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PRESSURIZED-WATER-REACTOR DEBRIS TRANSPORT IN DRY AMBIENT CONTAINMENTS— PHENOMENA IDENTIFICATION AND RANKING TABLES (PIRTs)

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December 14, 1999

Executive Summary

The United States Nuclear Regulatory Commission (NRC) has sponsored the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena and processes associated with the transport of debris in a pressurized water reactor (PWR) containment following the initiation of one or more accident sequences. The PIRT documented herein will be used to support decision making regarding analytical, experimental, and modeling efforts related to debris transport within a PWR containment.

The issue of degradation of long-term cooling by debris transport and deposition was considered during the early 1980s through efforts associated with unresolved safety issue (USI) A-43. The accumulation of debris on sump screens (or strainers) will increase the resistance to flow across the screen and thus reduce the net positive suction head available to the emergency core cooling system (ECCS) pumps drawing suction from the sump.

In 1993, following several suction strainer debris blockage events at boiling water reactor (BWR) stations, the NRC initiated a reevaluation of the potential for loss-of-coolant-accident (LOCA) generated debris to block BWR suction strainers and prevent the ECCS from performing its long-term cooling function. The BWR-focused evaluation concluded that debris generated during a LOCA might prevent the ECCS from performing its long-term cooling function. It was determined that the ECCS would not function as intended following events that generated and transported debris to the BWR wetwell. Based on the results of the evaluation effort, the NRC issued bulletin 96-03 and Regulatory Guide 1.82, Revision 2.

Given the insights developed from the BWR debris transport and blockage study, the NRC is now reassessing debris blockage of PWR sumps to determine if there is a need for further action to be taken for PWRs beyond the original resolution of USI A-43. One element of the reassessment is the preparation of the PIRT documented herein.

The PIRT development process facilitates the structured collection and documentation of informed (expert) judgment with respect to phenomena identification and ranking. The quality and accuracy of a PIRT are related directly to the expertise of the panel members and the technical database available to the panel. For this PIRT activity, a modest database of experimental and technical results existed to support the PIRT effort. A vita for each member of the PIRT panel is presented in Appendix A.

There are a number of PWR containment types, including large dry, subatmospheric, and ice condenser. An essential element of the PIRT process is that the panel focus on a specific containment design and accident scenario. Once the initial PIRT is completed, other containment designs and plant types can be considered, building on the base of the original PIRT. For the initial PIRT, the panel identified the base configuration as a Westinghouse four-loop PWR with a dry ambient containment. The panel selected a double-ended, cold-leg, large-break LOCA for the baseline scenario.

The event scenario was divided into three time phases: blowdown between event initiation and 40 s; post blowdown between 40 s and 30 min; and sump operation between 30 min and 2 days. Each phase was characterized with respect to physical conditions, key phenomena and processes, and equipment operation.

The containment was partitioned into three components: (1) the containment open areas, excluding the potential pool in the bottom of the containment and the debris-generating zone-of-influence in the vicinity of the break; (2) the containment structures; and (3) the containment floor upon which a liquid pool forms in the lower containment elevations.

The panel identified a primary evaluation criterion for judging the relative importance of the phenomena and processes important to PWR containment debris transport. The criterion was the fraction of debris mass generated by the LOCA that is transported to the sump entrance. Each phenomenon or process identified by the panel was ranked relative to its importance with respect to the transportation of debris to the sump entrance. Highly ranked phenomena and processes were judged to have a dominant impact with respect to the primary evaluation criterion. Medium-ranked phenomena and processes were judged to have a moderate impact with respect to the primary evaluation criterion. Low-ranked phenomena and processes were judged to have a small impact with respect to the primary evaluation criterion.

The results of the panel's identification and ranking efforts are tabulated below. All processes and phenomena that were ranked as being either of "Medium" or "High" importance relative to the primary evaluation criteria presented. The "High" ranked processes and phenomena are highlighted in bold type. The complete tabulation of processes and phenomena, and the ranking for each, are presented in Section 4.

During the 40-s blowdown phase, a single process/phenomenon was ranked "High," i.e., the gravitational settling of large pieces of debris was generated by the break jet flow in the first few seconds following LOCA initiation.

During the nearly 30-min post-blowdown phase, 14 highly ranked processes/phenomena were identified. Droplet motions and sweepout remove suspended debris from the containment open areas. The highly ranked processes/phenomena related to the containment structures are the movement of liquid along surfaces (draining); transport of debris in liquid streams (deluge transport); disintegration of calcium silicate insulation; and entrapment of debris, a debris depletion process. The highly ranked processes/phenomena at the containment floor are (1) the formation, agitation, and dynamics of a pool on the containment floor; (2) the entry into that pool of debris draining from vertical surfaces (film transport) and horizontal surfaces (liquid transport); (3) disintegration of calcium silicate; (4) transport of debris within the pool; and (5) the settling of the debris in the pool in locations where pool agitation was insufficient to keep debris suspended.

During the period of sump operation beginning at 30 min and continuing to 48 h, six highly ranked processes/phenomena were identified, all of which occur in the pool on the containment floor. Pool thermal-hydraulic processes of importance are pool agitation by liquid streams still entering the pool from above and the associated pool dynamics leading to reentrainment of debris that settle to the containment floor. Transport of the debris to the sump following sump activation and transport of debris over the sump curb to the trash rack were also of high importance.

A total of 25 processes/phenomena were judged to be of medium importance. Although priority is naturally assigned to highly ranked processes and phenomena, the medium-ranked processes and phenomena should also be considered when planning experimental and analytical efforts.

Blowdown Phase (0–40 s)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT OPEN AREAS	Thermal-hydraulic related	Pressure driven flows (bulk flows)	M
	Debris related	Advection	M
		Gravitational settling	H
CONTAINMENT STRUCTURES	Thermal-hydraulic related	Surface wetting (condensation, impact)	M
	Debris related	Entrapment	M
		Inertial impaction	M/L/-
		Adhesion	M/L/-
CONTAINMENT FLOOR	Thermal-hydraulic related	Sheeting flow dynamics	L/M/-
		Sheet transport	L/M/-
		Entrapment by porous structures	L/M/-

Post-Blowdown Phase (40 s–30 min)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT OPEN AREAS	Thermal-hydraulic related	**Droplet motions**	H
	Debris related	**Sweepout**	H
		Gravitational settling	M
		Condensation on particles	M
CONTAINMENT STRUCTURES	Thermal-hydraulic related	Surface pooling	L/M/L
		Surface draining	H
	Debris related	**Deluge transport**	H
		Film related transport	M
		Disintegration	M/H/L
		Entrapment	H
		Adhesion	M
CONTAINMENT FLOOR	Thermal-hydraulic related	**Pool formation**	H
		Pool agitation	H
		Pool flow dynamics	H
	Debris related	**Entry via film transport**	H
		Entry via liquid transport	H
		Disintegration	L/H/L
		Pool transport	H
		Settling	H
		Entrapment by porous structures	M

Notes

①: Multiple rankings appear, e.g., L/H/L if the panel found it necessary to differentiate between debris types; the justification is provided in the applicable appendix (see sections 4.1–4.3). The multiple rankings are, in order, for fibrous/calcium silicate/reflective metallic insulation, respectively.

Sump Operation Phase (30 min–48 h)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT OPEN AREAS	Thermal-hydraulic related	None ranked H or M	
	Debris related	None ranked H or M	
CONTAINMENT STRUCTURES	Thermal-hydraulic related	Surface draining	L/M/L
	Debris related	Deluge transport	L/M/L
		Film-related transport	L/M/L
		Disintegration	L/M/L
CONTAINMENT FLOOR	Thermal-hydraulic related	**Pool agitation**	**H**
		Pool flow dynamics	**H**
	Debris related	**Sump-induced flow**	**H**
		Entry via film transport	L/M/L
		Entry via liquid transport	L/M/L
		Reëntrainment	**H**
		Disintegration	L/M/L
		Pool transport	**H**
		Agglomeration in pool	M/L/L
		Settling	M
		Sump-induced overflow	**H**
		Debris-created flow obstructions	M

Notes

①: Multiple rankings appear, e.g., L/M or L/H/L if the panel found it necessary to differentiate between debris types; the justification is provided in the applicable appendix (see sections 4.1–4.3). The multiple rankings are, in order, for fibrous/calcium silicate/reflective metallic insulation, respectively.

The panel also assessed the applicability of the PIRTs developed for the selected dry ambient containment and other dry ambient containments. The panel concluded that the identified processes and phenomena appear to be generally applicable to all dry ambient containments. The panel also concluded that the importance of each of the processes and phenomena are somewhat dependent on the specific design of each containment type. The panel concluded that the plant-specific PIRTs appearing in Section 4 may be used as a tool to support plant-specific decision making about either the capabilities of analytical tools or the details of experimental test program if the focus is only on the identified processes and phenomena. However, if decisions are to be made based upon the phenomena rankings, a mini-PIRT effort should be conducted to ensure that the rankings apply to the specific facility or generate revised rankings that are specific to the given facility.

Acknowledgments

Several organizations and individuals were most supportive of the PIRT panel efforts. Although the PIRT panel maintained an independent and separate perspective, the panel acknowledges the help received from the following individuals.

- Michael Marshall Jr. of the NRC's Office of Nuclear Regulatory Research for his help in facilitating the panel's understanding of needs, as well as providing invaluable assistance in each of the panel's meetings.
- D.V. Rao and Bruce Letellier and other staff of LANL Group TSA-11 for their help in facilitating the panel's understanding of debris transport processes by assisting in our review of plant designs, experimental data, and analytical results.
- Gary Wilson, chairman of the counterpart boiling water reactor debris transport PIRT panel. Much of the structure and tables of the current document are modeled after the final report of that effort. Mr. Wilson had the lead role in preparing that document. We also acknowledge the contributions of the other members of the panel to the BWR debris transport PIRT document: Brent E. Boyack, Mark T. Leonard, Ken A. Williams, and Lothar T. Wolf.

Finally, we thank Gloria E. Mirabal of LANL Group TSA-10 for editing this report.

