
5. Transport/mixing due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping) can occur for cold leg breaks up to the time of core flushing. Reverse flows allow higher concentrations of solids and solvents to flow out of the lower plenum and into the lower downcomer. During insurges, lower concentrations flow from the DC and enter the lower plenum. This sloshing can provide passive dilution from the core through the lower plenum into the downcomer if global blockages are not present. The hot leg breaks do not produce the oscillatory flows observed by the cold leg breaks. This phenomenon is ranked as "L" for period P1, "M" for periods P2 and P3, and again "L" for periods P4 and P5 after the core flushing flows are established. The nature of the oscillatory flow is understood and a PWROG program is being undertaken to further understand and provide guidance to address these oscillatory flows. Therefore, this phenomenon is assigned a SoK of "M."
6. Transport of non-condensable gas, liquid, solutes, and solids to reactor vessel upper plenum (head) via upper head spray nozzles.	During period P1, the accumulators have not fully discharged and released their overpressure gas to the reactor vessel but there can be some small amount of dissolved nitrogen coming out of solution so this phenomenon is ranked as "L" for this time period. For periods P2, through and including P5, transport of non-condensable gas, liquid, solutes, and solids to reactor vessel upper plenum (head) via upper head spray nozzles or hot leg nozzle gaps can only occur for a HL break. CL breaks will not flow into the upper head. However, non-condensable gases from the discharge of the accumulators will have a small influence of heat transfer and no influence on chemical production rate in the containment building sump. Therefore, for periods P2 through and including P5, the ranking assigned to this phenomenon is "L." The transport and evaluation of the effect of non-condensable gases on heat transfer have been studied and models are available to predict the impact of non-condensables on heat transfer. Therefore, a SoK of "M" is assigned to this phenomenon.

Table 8-11 Upper Plenum Region

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Transport of solutes and solids due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	L	L	M	M	L	M
2. Molecular diffusion transport between liquid and vapor phases.	L	L	L	L	L	H
3. Turbulent transport/mixing within upper plenum region due to steam jetting and turbulence generated from and within upper plenum structure such as guide tubes.	L	L	L	L	L	M
4. Reduction of reactor vessel mixing volume due to increased pressured drop associated with deposition of solutes and solids (due to direct deposition or boiling/evaporation) on upper plenum structures.	L	L	L	L	L	H
5. Net liquid and solutes entrainment and transport above two-phase mixture level in upper plenum/hot leg regions.	L	H	M	L	L	M

Table 8-11 Upper Plenum Region (cont.)

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
6. Net solids entrainment transport above two-phase mixture level in upper plenum/hot leg regions.	N/A	N/A	L	L	L	H
7. For UPI plants, net liquid, solutes, and solids entrainment due to "splattering" of upper plenum injection impingement on structures.	N/A	M	L	L	L	M
8. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	M	L	L	M
9. Reduction of two-phase mixture level swell associated with void collapse related to interfacial heat transfer due to interaction with subcooled coolant from hot leg/upper plenum injection.	N/A	M	M	M	M	M

Table 8-11 Upper Plenum Region (cont.)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
10. ECCS flow from either hot leg injection or UPI flow (which is cooled by heat exchangers prior to being pumped into the upper plenum) results in a non-uniform distribution of solutes and solids, as well as a temperature distribution in the liquid in the upper plenum.	N/A	M	M	M	L	M
11. Entrapment of non-condensable gas (N_2) in upper regions of the reactor vessel as related either mixture level suppression of degraded heat transfer in the core.	N/A	L	L	L	L	M
12. Chemical products change surface tension and viscosity of coolant and thus affect moisture carryover in steam.	N/A	N/A	L	L	L	H

Table 8-12 Rationale for Upper Plenum Region

Phenomenon/Process Description	Rationale for Ranking
1. Transport of solutes and solids due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	For period P1, the reactor vessel is blowing down, no debris- or solute-laden liquid coolant is supplied to the reactor vessel and the time period is short (30 seconds). Therefore, this phenomenon is ranked as "L" for P1. Likewise, for P2, coolant is supplied to the RWST or BWST, no debris-laden coolant is supplied to the reactor vessel and the time period is also relatively short. Therefore, only solutes can be transported to the upper plenum and this transport decreases the concentration in the core region so this phenomenon is also ranked as "L" for P2. For periods P3 and P4, transport of solutes and solids due to RV refill and circulation/communication between upper plenum and hot leg regions of liquid mixing The fluid circulation is primarily induced by non-uniform core power distributions and variations in boiling rates for a cold leg break. It is supported by throughput of ECCS to a hot leg break with or without some boiling in the core. The mixing is higher for period P3 and it decreases during P4 with the decay heat and initiation of core flushing flows. However, this phenomenon is ranked as "M" for both periods. In the longer term represented by period P5, decay heat continues to decrease and the core flushing flows reduce the transport of solutes and solids due to circulation and communication between the upper plenum and hot leg regions. For period P5, this phenomenon is ranked as "L." The SoK for this phenomenon is ranked as "M" as there are models to predict this mixing behavior.
2. Molecular diffusion transport between liquid and vapor phases.	Molecular diffusion transport between liquid and vapor phases is small compared to the convective transport. Therefore, this phenomenon is ranked as "L" for all five periods (P1 through and including P5). The SoK assigned to this phenomenon is "H" as molecular diffusion transport is well understood.
3. Turbulent transport/mixing within upper plenum region due to steam jetting and turbulence generated from and within upper plenum structure such as guide tubes.	Turbulent transport/mixing within upper plenum region due to steam jetting and turbulence generated from and within upper plenum structure such as guide tube support housings occurs early during a large LOCA event but the turbulent mixing and steam jetting subsides after the blowdown and early reflood phases. Therefore, this phenomenon is ranked as "L" for all five periods (P1 through and including P5). The SoK assigned to this phenomenon is "M" as models are available to predict flows and flow rates post accident in the upper plenum region.

Table 8-12 Rationale for Upper Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
4. Reduction of reactor vessel mixing volume due to increased pressured drop associated with deposition of solutes and solids (due to direct deposition or boiling/evaporation) on upper plenum structures.	Period P1 is short and the reactor coolant system is releasing the primary side coolant to the containment with little opportunity for deposition by any mechanism other than flashing. Therefore, this phenomenon is ranked as "L" during this time period. For UPI plants, ECCS flow is directed into the upper plenum where it impinges on the upper internals structures and some boiling may occur. However, the heat capacity of those structures is limited. Since this is a short-lived phenomenon with limited deposition (this occurs prior to the introduction of debris- and solute-laden water being injected by the ECCS), is it ranked as "L" for UPI plants for time periods P2 through and including period P5. For time period P2 the RV is refilling for plants that evolve to hot leg injection, there is only flow from the core into the upper plenum. Therefore, this phenomenon is ranked as "L" for the short duration of this phase for these plants. For time periods P3, P4 and P5, the heat capacity of the upper plenum structures for plants that evolve to hot leg switchover is again limited. Since this is a short-lived phenomenon with limited opportunity for deposition, this phenomenon is also ranked as "L" for non-UPI plants for time periods P3, P4 and P5. The release of stored thermal energy of the upper plenum structures is readily calculated and models exist to evaluate the flow conditions in the upper plenum, therefore this phenomenon is assigned a SoK of "H."
5. Net liquid and solutes entrainment and transport above two-phase mixture level in upper plenum/hot leg regions.	For period P1, the reactor vessel is blowing down (voiding the reactor vessel) and the time is short (<30 seconds). Therefore, this phenomenon is ranked as "L" for this period. Net liquid entrainment transport above two-phase mixture level in upper plenum/hot leg regions is plant specific because the upper plenum geometries are different. Following reflooding of the core, and with decreasing decay heat from the core, the steam velocities in the upper plenum are small but it could contain some small liquid droplets near the mixture level surface. Thus, this phenomenon is ranked as "H" during period P2 when the core generates considerable steam as it is quenched and stored energy is removed. Following reflooding of the core, and with decreasing decay heat from the core, the steam velocities in the upper plenum decrease, but the core level swell extends into the upper plenum. The ranking of this phenomenon is decreased to "M" for period P3 to account for the decrease in steaming associated with only decay heat removal. The ranking of this phenomenon is further