Nomenclature

B&W	Babcock and Wilcox
BWR	Boiling Water Reactor
Cal-Sil	Calcium Silicate
CE	Combustion Engineering
CFD	Computational Fluid Dynamics
CL	Cold Leg
DEGB	Double-Ended Guillotine Break
ECCS	Emergency Core Cooling System
GSI	Generic Safety Issue
HL	Hot Leg
LB	Large Break
L/D	Length-to-Diameter Ratio
LOCA	Loss-of-Coolant Accident
LWR	Light-Water Reactor
MIT	Massachusetts Institute of Technology
NA	Not Applicable
NPP	Nuclear Power Plant
NPSH	Net Positive Suction Head
USNRC	United States Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
RHR	Residual Heat Removal
RMI	Reflective Metallic Insulation
USI	Unresolved Safety Issue
W	Westinghouse
ZOI	Zone of Influence

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FIGURES (cont)

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B. E. Boyack, T. S. Andreychek, P. Griffith, F. E. Haskin, and J. Till

Abstract

The United States Nuclear Regulatory Commission has sponsored the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena and processes associated with the transport of debris in a pressurized-water-reactor (PWR) containment following the initiation of selected accident sequences. The accumulation of debris on sump screens (or strainers) will increase the resistance across the screen and thus reduce the net positive suction head available to the emergency core cooling system pumps drawing suction from the sump. The PIRT will be used to support decision making regarding analytical, experimental, and modeling efforts related to debris transport within a PWR containment.

The PIRT panel identified and ranked processes and phenomena for a large-break loss-of-coolant accident in a Westinghouse four-loop plant with a large dry containment. The scenario was divided into three phases: blowdown (0–40 s), post-blowdown (40 s–30 min), and sump operation (30 min–48 h).

Each phenomenon identified by the panel was ranked relative to its importance with respect to a primary evaluation criterion: namely, the transport of debris to the sump entrance. A high-ranked phenomenon has a dominant impact on the primary evaluation criterion. The phenomena should be explicitly and accurately modeled in code development and assessment efforts. The phenomena should be explicitly considered in any experimental program. A medium-ranked phenomenon has moderate influence on the primary evaluation criterion. The phenomena should be well modeled; however, accuracy may be somewhat compromised in code development and assessment efforts. The phenomena also should be considered in any experimental programs. A low-ranked process/phenomenon has a small effect on the primary evaluation criterion. The phenomena should be represented in the code, but almost any model will be sufficient. The phenomena should be considered in any experimental programs to the extent possible.

During the blowdown phase, 1 phenomenon was judged by the PIRT panel to be of high importance and 9 were judged to be of medium importance. During the post blowdown phase, 11 phenomena were judged to be of high importance and 7 were judged to be of medium importance. During the sump operation phase, 6 phenomena were judged to be of high importance and 10 were judged to be of medium importance.

The panel also assessed the applicability of the PIRTs developed for the selected dry ambient containment and other dry ambient containments. The panel concluded that the identified processes and phenomena appear to be generally applicable to all dry ambient containments. The panel also concluded that the importance of each of the processes and phenomena are somewhat dependent on the specific design of each containment type.

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1. INTRODUCTION

The United States (US) Nuclear Regulatory Commission (NRC) has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena and processes associated with the transport of debris in a pressurized-water-reactor (PWR) containment following the initiation of one or more accident sequences. The remainder of this report collects and documents the findings of the PWR debris transport PIRT panel.

The report is organized into four sections and contains three supporting appendices. Section 1, Introduction, summarizes the issues associated with debris generation and transport, provides an overview of the PIRT process, identifies the members of the PWR Debris Transport PIRT panel, and identifies the objectives of the PIRT effort. Section 2, PIRT Preliminaries, describes elements of the PIRT process as applied to the PWR debris transport issue that precede the identification and ranking of phenomena and processes. Section 3, Experimental and Analytical Data Bases, documents the elements of the experimental and analytical database reviewed and used by the PIRT panel members in support of the phenomena identification and ranking process. Section 4, PWR Debris Transport PIRTs, contains the PIRTs for PWR debris transport for each of the three phases into which the accident scenario was partitioned, namely the blowdown, post blowdown, and sump operation phases of a large, cold-leg-break, loss-of-coolant accident (LOCA). Brief experience summaries for each panel member are provided in Appendix A. Important supporting information is provided in the remaining two appendices. Appendix B contains descriptions for each of the phenomena and processes identified as part of the PIRT effort. Appendix C contains the rationale for each ranking.

1.1. Background

10 CFR 50.46,[1-1] "Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Reactors" requires all light water reactors (LWRs) to provide an emergency core cooling system (ECCS) that is designed to meet five criteria. One of these criteria specifies the requirement for maintenance of long-term cooling. The criteria are [10CFR50.46(b)(5)]: *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 radio-activity of the core.*

The issue of degradation of long-term cooling by debris transport and deposition was considered during the early 1980s through efforts associated with unresolved safety issue (USI) A-43. Debris blockages may impede or prevent long-term cooling in several ways. First, the accumulation of debris on sump screens (or strainers) will increase the resistance across the screen and thus reduce the net positive suction head (NPSH) available to the ECCS pumps drawing suction from the sump. Second, the accumulation of debris at the sump screen or along the flow paths on the containment floor or basemat may form dams that prevent or impede the flow of water into the sump. If this happens, the water level in the sump can be drawn down, thereby reducing the NPSH available to the ECCS pumps. The USI A-43 evaluation and resolution focused primarily on PWRs, but its results were considered applicable to boiling water reactors (BWRs). The resolution of USI A-43 was documented in NRC Generic Letter 85-22[1-2] and Regulatory Guide 1.82, Rev. 1.[1-3]

In 1993, following several suction strainer debris blockage events at BWR stations, the NRC initiated a reevaluation of the potential for LOCA-generated debris to block BWR suction strainers and prevent the ECCS from performing its long-term cooling function. A review of incidents that have occurred to date indicated two general categories of ECCS strainer blockage mechanisms. The first category, as typified by an incident in the Barsebäck BWR plant in Sweden following a spurious opening of a safety valve, involves debris generation due to blast effects of high-velocity coolant discharge from the primary coolant system onto piping insulation. Transport of fibrous debris to, and collected on, sump debris screens reduces NPSH and degrades pump performance. The second category involved US incidents in which degraded residual heat removal (RHR) pump performance was observed as a consequence of preexisting debris and sludge in the suppression pool collecting on ECCS strainers.

The BWR-focused evaluation concluded that debris generated during a LOCA might prevent the ECCS from performing its long-term cooling function.[1-4] It was determined that the ECCS would not function as intended following events that generated and transported debris to the BWR wetwell. Accordingly, the NRC issued NRC Bulletin 96-03[1-5] and Regulatory Guide 1.82, Rev. 2.[1-6] Corrective actions were required in BWR plants that could not certify sufficient cooling.

Given the insights developed from the BWR debris transport and blockage study, the NRC is reassessing debris blockage of PWR sumps to determine if there is a need for further actions to be taken for PWRs beyond the original resolution of USI A-43. The review effort is encompassed within the scope of Generic Safety Issue (GSI)-191, "Assessment of Debris Accumulation on Pressurized Water Reactors Sump Performance."

1.2. PIRT Panel Membership

The panel members were selected after considering the phenomena and processes that could be expected to arise following PWR accidents that could (1) generate significant amounts of fibrous, particulate, and metallic debris; (2) transport debris to the containment basemat; and (3) reduce ECCS recirculation through the sump.

The PWR Debris Transport PIRT panel members are

- Mr. Tim Andreychek, Westinghouse Electric Corporation (W);
- Dr. Brent E. Boyack, Los Alamos National Laboratory, Panel Chairman;
- Dr. Peter Griffith, retired professor Massachusetts Institute of Technology;
- Dr. F. Eric Haskin, consultant; and
- Mr. Jack Tills, Jack Tills and Associates.

Brief experience summaries for each panel member are presented in Appendix A.

1.3. PIRT Overview

The PIRT process has evolved from its initial development and application[1-7, 1-8, 1-9] to its description as a generalized process.[1-10] After development, a PIRT can be used to support several important decision-making processes. For example, the information obtained through the application of the PIRT process can be used to support a definition of requirements for related experiments and/or analytical tools.

Because importance ranking is a fundamental element of the PIRT process, requirements can be prioritized with respect to their contributions to the reactor phenomenological response to the accident scenario. Because it is neither cost effective nor required to assess and examine all the parameters and models in a best-estimate code (or supporting experiment) in a uniform fashion, the methodology focuses on those processes and phenomena that dominate the transient behavior, although all plausible effects are considered. This screening of plausible phenomena to determine those that dominate the plant response ensures a sufficient and efficient analysis. PIRTs are not computer-code specific; that is, PIRTs are applicable to the scenario and plant design regardless of which code may be chosen to perform the subsequent safety analysis.

A typical application of the PIRT process is conceptually illustrated in Fig. 1-1 and described as follows. The PIRT process focuses on phenomena/processes that are important to the particular scenario, or class of transients, in the specified nuclear power plant (NPP), i.e., those that drive events. Plausible physical phenomena and processes and their associated system components are identified. From a modeling perspective, phenomena/processes important to a plant response to an accident scenario can be grouped in two separate categories: (1) higher-level system interactions (integral) between components/subsystems and (2) those local to (within) a component/subsystem. The identification of plausible phenomena is focused toward component organization, but experience has indicated it can be most helpful to relate the phenomena to higher-level integral system processes. Time can often be saved when it can be demonstrated that a higher-level integral system process is of low importance during a specific time phase. A subsequent and equally important step is the partitioning of the plant into components/subsystems. This latter step is a significant aid in organizing and ranking phenomena/processes. The phenomena/processes are then ranked with respect to their influence on the primary evaluation criteria to establish PIRTs. Primary evaluation criteria (or criterion) are normally based on regulatory safety requirements such as those related to restrictions in fuel rods (peak clad temperature, hydrogen generation, etc.) and/or

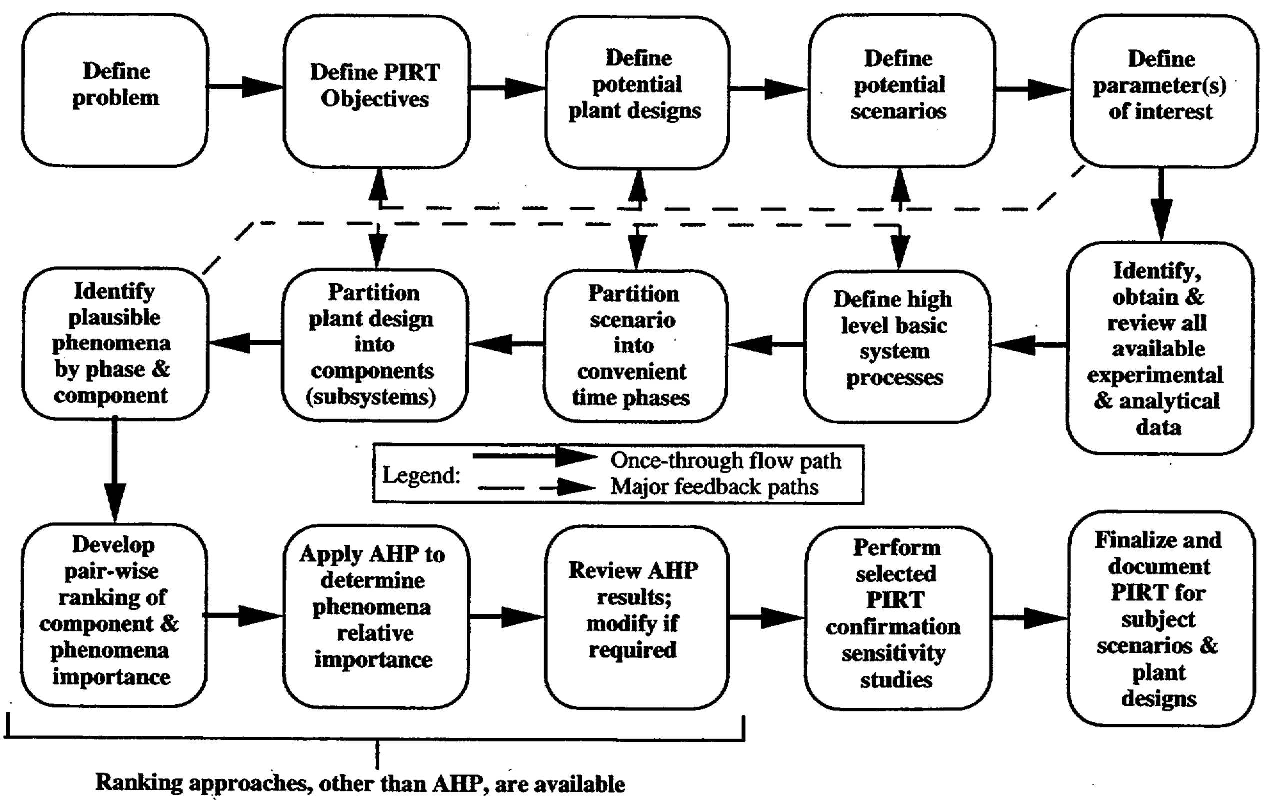

Fig. 1-1. Illustration of a typical PIRT process.

containment operation (peak pressure, ECCS performance, etc.). The rank of a phenomenon or process is a measure of its relative influence on the primary criteria (criterion). The identification and ranking are justified and documented.

The relative importance of phenomena is time dependent as an accident progresses. Thus, it is convenient to partition accident scenarios into time phases in which the dominant phenomena/processes remain essentially constant; each phase is separately investigated. The processes and phenomena associated with each component are examined, as are the interrelations between the components. Cause and effect are differentiated. The processes and phenomena and their respective importance (rank) are judged by examination of experimental data, code simulations related to the plant and scenario, and the collective expertise and experience of the evaluation team. Independent techniques to accomplish the ranking include expert opinion, subjective decision-making methods (such as the Analytical Hierarchy Process), and selected calculations. The final product of application of the PIRT process is a set of tables or PIRTs documenting the ranks (relative importance) of phenomena and processes by transient phase and by system component. Supplemental products include descriptions of the ranking scales, phenomena and processes definitions, evaluation criteria, and the technical rationales for each rank. In the context of the PIRT process application to PWR containment debris transport, the primary elements of interest are described in Section 2. The PIRTs resulting from this specific application are documented in Section 4.

1.4. PIRT Objectives

The PIRT panel has been organized to develop a PIRT for PWR debris transport. The PIRT is to be developed and documented so that it can be used to help guide future NRC-sponsored analytical, experimental, and modeling efforts conducted as part of the GSI-191 study.

1.5. References

1-1. Code of Federal Regulations, 10CFR50.46, Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Reactors, revised as of January 1, 1995.

1-2. United States Nuclear Regulatory Commission generic letter 85-22.

1-3. United States Nuclear Regulatory Commission Regulatory Guide 1.82, "Water Sources for Long Term Recirculation Cooling Following a Loss-of-Coolant Accident," Rev. 1.

1-4. G. Zigler, J. Brideau, D. V. Rao, C. Shaffer, F. Souto, and W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," Science and Engineering Associates, Inc., document NUREG/CR-6224 (SEA No. 93-554-0-A:1) (October 1995).

1-5. United States Nuclear Regulatory Commission Bulletin 96-03.

1-6. United States Nuclear Regulatory Commission Regulatory Guide 1.82, "Water Sources for Long Term Recirculation Cooling Following a Loss-of-Coolant Accident," Rev. 2.

1-7. TPG (Technical Program Group), "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," EG&G Idaho, Inc. document NUREG/CR-5249 (1989).

1-8. TPG (Technical Program Group), "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," *Nuclear Engineering and Design* **119** (1990): B. E. Boyack et al., Part 1: An Overview of the CSAU Evaluation Methodology; G. E. Wilson et al., Part 2: Characterization of Important Contributors to Uncertainty; W. Wulff et al., Part 3: Assessment and Ranging of Parameters; G. S. Lellouche et al., Part 4: Uncertainty Evaluation of LBLOCA Analysis Based on TRAC-PF1/MOD1; N. Zuber et al., Part 5: Evaluation of Scale-Up Capabilities of Best Estimate Codes; I. Catton et al., Part 6: A Physically Based Method of Estimating PWR LBLOCA PCT.

1-9. R. A. Shaw, T. K. Larson, and R. K. Dimenna, "Development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic Phenomena During a PWR LBLOCA," EG&G Idaho, Inc. report NUREG/CR-5074 (1988).

1-10. G. E. Wilson and B. E. Boyack, "The Role of the PIRT Process in Experiments, Code Development, and Code Applications Associated with Reactor Safety Analysis," *Nuclear Engineering and Design* **186**, 23–37 (1998).

2. PIRT PRELIMINARIES

Several important preliminary steps must be completed in advance of the identification and ranking efforts of the PIRT process. The PIRT objective was defined and documented in Section 1.4. During the PIRT development process, each PIRT is developed for a specific plant and scenario because both the occurrence of phenomena and processes and the importance of phenomena and processes are plant and scenario specific. After considering other plants and scenarios, it may be possible for the PIRT panel to certify that the PIRT has broader applicability. The plant and containment designs selected for the PWR debris transport PIRT effort are discussed in Section 2.1. The accident scenario selected for the PWR debris transport PIRT is discussed in Section 2.2. A given phenomenon or process does not always have the same impact on the transport of debris throughout the entire accident. Therefore, the accident scenario is divided into phases. The phases defined for the selected accident scenario are described in Section 2.3. Previous PIRT panels have found it helpful to divide the physical space in which the accident occurs into smaller units, e.g., components. The components defined for the PWR debris transport PIRT are described in Section 2.4. The PIRT panel performs the ranking effort relative to a primary evaluation criterion. Therefore, it is important that this criterion be explicitly defined, as done in Section 2.5. Finally, the ranking scale used by the PIRT panel must be explicitly defined, as done in Section 2.6.

2.1. Selected Plant and Containment

There are a number of PWR reactor and containment types, which are summarized in the following table for Babcock and Wilcox (B&W), Combustion Engineering (CE) and Westinghouse (W) plants.

	Containment Type[2-1]			
Plant Type	Ice Condenser	Dry Ambient	Sub-atmospheric	Subtotals
B&W Lowered Loop		8		8
B&W Raised Loop		2		2
CE		12		12
CE80		3		3
W Two Loop		6		6
W Three Loop		6	7	13
W Four Loop	9	22	1	32
Subtotals	9	59	8	76

As discussed in Section 1.3, the development of a PIRT proceeds by considering a specific plant and containment combination. However, the NRC staff is seeking PIRT insights covering the broadest set of plant types and containment combinations possible. The PIRT panel was asked to develop findings that would be applicable to the broadest possible set of plant, containment, and sump designs.

The PIRT panel approached this commission in a sequential manner. The obvious selection for the first plant/containment combination was a W four-loop plant with dry ambient containment. The panel did not focus on a specific W plant. The design considered in the initial PIRT effort included fan coolers and containment sprays. Because sump designs vary from plant to plant, even within the group of W plants, the panel considered two sump configurations with respect to curb height, i.e., the vertical height at the sump to which the water must rise before it is available to the ECCS via the sump. The panel considered a minimum curb height, defined to be ~1.5 in., and a nominal design curb height of ~6 in.

Subsequently, the panel extended its considerations to the following plant/containment types: B&W lowered loop, B&W raised loop, CE, CE System 80, W two loop, W three loop, and other W four loop.

2.2. Accident Scenario

GSI-191 addresses whether debris accumulation can degrade PWR ECCS delivery via the sump. Therefore, the spectrum of accident scenarios to be considered in the PWR debris transport PIRT effort is limited to those scenarios leading to recirculation of water from the containment sump to the core and containment cooling systems following the depletion of cooling water from the refueling water storage tank.