Table 8-12 Rationale for Upper Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
	decreased to "L" for periods P4 and P5 to account for the continuing decrease in steaming due to a further reduction in decay heat rate and initiation of core flushing flows. As there are models to predict decay heat, and there is test data to provide insights to liquid entrainment and carry-over, this phenomenon is assigned a SoK of "M."
6. Net solids entrainment transport above two-phase mixture level in upper plenum/hot leg regions.	For period P1, the reactor vessel is blowing down and no solids have been introduced to the reactor vessel. Therefore, this phenomenon is ranked as "N/A" for period P1. Similarly, although ECCS flow has been established in period P2, the ECCS flow is from the RWST/BWST which has no solids in the coolant. Therefore, the ranking of this phenomenon is also "N/A" for period P2. For periods P3, P4 and P5, the liquid droplet entrainment is replaced by the mixture level swell so the steady net solids entrainment transport above two-phase mixture level in upper plenum is even smaller. Thus, this phenomenon is ranked as "L" for periods P3, P4 and P5. Test data is available and models exist to predict steaming rates and moisture carry-over from flooding a core. Therefore the SoK assigned to this phenomenon is "H."
7. For UPI plants, net liquid, solutes, and solids entrainment due to "splattering" of upper plenum injection impingement on structures.	For UPI plants, there are two (2) upper plenum nozzles through which ECCS flow into the reactor vessel is pumped. For the blowdown (P1) portion of the LOCA, no credit is taken for ECCS flow. Therefore, this phenomenon is not applicable ("N/A") during this time. During the initial ECCS injection (P2) time period, ECCS flow at about 1000 gpm is provided through the UPI nozzles and impinges on structures in the upper plenum which results in the flow becoming dispersed. During this time period only solutes are introduced to the reactor vessel. As this is relatively early in the transient this phenomenon is ranked as "M" for this time. In time periods P3, P4 and P5, both solutes and particulates are introduced into the reactor vessel. However, by this time, the core is recovered and introduction of debris from the top of the core is not considered to be a challenge to long-term cooling. The phenomenon is ranked as "L" during the last three time periods. Test data is available to evaluate the break-up of the UPI ECCS flow provided to the upper plenum and the progression of the LOCA at a UPI plant is well understood. Therefore, the SoK assigned to this phenomenon is "M."

Table 8-12 Rationale for Upper Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
8. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	Transport/mixing due to unsteady oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping) can occur for cold leg breaks up to the time of core flushing. Level swell into the hot legs can allow higher concentrations of solids and solvents to flow out of the reactor vessel upper plenum into the hot leg. This process stops if the water level drops below the bottom of the hot leg. The hot leg breaks do not produce the oscillatory flows observed by the cold leg breaks. This phenomenon is ranked as "L" for period P1, "M" for periods P2 and P3, and "L" for periods P4 and P5. The basic phenomenon associated with initiating and maintaining the oscillatory flow is understood. Therefore, the SoK assigned for this phenomenon is "M."
9. Reduction of two-phase mixture level swell associated with void collapse related to interfacial heat transfer due to interaction with subcooled coolant from hot leg/upper plenum injection.	There is a reduction of two-phase mixture level swell in the core, and an associated collapse of the voiding in the core, due to interaction with subcooled coolant from either hot leg or upper plenum injection. • For plants with hot leg injection, the injection flow pours into the upper plenum and into the core, cooling the fluid in the boiling region of the core • For UPI plants, the UPI flow impinges on the upper plenum structures, causing the flow stream to "splatter." This splatter, in turn condenses steam in the upper plenum. For the P1 period, the reactor system is blowing down and there is neither hot leg injection nor UPI flow. Therefore this phenomenon is ranked as "N/A" for this time period. During time period P2, there is no hot leg injection flow for non-UPI plants. Therefore, the phenomenon is "N/A" for these plants. During time period P2 for UPI plants, there is UPI flow and this phenomenon is ranked as "M" for this time period. For time periods P3, P4 and P5, cool fluid is provided to the upper plenum of plants that have hot leg injection and UPI flow and this phenomenon is ranked as "M" for these periods. The influence of subcooled coolant from the hot leg on void collapse is predictable from available models. Therefore this phenomenon is assigned an SoK of "M."

Table 8-12 Rationale for Upper Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
10. ECCS flow from either hot leg injection or UPI flow (which is cooled by heat exchangers prior to being pumped into the upper plenum) results in a non-uniform distribution of solutes and solids, as well as a temperature distribution in the liquid in the upper plenum.	ECCS flow from either hot leg injection or UPI flow (both of which are cooled by heat exchangers prior to being ducted into the upper plenum) has a different density that the coolant already existing in the upper plenum. This difference results in a non-uniform distribution of solutes and solids, as well as a temperature distribution and density distribution in the liquid in the upper plenum. For period P1, there is no ECCS coolant pumped into the either the hot leg or the UPI nozzles. Therefore, this phenomenon is ranked as "N/A" for period P1. For UPI plants only, during period P2, coolant is injected directly into the upper plenum from the RWST. While not cooled by a HX, the ECCS coolant is cooler that the fluid in the upper plenum. Therefore, this phenomenon is ranked as "M" during period P2 for UPI plants. For hot-leg injection plants, hot leg injection does not occur in period P2 and the phenomenon is therefore "N/A" for hot leg injection plants. For periods P3 and P4 for both UPI and hot leg injection plants, coolant is recirculated from the reactor containment building sump and cooled prior to introduction into the hot leg or directly into the upper plenum and the amount of debris in the recirculating coolant may be high during these period of the transient. Therefore, this phenomenon is ranked as "M" for both UPI and hot leg injection plants for periods P3 and P4. In period P5, while there may be a temperature difference between the ECCS coolant supplied to the upper plenum by either hot-leg injection or UPI injection, the effect of the temperature distribution on non-uniform distribution of solutes and solids has diminished. Therefore, this phenomenon is ranked as "L" for this time frame. Models are available to predict both short-term and long-term temperature distributions in the ECCS and upper plenum coolant. Replacement sump screen test data also provides information regarding the clean-up of debris in the recirculating coolant. Therefore, this phenomenon is assigned a SoK of "M."

Table 8-12 Rationale for Upper Plenum Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
11. Entrapment of non-condensable gas (N_2) in upper regions of the reactor vessel as related either mixture level suppression of degraded heat transfer in the core.	For a hot-leg break, the complete discharge of the accumulators into the cold leg may result in the collection of some non-condensable gas in the reactor vessel upper plenum. This entrapment is limited to the portion of the upper plenum above the top of the hot-leg and as such, will have limited influence on either core heat transfer or mixture level suppression in the core. While some non-condensable gas may initially collect in the upper plenum, steaming during cold leg injection will tend to displace this gas during the initial cold leg injection from the RWST/BWST for hot leg injection plants. For UPI plants, in addition to steam, the UPI injection flow will also tend to displace the non-condensable gas. For period P1, the accumulators have not fully discharged. Therefore, the phenomenon is ranked as "N/A" for period P1. For periods P2 through and including P5, this phenomenon is ranked as "L." Models exist to predict the effect of non-condensable gases on mixture level and heat transfer. Therefore the SoK assigned to this phenomenon is "M."
12. Chemical products change surface tension and viscosity of coolant and thus affect moisture carryover in steam.	Chemical products produced by the reaction between the coolant, buffer agent and other materials inside containment that are subjected to the post-LOCA coolant mixture can change surface tension and viscosity of coolant and thus affect moisture carryover in steam. However the entrainment is small for lower decay heat levels, with or without chemical products. For period P1, the reactor vessel is blowing down and no buffer agent or chemical products are present. Therefore, this phenomenon is ranked as "N/A" for period P1. Similarly, for period P2, there is no buffer agent or post-accident chemical products present. Therefore, this phenomenon is also ranked as "N/A" for the period P2. For periods P3, P4 and P5, the decay heat has diminished such that this effect, if it exists, is minor. Thus, this phenomenon is ranked as "L" for periods P3, P4 and P5. Based on knowledge of the decay heat levels as a function of time, this phenomenon is assigned a SoK of "H."