The panel selected a double-ended, cold-leg (CL), large-break (LB)LOCA for the baseline scenario. The plant is assumed to be operating at full power at the time of event initiation. Because related studies to define the debris generation potential of a spectrum of LOCA break sizes were ongoing at the time the panel began its activities, the CL LBLOCA was selected as an event likely to generate a significant amount of debris and include all the pertinent processes and phenomena. This is thought to be adequate because the PIRT process focuses on the identification and ranking of processes and phenomena rather than evaluating the magnitude (quantifying) outcomes.

Another candidate sequence is a spectrum of hot-leg (HL) LOCA break sizes. The PIRT panel did not select these sequences because they do not progress along a path leading to recirculation of emergency core coolant from the sump.

For illustration, a generic representation of the break location in a W four-loop plant is found in Fig. 2-1.

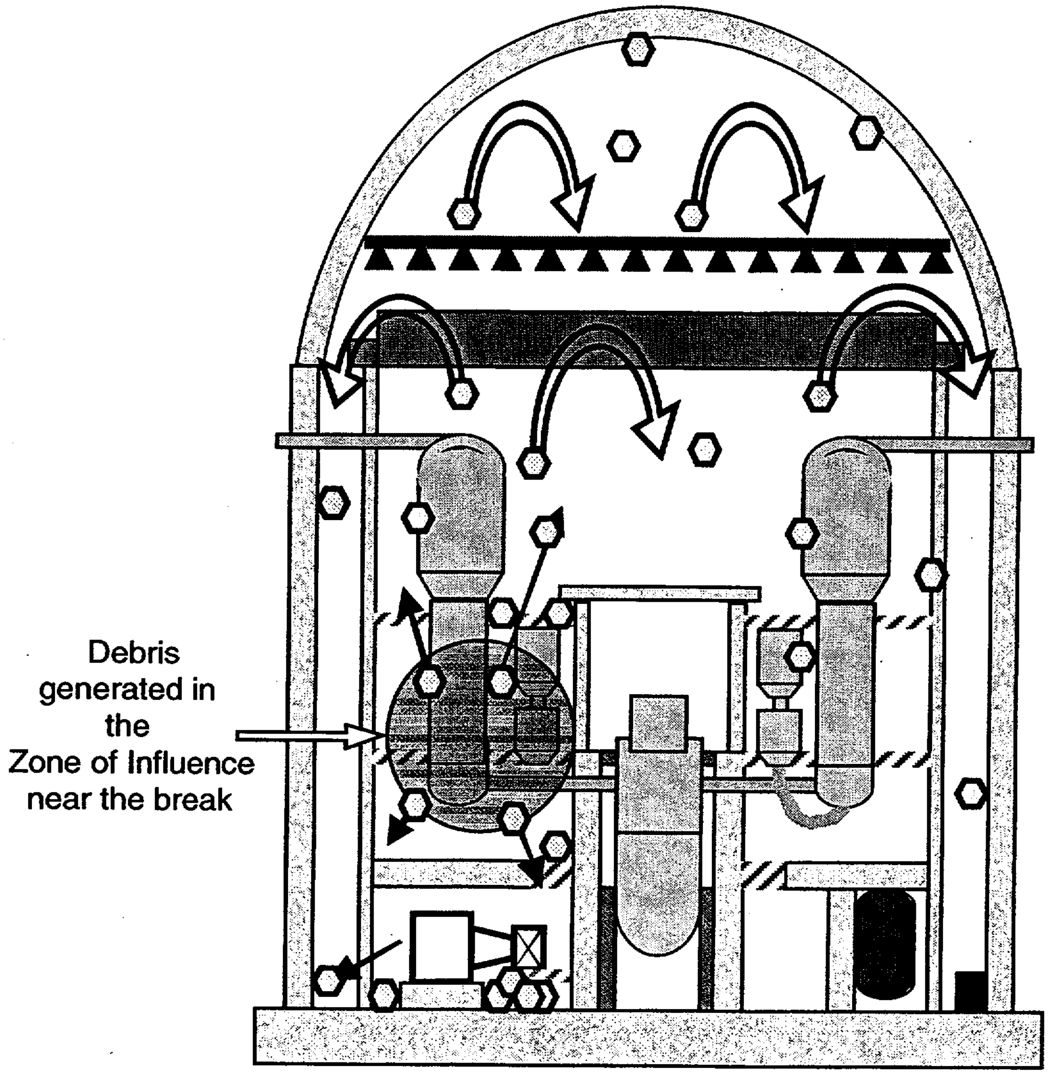

Fig. 2-1. Break location in a W four-loop plant.

2.3. Scenario Phases

The CL LBLOCA identified in Section 2.2 was divided into three time phases. Each phase is characterized in Table 2-1 with respect to physical conditions, key phenomena and processes, and equipment operation.

Table 2-1
Description of Scenario Phases

Phase	Time Interval (s)	Description
1 Blowdown	0–40	• Two-phase coolant is exhausted into the containment until the end of the phase. • Containment temperature peaks and begins to decrease; pressure approaches its peak value. • Debris is generated by the exhaust of two-phase coolant through the break into the containment open areas. Debris generation ends after ~10 s. Generated debris includes insulation on affected Nuclear Steam Supply System (NSSS) components and piping, containment and structural coatings, and particulate debris. • In-containment structural elements and NSSS components are wetted by the break coolant. • Liquid begins to accumulate on the containment floor. The liquid first appears as a sheet on the concrete surface that spreads due to liquid streaming down from above from the break, condensate draining from cooling elements of the fan coolers, and energetic air movement in the containment.
2 Post Blowdown	40–1800	• Containment temperature continues to decrease; the pressure peaks and begins to decrease. • The containment fan coolers continue to operate. • Two-phase coolant continues to exhaust into the containment from the vessel and pump ends of the double-ended break, but the energetics are small compared with the blowdown phase. • Agitation in the containment environment is at much lower levels than during the blowdown phase. • Safety injection and containment sprays are initiated from the refueling water storage tank (RWST). • The containment sprays wash debris deposited on structures during the blowdown from the structures. Transportable debris is carried with the fluid streams to the containment floor. • The pool height increases. Pool dynamics are dominated by the streams of water entering from above (sump not operating). Pool energetics are strongest where the water enters the pool and diminish with distance and depth. The pool reaches its maximum height at the end of this phase. • Switchover from RWST injection to sump recirculation occurs at 1800 s.[a] Containment spray supply and core coolant are drawn from the sump.
3 Sump Operation	1800 s–48 h	• Containment pressure and temperature continue to decrease. • The containment fan coolers continue to operate. • Two-phase coolant continues to exhaust into the containment from the both ends of the double-ended break. • Little additional washdown and transport of debris to the pool occurs. • Pool flow fields are established and pool dynamics dominated by the directed flows to the sump(s). • Containment sprays are terminated after 2 h, but recirculation to the core via the sump continues. The directed flows in the pool to the sump decrease in proportion to the decreased demands for sump flow with termination of the containment sprays.

[a] Assumed by the PIRT panel as the baseline; actual switchover times are plant dependent.

2.4. Containment Partitions (Components)

The PWR Debris Transport PIRT panel benefited from previous work[2-2] that provided insights regarding a consistent framework for partitioning the containment into the three components pictorially illustrated in Fig. 2-2 and described below.

- Open area: the free flow area, excluding the potential pool in the bottom of the containment and the debris-generating zone-of-influence (ZOI) in the vicinity of the break.
- Structures: all solid boundaries and barriers to the flow stream, including NSSS components, containment walls, pipes, cabinets, walls, grates, beams, component supports, cable trays, etc.
- Containment floor: the area where a liquid pool will form in the lower containment elevations.

<u>Boundary Conditions</u>

Several important regions that were not included in the PWR Debris Transport PIRT bound the components described above.

The first of these is referred to as the ZOI. The ZOI is that volume in which debris is generated by the direct action of jet impingement on nearby debris sources, e.g., insulation on pipes and NSSS components, containment and component coatings, etc. The ZOI concept was documented during the BWR debris transport study.[2-2, Section 3.4] The phenomena and processes occurring in this volume are the subject of a separate but related PWR Debris Sources PIRT.[2-3] The panel did consider various types of debris that would be generated by the selected accident scenario.

The second region not included in the PWR Debris Transport PIRT was the sump. The panel did consider all processes and phenomena in the containment floor area that could transport liquid and debris to the sump screens. This included processes and phenomena associated with any effective curbs, e.g., angle irons, upon which the sump screens were mounted or debris curbs located away from the sump screens on the containment floor.

2.5. System-Level Processes

During the preparation of an earlier BWR debris transport PIRT,[2-4] it was determined that major system-level interactions were important to the identification of the plausible phenomena, and were even more important in the subsequent ranking effort. Therefore, the following five high-level system processes, which were adopted to aid in the BWR effort, have also been used for the current PWR debris transport PIRT effort.

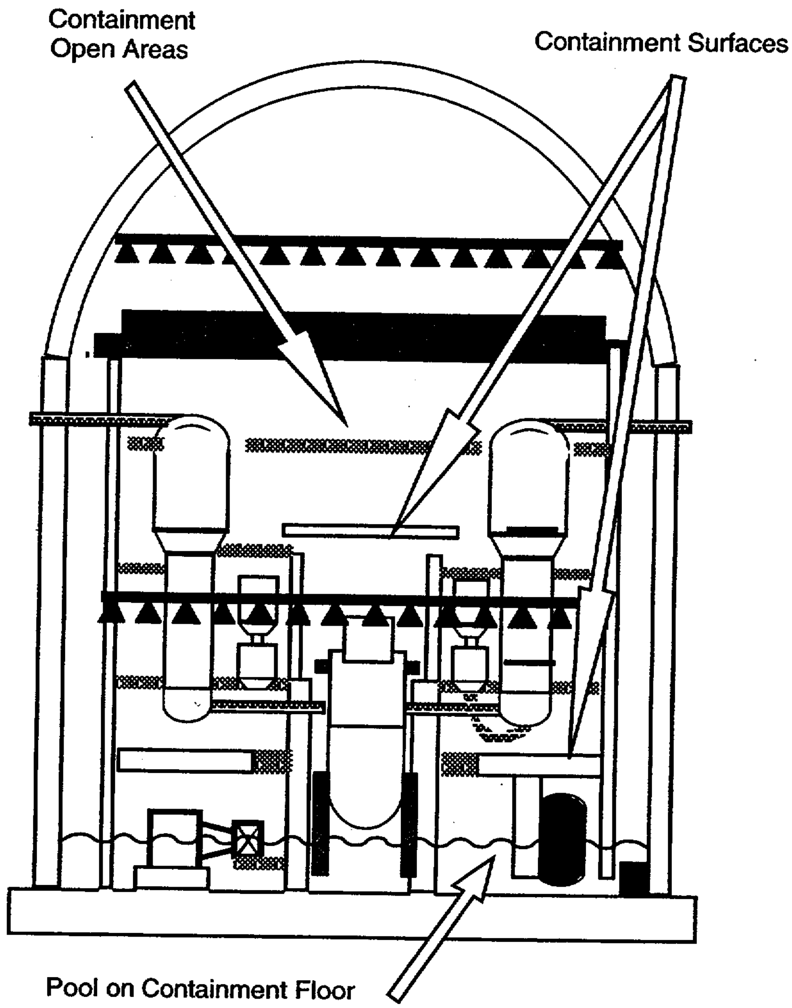

Fig. 2-2. Component partitioning of PWR containment.