Table 8-13 Hot Leg/Pressurizer Region

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking.** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Transport of solutes and solids due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	L	L	M	M	L	M
2. Natural circulation of higher concentration solution 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	L	M	M	L	M
3. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	L	M	M	M	L	M
4. Net liquid, solutes and solids entrainment transport above two-phase mixture level in the hot leg to steam generator.	L	M	M	L	L	M
5. Net transport of solutes and solids from upper plenum region to sump via the hot leg break or decay heat line which provides for re-filtering at the containment sump screen.	L	L	L	L	L	M

Table 8-13 Hot Leg/Pressurizer Region (cont.)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
6. Net transport of solids to upper plenum from recirculating ECCS coolant flow that has been re-filtered by the sump screen as related to ECCS flow split to upper plenum or to sump via hot leg break.	N/A	N/A	L	L	L	M
7. Net liquid mass addition related to hot leg injection due to interfacial heat transfer between liquid and vapor.	N/A	N/A	M	M	L	M
8. Additional transport/mixing in reactor vessel due to interfacial heat transfer between coolant and vapor in hot leg from hot leg injection and/or the pressurizer (via auxiliary spray).	N/A	N/A	L	L	L	L
9. Azimuthally asymmetric flow distribution due to headering of ECCS hot leg injection/spill as related to non-uniform flow fields in the upper plenum region.	N/A	N/A	L	L	L	M

Table 8-14 Rationale for Hot Leg/Pressurizer Region

Phenomenon/Process Description	Rationale for Ranking
1. Transport of solutes and solids due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume.	The upper plenum levels dictate the transport of solutes and solids due to circulation/communication between upper plenum and hot leg regions of liquid mixing volume. For period P1, the reactor vessel is blowing down and upper plenum is voiding. Therefore, for period P1, this phenomenon is ranked as "L." For period P2, the liquid level in the upper plenum is beginning to build. However, this period is when the RWST/BWST is injected and there are no solids in that coolant supply. Therefore, during period P2, this phenomenon is ranked as "L." During periods P3 and P4, debris-laden coolant is recirculated from the sump and there is coolant in the upper plenum. In addition, hot leg injection core flushing flows can be initiated so some solute and debris can be injected directly into the hot legs. This phenomenon is ranked as "M" for periods P3 and P4. In period P5, much of the solutes and solids have been filtered out. Therefore, during period P5, this phenomenon is ranked as "L." Models are available to predict the mixture levels and fluid flow in the upper plenum/and hot leg. Therefore, the SoK assigned to this phenomenon is "M."
2. Natural circulation of higher concentration solution from upper plenum/hot leg to other regions such as downcomer region via hot leg nozzle gap and/or RVVVs for B&W plants.	There are potential flow paths that allow circulation of higher concentration solutions from upper plenum/hot leg to other regions such as downcomer region via hot leg nozzle gaps if unplugged from debris or closed due to thermal considerations and/or RVVVs liquid overflow for B&W plants. For period P1, the reactor vessel is blowing down and upper plenum is voiding. Therefore, for period P1, this phenomenon is ranked as "L." For period P2, the liquid level in the upper plenum is beginning to build. However, this period is when the BWST is injected and there are no solids in that coolant supply. Therefore, during period P2, this phenomenon is ranked as "L." During periods P3 and P4, debris-laden coolant is recirculated from the sump and there is coolant in the upper plenum. Therefore, this phenomenon is ranked as "M" for periods P3 and P4. In period P5, much of the solutes and solids have been filtered out and the potential flow paths may no longer be flowing. Therefore, during period P5, this phenomenon is ranked as "L. Models are available to predict the mixture levels and fluid flow in the upper plenum/and hot leg. Therefore, the SoK assigned to this phenomenon is "M."

Table 8-14 Rationale for Hot Leg/Pressurizer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel / loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping) can occur for cold leg breaks up to the time of core flushing. Level swell into the hot legs can allow higher concentrations of solids and solvents to flow out of the reactor vessel upper plenum into the hot leg. This process stops if the water level drops below the bottom of the hot leg. The hot leg breaks do not produce the oscillatory flows observed by the cold leg breaks. This phenomenon is ranked as “L” for period P1, “M” for periods P2 and P3, and “L” for periods P4 and P5. The basic phenomenon associated with initiating and maintaining the oscillatory flow is understood. Therefore, the SoK assigned for this phenomenon is “M.”
4. Net liquid, solutes and solids entrainment transport above two-phase mixture level in the hot leg to steam generator.	The steam velocities can be high in the hot leg and this steam can continuously entrain liquid from the top of the two-phase mixture level in the hot leg and transport it to the steam generator inlet plenum and possibly into the SG tubes for an upper cold leg break. For period P1, the reactor vessel is blowing down. Therefore, this phenomenon is ranked as “L” for this time. For period P2, and for P3 for cold leg breaks, the steaming rate is relatively high due to the high decay heat. Therefore, for periods P2 and P3, this phenomenon is ranked as “M.” For periods P4 and P5, the steaming rate has decreased due to a decrease in decay heat. Therefore, during periods P4 and P5, this phenomenon is ranked as “L”. Models exist for calculate the decay heat rate, and therefore the steaming rate. Thus, the SoK assigned to this phenomenon is “M.”

Table 8-14 Rationale for Hot Leg/Pressurizer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
5. Net transport of solutes and solids from upper plenum region to sump via the hot leg break or decay heat line which provides for re-filtering at the containment sump screen.	For a hot leg break, the transport of solutes and solids from upper plenum region back to the sump by way of the break in the hot leg to mix the solutes and re-filter the solids at the containment sump screen. For period P1, the reactor vessel is blowing down and solids have not been introduced to the reactor coolant system. Therefore, this phenomenon is ranked as "L" for this time period. During period P2 the RV is refilling and there are no solids so it is ranked as "L." For periods P3 through and including P5, solids are introduced following sump recirculation and debris can collect in core locations and influence the level in the upper plenum and hot legs. If the level is not sufficient to allow for transport out of the hot leg it is effectively "N/A." If the level is sufficient, it will transport and this phenomenon is the means by which excess coolant supplied to the core is discharged from the upper plenum to the sump. Without significant blockage, this phenomenon is ranked as "L" for periods P3 through and including P5. Methods and models exist to predict the flow rate from the upper plenum to the hot leg. Therefore, the SoK assigned to this phenomenon is "M."
6. Net transport of solids to upper plenum from recirculating ECCS coolant flow that has been re-filtered by the sump screen as related to ECCS flow split to upper plenum or to sump via hot leg break.	Hot leg injection spills from the broken hot leg into the sump and is re-filtered through the sump screen before recirculating back to the hot leg or the cold leg, resulting in the net transport of solids to upper plenum as related to ECCS flow split to upper plenum or to sump via hot leg break. For periods P1 and P2, hot leg injection has not been initiated and there are no solids. Therefore, this phenomenon is ranked as "N/A." For periods P3, P4 and P5, this phenomenon occurs during hot leg injection operations and is ranked "L." Methods and models exist to predict the spilling rate of hot leg injection flow to the sump. Therefore, the SoK assigned to this phenomenon is "M."

Table 8-14 Rationale for Hot Leg/Pressurizer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
7. Net liquid mass addition related to hot leg injection due to interfacial heat transfer between liquid and vapor.	The subcooled hot leg injection can increase the net liquid mass due to condensation (i.e. interfacial heat transfer between liquid and vapor). For periods P1 and P2, hot leg injection has not been initiated. Therefore, this phenomenon is ranked as "N/A" for these periods. For a hot leg break, there is little steaming in periods P3 through and including P5. Therefore, this phenomenon is ranked as "N/A" for those periods for a hot leg break. For a cold leg break, there is considerable steaming in periods P3 and P4. Therefore, this phenomenon is ranked as "M" for these periods. For a cold leg break during period P5, steaming is decreased due to the continued decrease in decay heat rate. Therefore, this phenomenon is ranked as "L" during this period for cold leg breaks. Models are available to calculate the decrease in decay heat and interfacial heat transfer between liquid and vapor. Therefore, the SoK assigned to this phenomenon is "M."
8. Additional transport/mixing in reactor vessel due to interfacial heat transfer between coolant and vapor in hot leg from hot leg injection and/or the pressurizer (via auxiliary spray).	Additional transport/mixing in reactor vessel may occur due to interfacial heat transfer between coolant and vapor in hot leg from hot leg injection and/or coolant flow from pressurizer auxiliary spray. Interface condensation can be cyclical, but the magnitudes are small compared to the system related oscillations. There is no hot leg injection during the first two phases so it is ranked as "N/A" for periods P1 and P2. Hot leg injection may be initiated during P3 and P4 so this phenomenon is ranked as "L" for periods P3 through and including P5. The SoK is difficult to characterize because the flow rates are highly plant specific and these influence the mixing in the core. High flow rates provide considerable condensation and mixing while lower flows have a smaller effect. Given uncertainties of flow, mixing, and condensation the SoK assigned to this phenomenon is "L."

Table 8-14 Rationale for Hot Leg/Pressurizer Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
9. Azimuthally asymmetric flow distribution due to headering of ECCS hot leg injection/spill as related to non-uniform flow fields in the upper plenum region.	The headering of hot leg injection flow may result in slightly different flow rate being delivered to each hot leg. This, in turn, can result in azimuthal asymmetric flow distribution from the hot leg into the upper plenum, subsequently causing non-uniform flow fields in the upper plenum region. For periods P1 and P2, hot leg injection has not been initiated. Therefore, this phenomenon is ranked as "N/A" for periods P1 and P2. For periods P3, P4 and P5, this effect is evaluated as having a small effect on the phenomena and processes ongoing in the upper plenum. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. ECCS systems are set to provide approximately equal flows to each hot leg. Models are available to evaluate the consequences of unequal hot leg injection flow to the upper plenum. Therefore the SoK assigned to this phenomenon is "M."