- Gas/vapor transport—flow of noncondensables and steam through free stream paths and around structures.
- Suspended water transport—flow of liquid through free stream paths and around structures.
- Water depletion/accumulation/surface transport—capture, storage, and flow of liquid on the surface of containment internal structures.
- Debris transport—flow of debris through free stream paths and around structures, including transport via gas/vapor, liquid films, pool surfaces, and within pools.

- Debris depletion—capture and storage of debris by structures and liquid pools, including growth or fragmentation of the debris.

Features of these processes are pictorially illustrated in Figs. B1–B18 in Appendix B. These processes were used in their broadest sense solely as an aid in organizing the phenomena into tractable groups for further consideration in the ranking of relative importance. In this sense, relating a particular phenomenon to a system level process helps to define the context in which the importance of the phenomenon is judged.

2.6. Potential Debris Sources

The panel found it helpful to identify the potential sources of debris that could be generated by the scenario described in Section 2.2. Five sources of debris were considered by the panel are (1) fibrous insulation, (2) calcium silicate, (3) reflective metallic insulation, (4) paint chips, and (5) other debris such as dust and rust. Of these, the panel focused its ranking and identification efforts on the first three insulation systems and the debris that might be generated as these systems participated in the accident scenario.

Fibrous Insulation Systems

The insulation material can be of various types, including mineral, wool, and fiberglass. The insulation system may consist of the fiber in blankets and one or more coverings, including fabric and/or metal jacketing. The jackets are only provided on the outside of the insulation. Thus, a jacket does not protect the insulation on the pipe that breaks.

For example, the NUKON insulation system for piping consists of removable/reusable insulation blankets and removable/reusable metal jacketing. The NUKON blankets consist of the following five raw materials: (1) a low-density, flexible, resilient fibrous glass wool; (2) a woven fiberglass reinforcing scrim for the base wool; (3) a heavy, high-strength fabric cover; (4) a Velcro-type fastener; and (5) fiberglass thread. The metal jacketing is 22-gauge, 300-series stainless steel that wraps completely around the blankets. Jackets have rolled edges, lap joints, and a high-strength latch and strike combination riveted in place at least every 12 in. One jacket section is designed to overlap the adjacent section by ~3 in.

Two of the representative brands are NUKON and TRANSCO.

Calcium Silicate Insulation Systems

Calcium silicate molded block insulation is a molded, high-temperature pipe and block insulation composed of hydrous calcium silicate. Fibrous material may or may not be included. It is light weight, has low thermal conductivity, high structural strength, and is insoluble in water. Although insoluble, calcium silicate disintegrates when wetted. Calcium silicate particles remain suspended in water, presumably as a colloidal suspension. The molded blocks are provided in thicknesses of up to 4 in. and lengths of up to 3 ft. Fiber may be included in the block. The binder used to when preparing the insulated calcium shapes may be soluble.

The calcium silicate is encapsulated within a fiberglass cloth or a stainless steel or aluminum jacket. Sealing compounds are used to seal the joints against water intrusion.

Two of the representative brands are Newtherm 100 and Owens Corning.

Reflective Metallic Insulation Systems

The insulation used for piping is typically 2 ft or longer in length, 3 to 4 in. thick, and split into two sections with each section covering one-half of the pipe.

The insulation system consists of several layers of thin metallic sheets, typically 0.05 to 0.06 mm thick, which are usually encapsulated in a shell of a thicker metal sheet. The insulation is normally welded together in panels that are fitted to the hot structures. The dimensions and number of layers differ among manufacturers.

Two of the representative brands are Diamond Power and TRANSCO.

Coating Systems (Paint)

Coating systems are used extensively in containments, both on concrete and metallic structures. A variety of coating systems have been or are being used in containments. Some of these systems are listed below.

- Steel substrate, inorganic zinc primer, epoxy phenolic topcoat
- Steel substrate, epoxy phenolic primer, epoxy phenolic topcoat
- Steel substrate, inorganic zinc primer, epoxy topcoat
- Steel substrate, epoxy primer, epoxy topcoat
- Concrete substrate, surfacer, epoxy phenolic topcoat
- Concrete substrate, surfacer, epoxy topcoat
- Concrete substrate, epoxy phenolic primer, epoxy phenolic topcoat
- Concrete substrate, epoxy primer, epoxy topcoat

Several of the representative brands are Keeler and Long, Amercoat, Nu-Klad, and Dimetcote

Other

Grouped in the category of other are particulates such as concrete dust and particles of corrosion, i.e., rust.

2.7. Primary Evaluation Criterion

The primary evaluation criterion is used by the PIRT panel to judge the relative importance of the phenomena and processes important to PWR containment debris transport. For this PIRT effort, the primary evaluation criterion was based upon a single parameter, *the fraction of debris mass generated during the initial blowdown period within the ZOI that is transported to the sump entrance.*

Processes subsequent to the initiating event that substantially altered the transportability of debris (e.g., the degradation of calcium silicate when exposed to water) included the panel in the primary evaluation criterion as defined above.

2.8. Phenomena Ranking Scale

It was decided that the labor-intensive Analytical Hierarchy Process ranking methodology would not be used because of effort and cost constraints. Accordingly, it was decided that the low, medium, and high rank scheme should be adopted.

- High = The phenomena or process has dominant impact on the primary evaluation criterion, i.e., *the fraction of debris mass generated within the ZOI that is transported to the sump entrance.* The phenomena should be explicitly and accurately modeled in code development and assessment efforts. The phenomena should be explicitly considered in any experimental programs.

- Medium = The phenomena or process has moderate influence on the primary evaluation criterion. The phenomena should be well modeled, but accuracy may be somewhat compromised in code development and assessment efforts. The phenomena should also be considered in any experimental programs.

- Low = The phenomena or process has small effect on the primary evaluation criterion. The phenomena should be represented in the code, but almost any model will be sufficient. The phenomena should be considered in any experimental programs to the extent possible.

2.9. References

2-1. United States Nuclear Regulatory Commission information Digest: 1995 Edition, US Nuclear Regulatory Commission report NUREG-1350, Vol. 7 (March 1995).

2-2. G. Zigler et al., "Parametric Study of the Potential for BWR ECCS Strainer Blockage due to LOCA Generated Debris," Science and Engineering Associates, Inc. document NUREG/CR-6224 (October 1995).

2-3. B. E. Boyack, T. Andreychek, P. Griffith, F. E. Haskin, and J. Tills, "PWR Debris Source Term Phenomena Identification and Ranking Tables," Los Alamos National Laboratory draft document (June 28, 1999).

2-4. G. E. Wilson, B. E. Boyack, M. T. Leonard, K. A. Williams, and L. T. Wolf, "Final Report BWR Drywell Debris Transport Phenomena Identification and Ranking Tables (PIRTs)," Idaho National Engineering and Environmental Laboratory document INEEL/EXT-97-00894 (September 1997).

3. DATABASES

Although identification and ranking of processes and phenomena rely heavily on the expertise of the PIRT panel, both of these efforts proceed best when there are comprehensive databases of information upon which judgements are based. The experimental database used by the PWR Debris Transport PIRT panel is documented in Section 3.1. The analytical database used by the panel is documented in Section 3.2. Other information used by the panel is documented in Section 3.3. The relevant citations for each summary precede each summary, i.e., Refs. 3-1 through 3-23 are found in Section 3.1; Refs. 3-24 through 3-32 are found in Section 3.2; and Refs. 3–33 through 3.37 are found in Section 3.3.

3.1. Experimental

3-1. "Karlsham Tests 1992—Test Report—Steam Blast on Insulated Objects," ABB Atom document RVE 92-205 (November 1992).

Steam blast tests on a simulated containment geometry (very crude, and not scaled in any way) showed that a lot of fiber insulation is left behind in the complex geometry tested. These experiments are geometry sensitive and do not apply directly to PWR containments. The numerous pictures show fiber insulation plastered on practically every surface of the rig. In these tests, only 3% to 10% of the insulation made it into the location of the simulated pool.

During five of the steam-blast tests, mineral wool packed into silicon-coated fiberglass fabric was used. In one test, only mineral wool was used. The theory presented for condensate entrainment from a surface into the gas flow stream was based on flow velocity exceeding terminal velocity. The density of the thermal insulation varied from 100 kg/m^3 (dry) to 1,000 kg/m^3 (soaked through). The more superheat there is in the steam, the more insulation is transported because the insulation that is generated is not as wet.

3-2. "NUKON Blowdown Tests," Owens/Corning Fiberglass document 35947-2F (December 1984) (PROPRIETARY).

This report is not summarized as it contains proprietary information.

However, a letter transmitting the report to the NRC [G. H. Hart, "Original OCF Test Reports on NUKON Blowdown Tests at HDR in 1984," Performance Contracting, Inc. letter to M. Marshall (December 12, 19994)] does summarize some of the features of the test. Steam is provided at 11 MPa and 310°C. There is a plate in front of the break upon which the jet impinges initially. In the letter to the NRC, Hart asserts that the blankets were actually within 3 to 5 pipe diameters based on spherical zone. He states that blankets in the plant are held by Velcro, which would permit them to be blown away without disintegration, unlike the situation that occurred in the HDR facility. Finally, he stated that the report misleadingly refers to "loose fibers" that were, in fact, material that they never sought to find or measure.