Table 8-15 Steam Generator Region

	Initial Depressurization	**ECCS Injection**	**Cold Leg Recirculation**	**Cooldown and Depressurization of Containment Building**	**Long-term Cooldown of Containment Building**	**Overall State-of-Knowledge Ranking** *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	**P2 (30s-20m)**	**P3 (20m-12h)**	**P4 (12h-1d)**	**P5 (1d-30d)**	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Reduction of reactor vessel mixing volume due to increased pressure drop from solutes and solids deposition within steam generator tubes.	L	L	M	L	L	M
2. Transport/mixing in reactor vessel due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects driven by heat transfer between primary and secondary side such as evaporation of liquid, steam superheat, or vapor condensation.	L	L	M	L	L	M
3. SG secondary side stored energy (fluid inventory and structural metal) as related to steam superheat, boiling, or non-boiling evaporation on primary side.	L	L	L	L	L	H
4. SG secondary side stored energy (fluid inventory and structural metal) as related to siphoning-like behavior of coolant over SG U-tubes.	N/A	N/A	L	L	L	M
5. Net liquid, solutes, and solids entrainment transport above two-phase mixture level in the upper plenum and hot leg into steam generator.	L	M	M	L	L	M

Table 8-15 Steam Generator Region (cont.)

Phenomenon/Process Description	Initial Depressurization P1 (0-30s) Rank	ECCS Injection P2 (30s-20m) Rank	Cold Leg Recirculation P3 (20m-12h) Rank	Cooldown and Depressurization of Containment Building P4 (12h-1d) Rank	Long-term Cooldown of Containment Building P5 (1d-30d) Rank	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.* SoK
6. Accumulation, settling, or deposition, of solutes and solids in the SG inlet plenum.	L	L	L	L	L	M
7. Accumulation or deposition of solutes and solids in the SG tubes.	L	L	L	L	L	M
8. Net liquid transport of solutes and solids from cold leg to hot leg due to pumped ECCS flow (forced convection) as related to reactor vessel liquid inventory replenishment.	N/A	N/A	L	L	L	H
9. Entrapment of non-condensable gas (N_2) in U-bend or candy cane of hot leg.	N/A	L	L	L	L	M

Table 8-16 Rationale for Steam Generator Region

Phenomenon/Process Description	Rationale for Ranking
1. Reduction of reactor vessel mixing volume due to increased pressure drop from solutes and solids deposition within steam generator tubes.	An upper cold leg break can increase the RV and hot leg levels and result in level swell into the bottom of the SG tubes. When the secondary is at a higher pressure, solutes and solids, if present, can deposition within steam generator tubes from boiling. If the blockages are significant, the loop resistance is increased and the mixture level in the RV UP can be depressed from the increased resistance in the SG tubes. For period P1, the reactor vessel is blowing down and this phenomenon does not have time to occur. Similarly, for period P2, coolant inventory is recovering during this time and the phenomenon does not have sufficient time to occur. Therefore, for periods P1 and P2, this phenomenon is ranked as "L." For period P3, steaming rates are high and there is sufficient time to establish the conditions under which this phenomenon can occur. Therefore, this phenomenon is ranked as "M" for period P3. For periods P4 and P5, steaming rates are reduced and operators will have initiated hot leg injection core flushing flows that condense steam and reduces the carryout into the SG tubes. Therefore, for time periods P4 and P5, this phenomenon is less important and ranked as "L." Models are available to predict this behavior. Therefore the SoK assigned to this phenomenon is "M."
2. Transport/mixing in reactor vessel due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects driven by heat transfer between primary and secondary side such as evaporation of liquid, steam superheat, or vapor condensation.	Transport/mixing in reactor vessel due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects is enhanced by cyclic heat transfer rate changes from liquid level oscillations into the bottom of the steam generator tubes. This phenomenon has little time to act and influence thermal-hydraulic processes in periods P1 and P2. Therefore, this phenomenon is ranked as "L" for these two periods. For period P3, the stored energy of the secondary side of the SG may affect other system thermal-hydraulic behaviors to cause oscillatory flow behavior. Therefore, this phenomenon is ranked as "M" for period P3. For periods P4 and P5, the stored energy of the SG secondary side is partially dissipated. The hot leg injection has been initiated, carryout reduced, and interaction with other system thermal-hydraulics. Therefore this phenomenon is ranked as "L" for periods P4 and P5. Models are available to predict the reverse heat transfer from the steam generator secondary side to the primary side post-LOCA. Therefore the SoK assigned to this phenomenon is "M."

Table 8-16 Rationale for Steam Generator Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. SG secondary side stored energy (fluid inventory and structural metal) as related to steam superheat, boiling, or non-boiling evaporation on primary side.	The SG secondary side stored energy (fluid inventory and structural metal) is substantial and it can create steam superheat, boiling, or non-boiling evaporation on primary side. This behavior has little influence on the chemical effects generated in the sump or on the thermal-hydraulic mixing in the core. Therefore, this phenomenon is ranked as "L" for period P1 through and including P5. This phenomenon is understood and models are available to predict this behavior. Therefore, the SoK assigned to this phenomenon is "H."
4. SG secondary side stored energy (fluid inventory and structural metal) as related to siphoning-like behavior of coolant over SG U-tubes.	SG secondary side stored energy (fluid inventory and structural metal) as related to single or two-phase natural circulation on primary side. However, the stored energy on the secondary side can be rejected to the atmosphere if procedural guidance and steam dumps or atmospheric relief valves are available (particularly Westinghouse and CE plants). For period P1, the system is blowing down and the SG tubes cannot refill and produce a siphoning effect. Therefore this phenomenon is ranked as "N/A." Similarly, for period P2, the siphoning effect cannot be generated. Therefore, this phenomenon is also ranked as "N/A" for this time period. The SG of B&W plant designs do not have the capability to create a siphon so it is "N/A" for all phases for this plant design. For periods P3, P4 and P5, there is time for operator actions to reduce secondary side stored energy of SG for Westinghouse and CE plants. If the energy is not totally dissipated and there is core inlet blockage for a HL break, the ECCS not flowing through the core can refill the cold legs and SG tubes. A siphon effect could be established, but it is not critical to LTC. It can change the acceptance criteria for the blockage pressure drop, but the siphon will not change the conclusion of acceptable core cooling. Therefore, for periods P3, P4 and P5, this phenomenon is ranked as "L." Models are available to calculate the stored energy of the SG secondary and dissipation of that stored energy to containment. Also, procedural guidance is available for Westinghouse and CE plants to release SG secondary side stored energy via steam dump and/or atmospheric relief valves. Therefore the SoK assigned to this phenomenon is "M."

Table 8-16 Rationale for Steam Generator Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
5. Net liquid, solutes, and solids entrainment transport above two-phase mixture level in the upper plenum and hot leg into steam generator.	For a postulated cold leg break, there may be a steady, net liquid, solutes, and solids entrainment transport above two-phase mixture level in the upper plenum and hot leg into steam generator. For period P1, the reactor vessel is blowing down and the time is short. Therefore, this phenomenon is ranked as "L" for this time period. For periods P2 and P3, this behavior may occur as the decay heat level of the core is relatively high. Therefore, this phenomenon is ranked as "M" for periods P2 and P3. During periods P4 and P5, decay heat is low and the two-phase mixture level is reduced and hot leg injection is established. Therefore, this phenomenon is ranked as "L" for periods P4 and P5. Models are available to calculated decay heat and froth height. Therefore, the SoK assigned to this phenomenon is "M."
6. Accumulation, settling, or deposition, of solutes and solids in the SG inlet plenum.	If the level swell in the upper plenum and hot legs extends into the bottom of the SG tubes, the velocity decrease associated with entering the inlet plenum of an SG can allow de entrainment with accumulation, settling, or deposition of solutes and solids in the bottom of SG inlet plenum. While this may occur, the amount of solutes and solids will be small and the change in flow area inconsequential. Therefore, this phenomenon is ranked as "L" for all five periods, P1 through and including P5. Models are available to calculated decay heat and froth height. Therefore, the SoK assigned to this phenomenon is "M."
7. Accumulation or deposition of solutes and solids in the SG tubes.	If the level swell in the upper plenum and hot legs extends into the SG inlet plenum and on into the SG tubes, accumulation or deposition of solutes and solids in the SG tubes is possible. While this may occur, the amount of solutes and solids will be small and the change to the system flow resistance minor. Therefore, this phenomenon is ranked as "L" for all five periods, P1 through and including P5. Models are available to calculated decay heat and froth height. Therefore, the SoK assigned to this phenomenon is "M."