3-3. M. Blomquist and M. Dellby, "Barsebäck 1 & 2, Oskarshamn 1 & 2, Ringhals 1—Report From Tests Concerning the Effect of a Steam Jet on Caposil Insulation at Karlshamn, Carried Out Between April 22–23, 1993, and May 6, 1993," SDC 93-1174.

The test objective was to determine the damage resistance of Caposil (Newtherm 1000 brand name) insulation to steam jet impingement. Relationships between discharge distance, flow rate, and discharge time were sought. After some initial testing, an added objective was to characterize the particle distribution with respect to the distance from the break and, therefore, the debris cited term. The jet discharged onto a floor mounted, flat sample of size 450 x 450 mm. Thus, the insulation was flat and stationary.

The process by which the insulation (debris generation) was damaged was described as "erosion." Erosion was obtained in all tests up to an length-to-diameter (L/D) ratio of 10. The span of the damage area is approximately equal to the distance from the nozzle to the insulation. There appeared to be a damage limit expressed in terms of stagnation pressure with damage occurring when the stagnation pressure exceeded 1.67 bar.

Plant conditions for the parametric tests were a break flow of 1500 kg/s, a steam discharge lasting ~100 s, and a steam source pressure of 70 bar. The scaled condition for a 32-mm nozzle is ~3 kg/s. Difficulties were experienced in keeping the Caposil intact.

Virtually all the exposed Caposil insulation was removed as long as the cover on the Caposil was removed by the blast. Big pieces fell to the floor, whereas the small pieces were conveyed all around the rig.

A summary table is provided on page 13 of the cited report in which the size distribution of the generated debris was characterized. Between 15–20% of the initial material was lost.

3-4. D. Brocard, "Buoyancy, Transport, and Head Loss of Fibrous Reactor Insulation," Sandia National Laboratories document SAND82-7205, NUREG/CR-2982 (July 1983).

This report summarizes the investigation of buoyancy, transport, and head-loss characteristics of three types of fibrous insulation: (1) mineral wool covered with asbestos cloth and 0.5-mil Mylar film, (2) oil-resistant Filomat (high-density, short-fiber E-glass in needled pack) covered with an inner stainless steel knitted mesh and an outer silicon glass cloth, and (3) Filomat covered with 18-oz fiberglass cloth. Tested samples do not appear to have been treated thermally before experiments. Tests were performed in a 1.8-m-wide flume with a water depth of 0.8 m. Velocities needed to initiate transport of sunken insulation and to bring insulation pieces against the screen were measured. The water velocities needed to initiate motion of sunken insulation are 6 cm/s for individual shreds, 18 cm/s for individual pieces up to 10 cm on a side, and from 27 to 46 cm/s (0.9 to 1.5 in/s) for individual large pieces up to 60 cm on a side. Shreds, once in motion, tend to become suspended and collect on screen. The one reflective metallic insulation sample (20 x 20 x 8 cm^3 with 6 sheets of reflective metal and a fastening clamp) needed 80 cm/s (2.6 ft/s) to start moving. One foam glass insulation sample (15 x 10 x 5 cm^3) remained afloat at the water surface.

The transport studies revealed that the insulation core material sank more rapidly in hot water than in cold water. The studies also showed that the tested mineral wool insulation did not readily sink, but that fiberglass insulation did and that undamaged pillows could remain afloat for several days because of trapped air pockets forming inside the pillow covers.

3-5. D. Brocard, "Transport and Screen Blockage Characteristics of Reflective Metallic Insulation Materials," Alden Research Laboratory document ARL-124-83/M398F, NUREG/CR-3616 (January 1984).

This report documents tests to determine the characteristics of foil fragment transport in PWR-type conditions. Linear velocities required to transport various sizes of flat and crumpled foils were determined. Uncrumpled foils are transportable for velocities between 0.06 to 0.15 m/s (2.4 to 6 in./s) and, upon reaching the screen, flip onto it to their full dimension. Crumpled foils and larger pieces required higher velocities (0.15 to 0.3 m/s) to move.

The tests also revealed that thin metallic foils (0.0025 and 0.004 in.) could transport at low flow velocities, 6.1–15.2 cm/s (0.2–0.5 ft/s). Thicker foils (0.008 in.) transported at higher velocities, 12.2–23.4 cm/s (0.4–0.8 ft/s), and "as fabricated" half cylinder insulation units required velocities in excess of 30.5 cm/s (1.0 ft/s) for transport.

3-6. W. Durgin and J. Noreika, " The Susceptibility of Fibrous Insulation Pillows to Debris Formation under Exposure to Energetic Jet Flows," Sandia National Laboratories document SAND83-7008, NUREG/CR-3170 (March 1983).

Three types of insulation pillows were subjected to liquid water jets to determine the stagnation pressures at which failure (release of insulation material) occurred. Type 1 was mineral wool enclosed in a Mylar coated asbestos cover. Types 2 & 3 were fiberglass insulation covered with silicone glass cloth and fiberglass cloth, respectively. Type 1 failed at 30 psi and 35 psi for impact angles of 45° and 90°. Type 3 failed at 50 psi and 65 psi (45° and 90°). Type 2 did not fail at the greatest achievable stagnation pressure, 65 psi. Insulation debris formed in clumps that floated on the surface of the collection sump. However, because temperature is known to affect the permeability and flotation of insulation material (NUREG/CR-2982), this finding should not be generalized.

3-7. J. Fredell, "Karsham Tests 1992—Steam Blast on Insulated Objects, Logbook," ABB Atom report RVE 92-202 (November 1992).

Steam blasts were used to generate debris, following which the debris flow path required horizontal movement in duct geometry and vertical movement through grid plates (see Fig. 7 in the cited report). Detailed test conditions were recorded. The problem remains how to characterize the results. It appears that it will be difficult to extract much useful information from this log book write-up.

3-8. M. Gustafsson, "Block I—Transport of Insulation in the Reactor Containment—Test Results," OKG report 92-07528 (November 1992).

This test examined the movement of insulation material within a reactor containment, with the debris transport being the direct consequence of the operation of containment sprays. The tests seem to have been conducted in an actual plant, although there is no definitive statement of where the test was conducted. Insulation materials of 200 kg were placed on a drywell floor, and the sprays started. At the end of the test, 189 kg remained in the drywell and 11 kg moved to the wetwell.

3-9. D. Hill, "LOCA Testing of Unqualified Coating Systems—Determining Point of Failure during a 340F DBA/LOCA," BWR Owner's Group Containment Coatings Committee (September 9, 1998) (Presentation/Slide Package).

Surface preparation varied for the tests. Coatings were applied outside the conditions specified by the manufacturers. A coating system consists of the coating material, surface preparation, surface profile, and film thickness. If one of these is missing or is not in conformity to the way the product was DBA/LOCA qualified, the coating system is "unqualified" or of "indeterminate quality."

3-10. D. Hoffmann and A. Knapp, "RMI Debris Generation Testing—Pilot Steam Test with a Target Bobbin of Diamond Power Panels," Siemens AG—Power Generation Group document NT34/95/e32 (July 1995).

The test objective was to measure the amount and size distribution of insulation debris generated during a simulated double-ended guillotine break (DEGB) from Reflective Metallic Insulation (RMI) with buckle-type closure supplied by Diamond Power Panels. The initial saturated steam pressure was 80 bar and the blowdown duration was 11 s. The RMI specimens were 900 mm long, fitted a pipe with an outside diameter of 273 mm, and were 60 mm thick. Given the test setup, the system simulated only the destruction of insulation from steam passing radially outward underneath the insulation. Impingement destruction from the outside in was not simulated. The facility pressure decreases at a slower rate than in a reactor. Mass flow for the duration of the test was in the range 175 to 200 kg/s. Initial weight of panels 2A and 2B was 16.50 kg. The weight of "debris" after the test was 4.40 kg.

3-11. J. Hyvärinen and O. Hongisto, "Metallic Insulation Transport and Strainer Clogging Tests," Finnish Centre for Radiation and Nuclear Safety report STUK-YTO-TR 73 (July 1994).

The report documents experiments investigating the transport and clogging properties of metallic (metal reflective) insulation. Tests were conducted for a wide size range of various shapes of foil pieces (parametric approach because the size of debris that would arise in a real event is uncertain). Sedimentation velocities were in the range of 0.04 to 0.08 m/s (1.6–3.1 in./s). All tested pieces became waterborne as the vertical velocity exceeded the sedimentation velocity.

The horizontal transport tests involved dropping debris into a pool with a previously established horizontal flow pattern. Horizontal flow velocities at the bottom of the pool ranged between 0.05 and 0.2 m/s. The particle motion can be envisioned as the superposition of horizontal motion and vertical descent. None of the pieces remained waterborne. Tumbling along the bottom by crumpled particles begins at about 0.08 to 0.15 m/s (3.1 to 5.9 in./s). Below 0.08 to 0.1 m/s, pieces do not move along the bottom. See Table 1, pg. 21 for a more complete characterization

The focus on vertical flows is applicable to the BWR torus. The report notes that the flows in a PWR lower compartment are (in most cases) essentially horizontal.

Metallic insulation panels contain thin gauge stainless steel foils, and the foil area of a panel for large diameter pipes can be several tens of square meters per meter of pipe.

A preparation step for the sedimentation testing should be considered. The report states (p. 19), "Each piece, in turn, was placed on the water surface and made to sink by gently tilting a side or an edge (otherwise, most of the pieces would have floated indefinitely because the dimples trap air under the foil)."

The clogging experiments measured differential pressures because of the accumulation of both pure metallic and a mixture of metallic and fibrous (mineral wool) debris. Pressure drops are significantly greater for a combination of metallic and fibrous debris than for either of the constituents alone.

3-12. A. Johnson et. al., "NUKON™ Insulation and Sludge Settling Following a LOCA in a BWR Suppression Pool," Alden Research Laboratory, Inc., document 114-95/M787F (June 1995).

The test was BWR geometry specific, namely, a 1:2.4 geometric-scale model of a segment of a Mark I suppression pool, including four downcomers fitted with pistons that simulated the steam-water level oscillations during chugging. Debris included NUKON fibrous insulation, sludge (iron oxide), and combinations of insulation debris and sludge. Mass concentrations were measured from strained water samples taken at known time intervals from know elevations in the pool. Test results were that even for the lowest energy input to the pool expected during chugging, all sludge and fibrous insulation debris remained entrained and fully mixed in the suppression pool. About 20 min after chugging stopped, about 50% of the initial insulation debris and 70% of the sludge had settled to the pool floor.

3-13. A. Johnson et. al., "Reflective Metallic Insulation Settling Following a LOCA in a BWR Suppression Pool," Alden Research Laboratory, Inc. document 170-95/M787 (December 1995).

The test was BWR geometry specific, namely, a 1:2.4 geometric scale model of a segment of a Mark I suppression pool, including four downcomers fitted with pistons that simulated the steam-water level oscillations during chugging. For even the lowest energy input to the pool expected during chugging, as much as half of the RMI debris remained entrained. After chugging, the turbulence decayed and settling occurred; although there was a noticeable effect of residual turbulence, the scales of no turbulence and residual turbulence only increased the settling time from 48 to 120 s.

3-14. T. Kegel, "Air Blast Destructive Testing of NUKON® Insulation Simulation of a Pipe Break LOCA: Tests 1, 2, 3, 4, 7 and 8," Colorado Engineering Experiment Station, Inc. (performed for Performance Contracting, Inc.) (October 1993).

The test objective was to characterize the extent and the nature of the debris that would result from a LOCA impingement on flat NUKON insulation blankets and in a separate test on a stainless-steel foil 0.0025 in. thick. The NUKON blankets were mounted on a horizontal grating, and the jet was directed vertically downward. The following were concluded: (1) it takes several seconds for the air jet to penetrate the cover over the insulation, (2) dust-like debris is produced after the outer layer of fiberglass cloth has been penetrated, (3) 95% by weight of the debris is small enough to pass through a 0.10-in. screen, (4) most of the debris is generated in the first few seconds of the test, and (5) the jet created a hole in the insulation blanket at the point of impact. For the foil test, the test article was fragmented into many pieces sized from under 0.10 in. to over 1.0 in.

Six air-impact tests on NUKON insulation were also conducted. Results were compared with the NUREG/CR-0897 described destruction zone formed by a 90° cone extending seven nozzle diameters (7D) from the exhaust nozzle. Less than 30% (by weight) of NUKON base wool in 7D zone was fragmented into small, easily transported pieces. The pipe upon which the insulation was mounted provided "shadowing" protection for insulation on the backside. NUKON metal jacketing can provide significant protection from fragmentation as close as 2.2 nozzle diameters from the exhaust. On the other hand, jacket failure is likely when the jet impacts the latch side. The different shape of the destruction zone proposed in Fig. 34. of the cited report is capable of being transported.

3-15. T. Kegel, "Air Blast Testing of Nuclear Power Plant Insulation: Tests 5, 6, and 10," Colorado Engineering Experiment Station, Inc. (performed for Performance Contracting, Inc.) (September 1994).

The test objective was to characterize the extent and the nature of the debris that would result from a LOCA jet impingement on insulation. The tested insulation was a NUKON Thermal Insulation System. Test results are observational, not quantitative. Three tests were performed to determine the nature of debris generated by a continuous air jet of 30-s duration in a confined space. Destruction was by a blast resulting from airflow blowing down from a nozzle so that the effluent impacted the insulation system. The zone of destruction was a 90° cone extending seven nozzle diameters from the exhaust nozzle. Two tests of NUKON flat insulation blankets found dust-like debris produced after the outer layer of fiberglass cloth were penetrated. The jet created a hole in the blanket at the point of impact. It is possible that some of the fine debris may result from the collection process. Test 10 was performed on three pieces of stainless-steel foil with a thickness of 0.025 in. The foil was shredded into dozens of pieces ranging in size from under 0.10 in. to over 1.0 in. Most of the foil pieces remained reasonably flat; very few were crumpled into spherical shapes. It is postulated that the foil pieces cut into each other while being transported within the test tank. The following conclusions were reached: (1) <30% by weight of the NUKON base wool located within the zone of influence is fragmented into small pieces that are believed to be potentially transportable (to a BWR wet well), (2) the pipe provides some protection from fragmentation because it blocks the direct impact of the jet, and (3) NUKON metal jacketing can provide significant protection from fragmentation as close as 2.2 nozzle diameters from the exhaust.

3-16. T. Kegel, "Air Blast Testing of Metallic Foil Insulation: Test 9," Colorado Engineering Experiment Station, Inc. (performed for Performance Contracting, Inc.) (December 1993).

The test objective was to determine the extent of destruction and to characterize the debris resulting from an impacting high-pressure gas jet that would initially result from a LOCA. The tested insulation was RMI. The tested article was RMI designed to insulate a 36-in. length of 12.75-in. OD pipe. The insulation is fabricated in two halves, and a pair of latches holds the pieces in position. The insulation assembly consists of inner and outer shells, end plates, 16 foil layers, and foil spacers. The insulation surface was 8 in. from the discharge nozzle exit. The foil layers and foil spacers where broken into small pieces. The collected pieces were characterized by size classes. Approximately 50% of the foil that makes up insulation system was released as debris as the result of an air blast. Debris size classes were: <0.02 lb_m, 9.4%; 0.02–0.2 lb_m, 22%; and >0.2 lb_m, 19.8%. The remainder remained attached to the heavier gauge pieces that make up the casing of the insulation. The pieces of foil insulation were all large enough and dense enough so that they would not be transported for typical pool velocities.

3-17. A. Molander et. al., "Steam Jet Dislodgement Tests of Thermal Insulating Material," Studsvik Material document M-93/24 (March 1993).

A blanket from a BWR plant was cut into six pieces, ~300 x 300 mm each. The blankets had a cloth cover. The blankets were affixed to a flat horizontal surface, and the jet blew vertically downward (see cited report Fig. 4, pg. 7). The blankets had a cloth cover. Photos were taken of damage, but the test data do not appear to provide much by way of insights.

3-18. J. Nystrom, "Evaluation of Transport Velocity for NUKON™ Insulation Base Wool at Elevated Temperature and pH," Alden Research Laboratory, Inc. document 66-91/M670F (sponsored by Performance Contracting, Inc.) (May 1991).

The data are applicable to PWR sumps. Tests were conducted to determine the minimum flow velocity required to initiate transport of NUKON insulation base wool debris by a moving water flow (flume arrangement). The insulation was heat treated to simulate in-service material and was shredded to simulate debris that would be generated by a LOCA. The material was placed in the flume while in a no-flow state. A flow of 0.023 m/s (0.9 in./s) was established and any debris movement observed and recorded. The flow was further increased in increments of 0.008 m/s (0.9 in./s) until all the material had been transported. One case of interest was for an isolated 3.5-in. square x 1/8-in.-thick fragment. Initial movement occurs at 1.2 in./s, and full transport is completed at a velocity of 2.7 in./s. The critical velocity for isolated fragments is ~0.0046 m/s (1.8 in./s).

3-19. P. Tarkpea and B. Arnesson, "Steam Jet Dislodgement Tests of Thermal Insulating Material of Type Newterm 1000 and Caposil HT1," Studsvik Material (April 1993).

In these test series, insulating materials for the Ringhals 1 and Oskarshamm 1 nuclear power plants were fixed in place and subjected to steam jet Dislodgement tests. The eroded mass was estimated by the volume of a mold required to fill the eroded area and by actual collection of fine debris. The wear loses determined from the debris contents of slurries are as much as five times the wear loses estimated by volume measurements. The reason is probably the jetting into gaps, which causes wear of the gap sides. The steam source was at 80 bar and 280°C. The steam flow rate was estimated to be ~0.8 kg/s. During testing, a water spray was used to condense some of the steam. Scanning electron microscope examinations of filtered debris indicated the presence of asbestos and mineral wool fibers. Few inferences are made by the authors concerning the test results; however, the results seem to indicate difficulties involved in generating large quantities of "transportable" debris from Newtherm and Caposil insulations.

3-20. P. Tarkpea and B. Arnesson, "Steam Jet Dislodgement Tests of Two Thermal Insulating Materials," Studsvik Material document M-93/60 (May 1993).

Two insulating materials (Caposil HT1 and Newtherm 1000) were subjected to steam jet Dislodgement tests. The blankets were affixed to a horizontal surface at a 45° angle, and the jet blew vertically downward (see cited report, Fig. 1, pg. 7). Photos were taken of holes in the insulation and other damages that occurred, but the test data do not appear to provide many insights.

Photographs of the filter cake show that screen blockages consist largely of a mixture of fibers with particles trapped within them. The fibers support the individual particles that, in turn, cause most of the blockage. The relative amounts of the two constituents vary widely, but are comparable in amount. All samples showed both fibers and particles, so both constituents are needed for a blockage to form.

3-21. J. Trybom, "Metallic Insulation Jet Impact Tests," Vattenfall Energisystem document GEK 77/95 (June 1995).

Experiments on the effect of high-velocity jets on RMI have been performed. The jets managed to bend, buckle, shred and tear the RMI but did not manage to pulverize it. The smallest particles were large enough to settle out in a PWR pool. It is quite unlikely that they would be reentrained at typical pool velocities. Seven tests were conducted. Distances from nozzle to insulation varied from direct contact to 25 nozzle diameters. The nozzle diameter was 200 mm and the source pressure typically was 100 bar. Damage from the water jet consisted of crumpling, whereas insulation exposed to saturated steam was fragmented. The size and shape of the debris depended on the testing parameters, but in all cases the insulation disintegrated when it was hit by a direct stream jet. Insulation outside the core of the jet was not damaged. It was concluded that the multiple region insulation debris generation model in Reg Guide 1.82, Rev. 1 grossly underestimates the destruction range of a steam jet. Different target positions were tested, called Guillotine break, side impact, and front impact (see pg. 6). The side impact was perpendicular to the axis of the insulation, whereas front impact is parallel to it.