Table 8-16 Rationale for Steam Generator Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
8. Net liquid transport of solutes and solids from cold leg to hot leg due to pumped ECCS flow (forced convection) as related to reactor vessel liquid inventory replenishment.	For a hot leg break, a debris bed can build on fuel elements such that there is a net liquid transport of solutes and solids from cold legs through the SG tubes to hot legs due to pumped ECCS flow (forced convection). This behavior may occur before flow to the core is reduced below that needed for successful long-term cooling. For time periods P1 and P2, no debris is in the ECCS water. Therefore, the phenomenon is ranked as "N/A" for these two periods. For periods P3, P4 and P5, the debris-laden water is in the ECCS coolant that is pumped to the core. The current limits on fibrous debris that can reach the core prior to hot-leg injection precluded this from occurring. Therefore, this phenomenon is ranked as "L" for periods P3, P4 and P5. Available test data and regulatory limits preclude this phenomenon from occurring. Therefore the SoK for this phenomenon is "H."
9. Entrapment of non-condensable gas (N_2) in U-bend or candy cane of hot leg.	The discharge of nitrogen from accumulators can result in entrapment of non-condensable gas (N_2) in U-bends or the candy cane of steam generators and result in degraded heat transfer in the steam generator. For period P1, the accumulators have not completely discharged. Therefore, this phenomenon is ranked as 'N/A" for period P1. The SG do not play an important role in post-accident heat transfer for either a larger hot or cold leg break. Therefore, this phenomenon is ranked as "L" for periods P2 through and including P5. This phenomenon is more important for a small LOCA not explicitly addressed in this PIRT. Models are available to predict the system response to postulated LOCA and account for heat transfer to and from the steam generators. Therefore the SoK assigned for this phenomenon is "M."

Table 8-17 Cold Leg (Includes pump suction and discharge)/Reactor Coolant Pump Region

Phenomenon/Process Description	Initial Depressurization P1 (0-30s) Rank	ECCS Injection P2 (30s-20m) Rank	Cold Leg Recirculation P3 (20m-12h) Rank	Cooldown and Depressurization of Containment Building P4 (12h-1d) Rank	Long-term Cooldown of Containment Building P5 (1d-30d) Rank	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.* SoK
1. Transport/mixing in reactor vessel due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects driven by loop seal refill/clearing or interfacial heat transfer between coolant and vapor.	L	M	M	L	L	M
2. Generation and transport of turbulence associated with cold leg discharge into downcomer as related to turbulent transport/mixing of fluid solutes and solids within the reactor vessel.	L	L	L	L	L	M
3. Transport and generation of secondary flow patterns within cold legs as related to mixing in reactor vessel downcomer.	L	L	L	L	L	M
4. Transport of solids to lower plenum due to re-filtering of coolant at the sump screen as related to ECCS flow split to lower plenum via downcomer or to sump via cold leg break.	N/A	N/A	H	M	M	M

Table 8-18 Rationale for Cold Leg/Reactor Coolant Pump Region

Phenomenon/Process Description	Rationale for Ranking
1. Transport/mixing in reactor vessel due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects driven by loop seal refill/clearing or interfacial heat transfer between coolant and vapor.	Transport/mixing within the reactor vessel may be enhanced due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects driven by loop seal refill/clearing or interfacial heat transfer between coolant and vapor. This phenomenon is ranked as "L" for period P1 as the reactor coolant system is blowing down during this period. This phenomenon is rated as "M" for periods P2 and P3, as this is the time prior to initiation of hot leg injections and the excess ECCS could refill the CLPD and CLPS regions of the loops. This phenomenon is ranked as "L" for periods P4 and P5 as hot leg injection is available during these times and this injection can reduce the core steam flow that causes the loop seal clearing following reformation. The hot leg breaks do not produce the oscillatory flows observed by the cold leg breaks. The basic phenomenon associated with initiating and maintaining the oscillatory flow is understood. Therefore, the SoK assigned for this phenomenon is "M."
2. Generation and transport of turbulence associated with cold leg discharge into downcomer as related to turbulent transport/mixing of fluid solutes and solids within the reactor vessel.	Generation and transport of turbulence associated with cold leg discharge or direct downcomer injection into downcomer can facilitate or promote transport/mixing within the downcomer annulus. The number of ECCS trains and single failure assumptions are important in determining this mixing process. However, the overall effect of this phenomenon on debris generation or debris transport to the core is limited. Therefore, this phenomenon is ranked as "L" for all five periods (P1 through and including P5). Downcomer mixing has been studied and models are available to predict this mixing. Therefore, SoK assigned to this phenomenon is "M."
3. Transport and generation of secondary flow patterns within cold legs as related to mixing in reactor vessel downcomer.	The secondary flow patterns within the cold legs are small related to the global circulation patterns that determine mixing in reactor vessel downcomer. Therefore, this phenomenon is ranked as "L" for all five periods (P1 through and including P5). Models are available to predict cold leg flow patterns under ECCS operating conditions. Therefore, SoK assigned to this phenomenon is "M."

Table 8-18 Rationale for Cold Leg/Reactor Coolant Pump Region (cont.)

Phenomenon/Process Description	Rationale for Ranking
4. Transport of solids to lower plenum due to re-filtering of coolant at the sump screen as related to ECCS flow split to lower plenum via downcomer or to sump via cold leg break.	Cold leg breaks result in ECCS flows to the core that match the boil-off and liquid refill rates in the core and upper plenum regions. The remainder of the ECCS injection flows around the downcomer and spills out the break back into the sump. Some solids are transported to the lower plenum with the ECCS flow and some flow back to the sump with the spilled ECCS flow. The spilled ECCS flow that reenters the sump is re-filtered at the sump screen based on the ECCS flow split to lower plenum via downcomer for the cold leg break. For periods P1 and P2, ECCS flow is from the RWST/BWST and no debris is introduced to the cold leg. Therefore, for periods P1 and P2, this phenomenon is ranked as "N/A." For period P3, the debris-laden coolant begins to be drawn from the sump. Therefore, for period P3, this phenomenon is ranked as "H." For periods P4 and P5, the sump continues to be recirculated and there is repeated filtering of the recirculating ECCS coolant several times with the result of less and less debris remains in the recirculating coolant. Therefore, this phenomenon is ranked as "M" for periods P4 and P5. The rank is not reduced below "M" because of the potential effects of the chemical precipitates. The performance of sump screens has been demonstrated by test by each licensee. Therefore the SoK assigned to this phenomenon is "M."

Table 8-19 Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W NSSS)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Diminished transport/mixing in the reactor vessel related to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (de-coupling of the reactor vessel from the steam generator and loop piping) due to presence of RVVV.	L	L	L	L	L	H
2. Transport of solutes and solids to downcomer region due to carryover from upper plenum to downcomer via the RVVV.	L	H	H	M	M	M
3. Transport of solutes and solids to hot leg region as related to liquid/vapor separation in upper plenum cylinder region.	L	L	L	L	L	H

Table 8-20 Rationale for Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W NSSS)

Phenomenon/Process Description	Rationale for Ranking
1. Diminished transport/mixing in the reactor vessel related to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (de-coupling of the reactor vessel from the steam generator and loop piping) due to presence of RVVV.	The RVVV are inertial check valves that open under small differential pressure to provide a venting path for the core steam to enter the upper downcomer and flow to and out of a cold leg break. This direct bypass path does not require the core steam to flow through the hot leg and SG through the cold leg pump suction (CLPS) leg and RCP regions to flow out of the break as it would need to for a plant without RVVV. The direct bypass is always available when the core is boiling and it stabilizes the core flows and removes the oscillatory flow forcing function that the loop system (hot leg, SG, CLPS regions) can produce without RVVV. With lower flow oscillations when RVVV are used, the core and upper plenum mixing volume does not vary so it is simpler to compute the concentrations of solutes and solids. It is noted that all RVVV plants use an upper plenum cylinder, which increases the mass of liquid in the upper plenum and outlet annulus region outside of the plenum cylinder. This liquid mass plus the mass in the core, core baffle, and core bypass constitute the core mixing liquid mass. The rankings are listed as "L" for all phases. RVVV steam flow is important overall to core cooling as it controls RV liquid levels, but reduction in oscillatory behavior is not important to the mixing results that occur in the core region for a cold leg break. The internal circulation that occurs in the core and upper plenum keeps the core mixing region concentrations uniform without credit for system related oscillations. The RVVV are even of less importance for a hot leg break because there is already a direct venting path to the containment by virtue of where the break is located. The performance of the RVVV is well characterized and the transient behavior observed in all shorter term LOCA analyses therefore a "H" SoK is assigned to this phenomenon.
2. Transport of solutes and solids to downcomer region due to carryover from upper plenum to downcomer via the RVVV.	For hot leg breaks, there is a direct venting path for the transport of solutes and solids to the containment so the RVVV are not needed to provide this transport and they do not play an important role. However, for cold leg breaks, the RVVV recirculate steam and possibly liquid, solutes, and solids. The RVVV flow and inlet fluid conditions are controlled primarily by the cold leg break location (elevation and orientation in the cold leg pipe) and the elevation of the core axial power peak. Guillotine breaks near the RV nozzle or those on the bottom of the CL piping on the elevation of the CL nozzle result in the lowest downcomer level and least elevation head supporting the RV level. A break on the top of the CL pipe or one near the RCP discharge (at a higher elevation) or CLPS produces a

Table 8-20 Rationale for Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W NSSS) (cont.)

Phenomenon/Process Description	Rationale for Ranking
	higher water level after refill near the top of the CL nozzle. This additional elevation head raises the mixture level in the RV upper plenum and results in liquid spillover through the RVVV. Under these conditions, the RVVV provide a transport path back into the downcomer for discharge of solutes and solids that can return to the core inlet or flow back out of the cold leg break depending on the flow splits and fluid velocities and transport patterns. If the axial power shape is skewed to the core inlet, then there is additional level swell due to increased voiding in the core that produces even more core level swell and this supports additional RVVV liquid spillover. The ranking is listed as "L" for P1 because of the blowdown effects and short duration. The ranking increased to "H" for P2 as the core refills and the high steam flow from core boil-off and flashing entrains liquid droplets and the solutes through the RVVV. With time, the decay heat decreases and after core quench the stored energy boil-off is reduced so the entrainment decreases, however, the mixture level builds such that the entrainment liquid flow is offset or replaced by RVVV mixture level spillover. Therefore, the ranking remains "H" during period P3, during which solids are introduced into the RV and the time when some form of core flushing flow may be initiated (presumably forward core flow via dump-to-sump from the hot leg decay heat drop line). Decreasing decay heat levels and possibly some inlet core subcooling results in lower void fractions in the core and UP region so the mixture level swell and amount of RVVV mixture level liquid spillover reduces so the ranking was reduced to "M" during P4. It declines even more during P5, but in this phase the break location and potential chemical effects become more important. The ranking during P5 is left as "M" primarily for top of the pipe breaks. The ranking is much lower or non-existent for bottom of the pipe breaks as liquid overflow may cease. The SoK of "M" was selected as a compromise between the better-characterized phenomena for the first three phases, contrasted with the uncertainty of many key parameters and the potential debris collections and chemical effects in the later phases of the transient event.

Table 8-20 Rationale for Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W NSSS) (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Transport of solutes and solids to hot leg region as related to liquid/vapor separation in upper plenum cylinder region.	The RV plenum cylinder in the B&W plants with RVVV provides a geometry that promotes physical separation of the steam and liquid flows exiting from the top of the mixture level through holes in the upper plenum cylinder. The steam and possibly some liquid, solute, and solids can flow through the RVVV for a cold leg break. When the outlet annulus level is lower, the liquid, solutes, and solids recirculate down in the outlet annulus region and split into the hot leg horizontal region (small effect because of no throughput for a CL break) or back into the upper plenum through holes in the plenum cylinder region adjacent to the hot legs (majority of the flow for a CL break). There is a potential for some of the solids to fall out of the outlet annulus flow field as the flow changes direction to reenter the UP. Any solids that separate may settle in the bottom of the outlet annulus region and not reach the core or any other location where blockage could be of concern. For the hot leg break, the majority of the core flow exits out of the hot leg horizontal and the solutes and solids in this flow can exit the break. The solids and chemicals that spill may settle in the containment or return to the sump screen where it will be refiltered and possibly trapped at the screen before potentially being recirculated back to the RV. The rankings are listed as "L" for all phases and this is applicable to both hot and cold leg breaks. There is little flow into the hot leg horizontal during phases P2 and P3 until a core flushing flow is initiated. The hot leg liquid mass is not credited in the core mixing volume calculations so it is low in importance. After the core flushing flow is initiated the concentrations are depleted so the phase separation of the plenum cylinder does not play an important role in the transport of the solutes or solids. Since the effect of the hot leg region is not really considered, it is of low consequence and since it is not credited there is a "H" SoK assigned.

Table 8-21 Transport of Solids and Solutes from the Reactor Containment Building Sump

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
1. Transport of solids and solutes due to containment spray run-off. Spray fluid washes latent debris, corrosion products, insulation materials, & coating debris into containment pool.	L	M	L	L	L	H
2. Capture of solutes and solids within the debris bed/filter formed by collection of debris on the containment building sump recirculation screen or entrapment of those materials by the bed/filter.	N/A	N/A	H	M	M	M
3. Transport of solutes or solids to the decay heat cooler if suction to one low pressure injection (LPI) pump is switched to the hot leg decay heat drop line.	N/A	N/A	H	M	M	M
4. Transport of solutes or solids due to cooling of the recirculating coolant by heat exchangers in the ECCS lines, the CSS lines and, when aligned to draw suction from the sump, the DHC, such that precipitates are formed due to the cooling of the coolant.	N/A	N/A	M	M	M	M

Table 8-21 Transport of Solids and Solutes from the Reactor Containment Building Sump (cont.)

	Initial Depressurization	ECCS Injection	Cold Leg Recirculation	Cooldown and Depressurization of Containment Building	Long-term Cooldown of Containment Building	Overall State-of-Knowledge Ranking *If SoK changes by period, multiple entries (separated by '/') are used.*
	P1 (0-30s)	P2 (30s-20m)	P3 (20m-12h)	P4 (12h-1d)	P5 (1d-30d)	
Phenomenon/Process Description	**Rank**	**Rank**	**Rank**	**Rank**	**Rank**	**SoK**
5. Transport phenomena associated with amorphous coatings. Amorphous silica forms on surface of chemical precipitates (e.g., AlOOH, FeOOH). Coatings increase density and make it less likely for products to transport to sump screen.	L	L	L	L	L	L

Table 8-22 Rationale for Transport of Solids and Solutes from the Rector Containment Building Sump

Phenomenon/Process Description	Rationale for Ranking
1. Transport of solids and solutes due to containment spray run-off. Spray fluid washes latent debris, corrosion products, insulation materials, & coating debris into containment pool.	Transport of particulate, solute and solid debris due to containment spray run-off. Spray fluid washes latent debris, corrosion products, insulation materials and coating debris into containment pool. Time period P1 is brief and debris is being generated by the break and distributed about the containment building and sprays may not yet be initiated. This phenomenon is ranked "L" for this time period. During time period P2, the sprays act to wash down containment walls, floors and walkways. Latent debris is washed into the sump as is other debris generated by the break. Therefore, during period P2, this phenomenon is ranked as "M." During time periods P3, P4 and P5, the latent debris and debris generated by the break has already been washed into the sump by the spray flow. During this time, surface corrosion products on materials subject to spray may be washed into the sump, which is considered to be a small contributor to the total chemical debris load. Therefore, during these time periods, this phenomenon is ranked as "L." The SoK assigned to this phenomenon is "H" based on corrosion testing, the design of containment spray systems and testing of containment sprays.
2. Capture of solutes and solids within the debris bed/filter formed by collection of debris on the containment building sump recirculation screen or entrapment of those materials by the bed/filter.	A debris bed, particularly the fibrous portion of that debris bed that forms on the reactor containment building sump screen will act to capture or trap solids and possibly solutes in the recirculating coolant flow. As there is no recirculating flow during time periods P1 and P2, this phenomenon is ranked as "N/A" for these time periods. In time period P3, the debris bed is forming and collecting both particulate and fibrous debris as well as chemical precipitates and possibly solutes. Therefore, this phenomenon is ranked as "H" for this time period. In time periods P4 and P5, much or most of the debris generated from the break, along with latent containment debris, has been collected by debris beds formed on the sump screen and fuel. Chemical debris is generated during this time. However, the rate of generation is decreasing due to cool-down of the sump fluid and the amount of coolant needed for heat removal is also decreasing due to a decrease in decay heat. Thus, the importance of this phenomenon during periods P4 and P5 is ranked as "M." A "M" SoK ranking was given to this phenomenon as each plant has performed plant-specific testing of the debris capture capabilities of the replacement sump screens installed in each PWR in the U.S.

Table 8-22 Rationale for Transport of Solids and Solutes from the Rector Containment Building Sump (cont.)

Phenomenon/Process Description	Rationale for Ranking
3. Transport of solutes or solids to the decay heat cooler if suction to one LPI pump is switched to the hot leg decay heat drop line.	Transport of solutes or solids to the decay heat cooler (DHC) can occur if suction from one LPI pump is switched to the hot leg decay heat drop line. This suction transfer is a manual operator action that will not be transferred until after sump switchover so a ranking of "N/A" is given for phases P1 and P2. Sump recirculation begins in phase P3, so it is possible that this alignment could be established if there is adequate level in the hot leg, or alternatively it might be one of the mechanisms to initiate core flushing flow. If this flow is initiated following a cold leg break after the core region concentrations of solutes and solids have increased, the cold temperatures inside the tubes of the DHC could lead to precipitation of the RCS solutes or chemicals in the fluid and this could increase the resistance to flow. An "H" ranking is assigned based on these considerations. The rankings were reduced to "M" in periods P4 and P5 because in these phases because some form of core flushing flow would be introduced and the solute and solid concentrations would be much lower. The ranking could be lower during the latter phase, but it was not reduced because of the uncertainty of the chemical effects that may not be present until this later time. A "M" SoK ranking was given for this item, however, because of the potential to precipitate in the DHC this manual action is not recommended or prescribed in the EOP. If this method is not available or it is not used, then the rankings are all "N/A" with an "H" SoK.

Table 8-22 Rationale for Transport of Solids and Solutes from the Rector Containment Building Sump (cont.)

Phenomenon/Process Description	Rationale for Ranking
4. Transport of solutes or solids due to cooling of the recirculating coolant by heat exchangers in the ECCS lines, the CSS lines and, when aligned to draw suction from the sump, the DHC, such that precipitates are formed due to the cooling of the coolant.	In the recirculation mode of operation, the heat exchangers in the ECCS, CSS (for some plants) and the DHC (when aligned to draw suction from the reactor containment building sump) may cool sump water such that solubility limits of chemical products in the recirculation coolant are sufficiently lowered as to allow chemical precipitates to form. As there is no recirculation during time periods P1 and P2, this phenomenon is ranked as "N/A" for these two time periods. Time period P3 is relatively short and chemical reactions have not had much time to occur and build up concentration. However, recognizing that this is the beginning of the generation of chemical reactions that place solutes in solution, the phenomenon is ranked as "M" for this time period. In time periods P4 and P5, the sump temperature is decreasing due to general cooldown of the containment building. With the cooldown, chemical reactions are also slowing down and hence the production of corrosion and chemical products is decreasing. Thus, the ranking of importance of this phenomenon during the P4 and P5 time periods is ranked as "M." A "M" SoK was given to this phenomenon to acknowledge the recent efforts and experimental work that has been performed to understand chemical products that may be produced by the post-LOCA recirculating coolant and the behavior of those chemical products.
5. Transport phenomena associated with amorphous coatings. Amorphous silica forms on surface of chemical precipitates (e.g., AlOOH, FeOOH). Coatings increase density and make it less likely for products to transport to sump screen.	The densities of the pure, crystalline materials are not very different. The densities of the amorphous materials will differ even less. The proposed effect on transport is unlikely to occur. In addition, the formation of coating silica on another particle can only occur if the release of silicates into solution is significantly delayed after the release of Al or Fe. If the releases are at roughly the same time, formation of aluminosilicates or iron silicates would be more likely. If silicate release is delayed significantly it is likely that the Al or Fe particles have already been captured by the strainers or deposited elsewhere. Amorphous silica is very soluble and is not expected to precipitate. The ranking of importance for this phenomenon during the P1 through the P5 time periods is "L." Information available on the formation of amorphous material on chemical precipitates in post-LOCA chemistry is not well studied. Therefore a "L" SoK was assigned to this phenomenon.

9 HIGH RANKED PHENOMENA

This section gives a summary of the PIRT tables developed for the PWROG to support their program to provide plants with sufficient information to close GSI-191. As noted earlier, the focus of the this PIRT is specifically period P3, start of recirculation from the sump to 12 hours (actually, time of active boron dilution is HLSO for CE and Westinghouse plants and initiation of hot leg drop line flow for B&W units). The emphasis of the summary will focus on period P3 and earlier periods P1 and P2 as they may affect the phenomena and/or processes in period P3 as well as those that could extend or develop into periods P4 or P5. Those phenomenon that are ranked as "H" in only periods P4 and/or P5 are included for completeness.

9.1 SUMMARY OF HIGH RANKED CHEMICAL EFFECTS

This section identifies the highly ranked phenomena and processes in period P3 and earlier. Also identified are those cases where the high ranking is carried forward into periods P4 and P5.

The first grouping of phenomena and processes considered are those associated with Source Terms.

Table 9-1 High Ranked Source Terms (From Table 7-1)

	High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
1.	Break location variation could result in different debris mixes and particle/fiber ratios.	P1 to P5	M
9.	Corrosion due to containment spray containing NaOH. Containment sprays wet surfaces subjected to direct spray and run-off of the spray. This creates liquid films on those surfaces that contain boron, LiOH, hydrogen, and for some plants NaOH.	P2 to P5	M
12.	TSP inhibits the corrosion of aluminum.	P5	M
13.	Corrosion of submerged source terms: inhibition due to fiberglass. Leaching of fiberglass inhibits corrosion of certain metals (e.g., aluminum).	P5	M
19.	Fiberglass leaching. Fiberglass-based insulation products begin leaching constituents (e.g., silicon, aluminum, magnesium, calcium, etc.)	P3, P4, P5	H
28.	Corrosion from submerged source terms: aluminum. Less dissolved aluminum than was observed in ICET #1 affects the type and quantity of chemical byproducts that form at high pH values	P2 to P5	H
43.	Mass transport of the dissolution products away from the surface, creating a concentration gradient that promotes dissolution (flow accelerated corrosion).	P1 to P5	H
45.	Straining removes materials at the strainers, preventing full loading of debris in the core.	P3, P4	H
46.	If surface deposition dominates bulk precipitation, large fiber debris sources scavenge inventory	P3, P4, P5	M

The second grouping of phenomena and processes is for reactor coolant chemistry.

Table 9-2 High Ranked Coolant Chemistry (From Table 7-1)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
47. RCS coolant boron concentration at the time of the break. The RCS coolant chemistry varies over the fuel cycle with boron concentrations ranging from about 2000 ppm at the beginning of the fuel cycle to near 0 ppm at the end of fuel cycle.	P1	H
49. RCS coolant pH variability. pH of the coolant at 60°C at beginning of fuel cycle is acidic (pH ≅ 6) and is alkaline (pH ≅ 9) at end of the fuel cycle. The pH variation is less at higher temperatures.	P1	H
56. Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.	P4 and P5	L
60. Rate of release of NaTB pH control agent. Released to pool on containment floor with melting of ice beds or dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	P3	H
61. Rate of dissolution of TSP for pH control. Released to pool on containment floor due to dissolution of material in baskets submerged by pooling coolant on containment floor during a LOCA.	P3	H
70. Temperature of containment pool affects the reaction rate and the solubility of some chemical species.	P2 to P5	H
73. For a cold-leg break, the boiling process in the core increases the concentration of chemicals in the reactor, increasing or decreasing the risk of precipitation.	P3	H
77. For a cold-leg break, fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	P3, P4, P5	L
79. For a cold-leg break, chemical products in combination with fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	P3, P4, P5	L
82. For a hot-leg break, chemical products in combination with fibrous debris collecting on fuel elements alters flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.	P3, P4	L

The third grouping of chemical effects phenomena and processes is for precipitation and deposition processes.

Table 9-3 High Ranked Coolant Chemistry (From Table 7-1)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
86. Boundary layer precipitation. As dissolution occurs, concentrations are highest in the boundary layer at the surface of the solid, due to normal phenomena of mass transfer. Since concentrations are highest in the boundary layer, it also suggests that precipitation might also be most likely to occur at the solid surfaces.	P2 to P5	H
88. Inorganic adsorption. Inorganic species adsorb on surfaces of solids, altering growth rates or the crystalline habit of precipitates.	P3 to P5	H
91. Inorganic Flocculation. Formation of larger clumps of smaller particulates: Depends on PZC of the particles and ionic strength of the solution (the higher the strength the smaller the distance for agglomeration).	P2 to P5	H
92. Formation of a coagulant. Inorganic chemical species attach to or coat particulate debris, which leads to agglomeration.	P2 to P5	H
96. Change in debris bed properties due to changes in surface charge by adsorption of inorganic species.	P3, P4, P5	M
99. Particulate nucleation sites. Particles within containment create nucleation sites for chemical precipitation: examples include: dirt particles, coating debris, insulation debris, biological debris, etc.	P2 to P5	H
102. Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.	P2 to P5	L
103. Settling of debris and chemical products in the containment pool. Chemical products formed during this time period may settle within containment pools.	P3, P4, P5	M
104. Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for cold leg injection for cold leg breaks) within reactor.	P3, P4, P5	L/M
105. Deposition. Chemical products formed during this time period may deposit on other surfaces.	P2 to P5	L/M
108. Heterogeneous precipitation on ECCS heat exchanger tubes. Precipitation on heat exchanger surfaces and subsequent debris deposition within close-packed heat exchanger tubes (5/8" diam.) while at the same time reducing the concentration of chemical available for precipitation downstream.	P3, P4, P5	M
111. For a cold-leg break, the boiling process in the core concentrates coolant chemicals affecting the pH, influencing precipitation	P3	H
115. For a cold-leg break, dissolved chemicals in steam moisture carryover deposit on hot surfaces such as the steam generator tubing.	P2, P3	M

Finally, from the fourth grouping of phenomena and processes titled, Additional Items on phenomenon or process are ranked high either during or before period P3 and is listed below.

Table 9-4 High Ranked Additional Items (From Table 7-1)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
120. Particle Stickiness.	P3, P4, P5	H

As an observation, it is noted that there is only one phenomenon, Item #56, that was rated as either "L" or "M" in periods P1, P2 and P3 that was then ranked "H" in period P4 and/or P5.

Reviewing the Chemical Effects table of Section 7, many of the chemical effects phenomena or processes were evaluated as having an importance of "M" and assigned a SoK of "M" by the PIRT panel. This suggests that there is at least some knowledge of the phenomena or process with which to understand and model it, and evaluate the uncertainty associated with it.

9.2 SUMMARY OF HIGH RANKED THERMAL-HYDRAULICS AND TRANSPORT PHENOMENA

For Table 8-1, Core – Boiling Region, seven (7) phenomenon or processes have been ranked as being "H" or of high importance in period P3 or earlier. Those phenomenon or processes, and their associated SoK are:

Table 9-5 High Ranked Core – Boiling Region (From Table 8-1)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
1. Bulk accumulation of solutes and solids in liquid mixing volume due to decay heat boil-off of liquid mixing volume	P3	M
2. Turbulent transport/mixing (convection/dispersion) due to void (i.e., vapor phase) motion and power distribution within core boiling region	P3	M
3. Transport due to circulation/communication between core and upper plenum regions of liquid mixing volume.	P3	M
8. Natural convection transport of higher concentration solution from core region to other regions of reactor vessel where concentration is lower (fluid density instability type convection driven by density gradient in reactor vessel analogous to Rayleigh-Bénard convection).	P3	M
11. Transport/mixing and unsteady liquid entrainment due to unsteady or oscillatory flow resulting from reactor vessel/loop system interaction effects (due to coupling between the reactor vessel, steam generator, and loop piping).	P3	M
14. Secondary circulation due to two-phase flow regime transition from homogeneous (uniform) to heterogeneous (non-uniform) void distribution (analogous to thermally driven Rayleigh-Bénard convection).	P2	M
18. Capture within bed/filter or entrapment by bed/filter.	P3, P4, P5	M

Similarly, from Table 8-3, Core – Non-Boiling Region, only one (1) phenomenon or process has been ranked as being "H" or of high importance in period P3 or earlier. That phenomenon or process, and its associated SoK is:

Table 9-6 High Ranked Core – Non-Boiling Region (From Table 8-3)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
12. Capture within bed/filter or entrapment by bed/filter.	P3, P4, P5	M

From Table 8-5, Baffle-Former-Barrel Region (Upflow Designs), only one (1) phenomenon or process has been ranked as being "H" or of high importance in period P3 or earlier. That phenomenon or process, and its associated SoK is:

Table 9-7 High Ranked Core – Baffle-Former-Barrel Region (Upflow Designs) (From Table 8-5)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
1. Natural convection transport due to density gradient from core region to barrel/baffle region via top, intermediate (at pressure relief holes), or bottom flow gaps.	P3, P4, P5	M

From Table 8-11, Upper Plenum Region, only one (1) phenomenon or process has been ranked as being "H" or of high importance in period P3 or earlier. That phenomenon or process, and its associated SoK is:

Table 9-8 High Ranked Upper Plenum Region (From Table 8-11)

High-Ranked Phenomenon/Process	Period(s) of High Ranking	SoK
5. Net liquid and solutes entrainment and transport above two-phase mixture level in upper plenum/hot leg regions.	P2	M

From Table 8-17, Cold Leg/Reactor Coolant Pump Region, only one (1) phenomenon or process has been ranked as being "H" or of high importance in period P3 or earlier. That phenomenon or process, and its associated SoK is:

Table 9-9 High Ranked Cold Leg/Reactor Coolant Pump Region (From Table 8-17)

High-Ranked Phenomenon/Process	Period of High Ranking	SoK
4. Transport of solids to lower plenum due to re-filtering of coolant at the sump screen as related to ECCS flow split to lower plenum via downcomer or to sump via cold leg break.	P3	M

From Table 8-19, Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W-NSSS), one (1) phenomenon or process has been ranked as being "H" or of high importance in period P3 or earlier. That phenomenon or process and its associated SoK is:

Table 9-10 High Ranked Reactor Vessel Vent Valves/Upper Plenum Cylinder Region (B&W-NSSS) (From Table 8-19)

High-Ranked Phenomenon/Process	Period of High Ranking	SoK
4. Transport of solutes and solids to downcomer region due to carryover from upper plenum to downcomer via the RVVVs.	P2, P3	M

From Table 8-21, Transport of Solids and Solutes from the Reactor to the Reactor Containment Building, two (2) phenomena or processes have been ranked as being "H" or of high importance in period P3 or earlier. Those processes or phenomena and their associated SoK are:

Table 9-11 High Ranked Transport of Solid and Solutes from the Reactor to the Reactor Containment Building (From Table 8-21)

High-Ranked Phenomenon/Process	Period of High Ranking	SoK
2. Capture of solutes and solids within the debris bed/filter formed by collection of debris on the containment building sump recirculation screen or entrapment of those materials by that bed/filter.	P3	M
3. Transport of solutes or solids to the decay heat cooler if suction to one LPI pump is switched to the hot leg decay heat drop line	P3	M

Reviewing the above excerpts, it is noted that, in all cases, when the thermal-hydraulic mixing phenomena or process importance was ranked as "H", the PIRT panel determined that the state of knowledge was medium. This suggests that there is at least some knowledge of the phenomena or process with which to understand and model it, and evaluate the uncertainty associated with it.

10 RECOMMENDATIONS

The PIRT tables provide guidance for the PWROG comprehensive test and analysis effort to close GSI-191. As the PIRT evaluation of Thermal/Hydraulic Mixing phenomena processes ranked the States of Knowledge for the high-ranked phenomena and processes as "M", this guidance is heavily directed at chemical effects phenomena and processes.

Those phenomena and processes that are ranked "H" in importance and "L" for a State of Knowledge are candidates for additional study to improve the SoK associated with such phenomena or processes. Specifically, these phenomena and processes include:

- Radiation-induced debris bed chemical reactions. Concentration of radionuclides leads to locally high radiation fields and changes in dissolution and precipitation processes.[1]
- For a cold-leg break, fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration.
- For a cold-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration
- For a hot-leg break, chemical products in combination with fibrous debris collecting on fuel elements alter flow patterns and mixing volumes, changing the risk of precipitation due to boiling concentration
- Impact of kinetics of precipitation. Non-equilibrium effects are a benefit as they may delay precipitation.
- Particulate settling in the reactor. Particulate settling may occur due to relatively low, upwards flow (for cold leg injection for cold leg breaks) within reactor.
- Deposition. Chemical products formed during all periods of ECCS operation may deposit on other surfaces.

In addition, there may be some advantage to gaining additional information for some phenomena or processes that are ranked "H" in importance but whose SoK is ranked as "M." For these phenomena, it is further suggested that a cost-benefit exercise be performed before work is undertaken to determine if the increase in SoK is worth the cost of obtaining the information.

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[1] This phenomenon is ranked as "N/A" in periods P1 and P2, as "M" in period P3 and as "H" in periods P4 and P5. Although the focus of this PIRT is on period P3, this phenomenon is included in this list for completeness.

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