3-22. D. Williams, "Measurements on the Sink Rate and Submersion Time for Fibrous Insulation," Illinois Institute of Technology document ITR-93-02N (sponsored by Transco Products, Inc.) (May 1993).

Samples of fibrous, nonaged, insulation materials cut to the following sizes, all measurements in inches (1/4 x 1/4 x 1/8; 1 x 1 x 1; 4 x 4 x 1; and 8 x 8 x 1) were tested to determine sink rate when placed in a water pool. One side of the sample was smooth cut and one side was torn. A two-phase process was observed. For a period after being placed on the water surface, the samples floated while they absorbed water. The free-fall period was observed once sufficient water was observed to sink below the free surface. Two time intervals were recorded, the time for complete submersion and the total time to reach the bottom of the pool. The first time period is strongly related to water temperature with much more rapid submersion taking place at higher temperatures. The sink rate is weakly dependent upon pool temperature. The sink rate increases with debris size.

3-23. L. Lönn and E. Dahlquist, "Determination of Particle Distribution in Samples from a Simulated Pipe Break Test Carried Out by ABB Atom AB," CRC/KC/LR-93/3238, ABB Atom AB (June 1993).

Various jet-impacting directions and cover materials for Caposil and Newtherm were tested. Covers substantially reduce the damage to the underlying insulation. Jets impacting the insulation at an oblique angle often got under the cover and caused tunneling, which led to substantially increased insulation destruction.

3.2. Analytical

3-24. "Containment Sump Zone of Influence for Coatings," 22S-B-040M-002, Rev. 2, Zion Nuclear Station (January 1997). Attachment A to letter from J. H. Mueller to U. S. Nuclear Regulatory Commission Documents Control Desk, Commonwealth Edison Company (February 5, 1997).

The ZOI was calculated for the containment sump, defined as the radius extending from the center of the sump enclosure projected onto the water surface into which fallen debris would be transported to the sump screen by the flow of water rather than settling on the containment floor. This calculation considers the debris to be various types of paints and coatings that have flaked or peeled off containment structures or components. The minimum water velocity required to move a debris particle along the containment floor is calculated, and the velocity is computed for various particle configurations. The maximum particle size is assumed to be equal in size to the outer screen mesh opening or 0.5 in. The RHR pumps have a maximum flow rate of 4500 gpm each or a total 9000-gpm system flow rate. The maximum containment flood level is 5.06 ft above the containment floor. The minimum containment flood level at the start of recirculation is 1.0 ft above the containment floor. Debris with a specific gravity of 1.05 or more will likely settle on the containment floor before reaching the sump screen if the velocity ahead of the sump screen is at or below 0.2 ft/s. The effective containment floor surface area with the reactor cavity full is 10,638 ft^2. The methodology was submitted with Comanche Peak Station "Evaluation of Paint and Insulation Debris Effects on Containment Emergency Sump Performance." To determine the force required to cause motion, the sunken debris is analyzed as tumbling, sliding, and stationary. Results: For the minimum coating thickness of 1.0 mil, the maximum zone of influence is 49.1 ft for a specific gravity value of 1.5. Higher specific gravity and greater coating thickness serve to reduce the ZOI. The ZOI for a Carbo Zinc 11 having a specific gravity of 5.6 and 3.0 mil thickness was 8.4 ft.

3-25. "Evaluation of Paint and Insulation Debris Effects on Containment Emergency Sump Performance," Gibbs & Hill, Inc. (Comanche Peak Steam Electric Station) (October 1984).

Comanche Peak is a Westinghouse four-loop plant with a large dry containment. There are some helpful figures (see cited report Figs. 3.2-1, 3.2-2, 5.3-1, 6.2-3, and 6.2-4). The containment base is at the 808-ft elevation. Assuming reactor coolant, RWST, accumulators, and miscellaneous water inventories, the maximum water level is 817.5 ft and the minimum water level is 814.8 ft.

The containment spray system is shown in cited report Fig. 5.3-1. There are four spray zones, each zone covers the space above the floor in the zone. Each floor in the containment is provided with 4-in.-high curbs all around. The flow discharge from each floor will be through spill openings available, i.e., sectors where there is no curb.

See the write-up for Ref. 3-24 for similar information. Reference 3-24 followed the methodology in this citation. A three-step approach was followed. First, the water velocities inside the containment in each zone of the containment were determined. Second, the quantities of paint and insulation debris in each zone of the containment were calculated. It was concluded that there is no potential for insulation debris to reach the sumps. Most of the thermal insulation is RMI. Third, the transport velocities for paint particles in each zone were calculated, and the quantity of paint transported to the sump screen was calculated.

Approximately 285,000 ft^2 of concrete and 333,000 ft^2 of steel are coated, the former with Phenoline 305 by Imperial Professional Coating Corporation and the latter with Carbozinc 11 by Carboline Co.

The analysis determined that ~95,000 ft^2 (~300 ft^3) of paint could reach the vicinity of the sump screens. This number arises from postulating that all the paint fails. The extent of the screen blockage by paint debris was calculated to be 145 ft^2 for one sump and 102 ft^2 for the other. This left an open area of 259 ft^2 for one sump and 302 ft^2 for the other, and it was concluded that the ECCS would still function. The minimum velocity to transport paint chips was taken as 0.27 ft/s; the paint chips were all taken to be circular particles one-eighth inch in diameter. Smaller particles would pass through the sump screens and larger particles would not transport as readily.

3-26. F. Moody and T. Green, "Evaluation for Existence of Blast Waves Following Licensing Basis Double-Ended Guillotine Pipe Breaks," GE Nuclear Energy document DRF-A74-00003 (draft) (March 1996).

For circumferential double-ended guillotine pipe breaks, it has been determined for 1.0- to 2.0-ft-diameter pipes that blast waves will not occur if the pipe rupture time exceeds 0.005 to 0.009 s. Analysis has shown that when a circumferential crack suddenly releases the two ends of a pressurized pipe at typical BWR pressures, and they separate on the axis, the pipe opening time from zero discharge to full double-ended blowdown flow is ~0.19 s. This is more than an order of magnitude too slow for a blast wave to form. Supplemental fracture mechanics evaluations demonstrate that independent of the time required to physically separate the pipe axially, crack propagation alone will probably be slow enough to preclude blast wave formation.

3-27. K. Niyoci and R. Lunt, "Corrosion of Aluminum and Zinc in Containment Following a LOCA and Potential for Precipitation of Corrosion Products in the Sump," United Engineers and Constructors, Inc. (September 1981).

The plant is not specified.

Following a LOCA, materials in the containment come into contact with alkaline emergency cooling and containment spray solutions. This report considers the solubility of the corrosion products from aluminum and zinc to determine the potential for precipitation in the sump.

Boron concentration in the RWST is 1900 ppm (350,000 gal. in tank) and NaOH in the spray additive tank constitutes 20% by weight (~10,000 gal. in tank). Tables of corrosion mass with time are presented for aluminum and zinc. Corrosion products for aluminum and zinc one day after event initiation are estimated to be 262.6. lb for the former and 761.9 lb for the latter (see cited report Tables 4 and 5 for time-dependent corrosion estimates). It is estimated that 90%–95% of the aluminum would be expected to precipitate. Similarly, 99% of the estimated quantity of zinc corroded can precipitate.

3-28. M. Teske et. al., "Zone of Destruction as Defined by Computation Fluid Dynamics," Rev. A, Continuum Dynamics, Inc. document 96-01 (prepared for GE Nuclear Energy) (February 1996).

The title summarizes the document. Several break geometries were examined, e.g., separation and axis offset and separation and no axis offset. Isobar plots are presented. If there is a direct correlation between damage, e.g., mass flow and isobars, some insights as to the extent of damage regimes are possible. However, no additional solid surfaces are modeled, e.g., pipes upon which insulation would be present but which would also disrupt the flow.

3-29. G. Weigand et. al., "Two Phase Jet Loads," Sandia National Laboratories document SAND82-1935, NUREG/CR-2913 (January 1983).

A computational model was developed for predicting two-phase water jet loadings on axisymmetric targets. The model is two dimensional. The model ranges in application from 60 to 170 bars pressure and 70°C subcooled liquid to 0.75 or greater quality. The model displays in a series of tables and charts within the cited report the target load and pressure distributions as a function of vessel (or break) conditions. The high-pressure and high-temperature fluid that exists the break expands with supersonic velocities downstream of the break. Upon encountering a target (or obstacle), a shock wave forms in the

flow field and it is the thermodynamic properties downstream of this shock that determine the pressure field and load on the target.

3-30. T. S. Andreychek, "Evaluating Effects of Debris Transport within a PWR Reactor Coolant System during Operation in the Recirculation Mode," OPL Licensing, Westinghouse Electric Corporation (May 13, 1994).

The transportability of paint chips was modeled based upon a force-balance approach. While in the recirculation mode, larger chips settle out in the bottom head of the reactor vessel. NUREG/CR-2792 was cited for residual heat removal pump hydraulic degradation. This removal mechanism was determined to be negligible for particulate concentrations 1% (0.1% abrasive) by volume. Chloride in paints (avoided) could induce stress-corrosion cracking. Fluorides would form fluoroborates.

3-31. J. J. Wysocki, "Probabilistic Assessment of Recirculation Sump Blockage due to Loss of Coolant Accidents," Sandia National Laboratories document SAND83-7116, NUREG/CR-3394, Vols. 1 and 2 (July 1983).

The factors of interest to the current PIRT panel are parameterized. In particular, transportable debris is defined as all fibrous debris within the zone of influence, and 4 possible influence zones are considered: 3, 5, and 7 pipe break diameters. The bulk of the text deals with alternative methods for estimating the frequency of occurrence of pipe breaks inside containment and inside the steam generator compartments where most of the insulation resides. The document cites NUREG/CR-2403 and NUREG/CP-0033 for stagnation pressures leading to debris formation. It cites NUREG/CR-2982 for identification of "fibrous insulation types having the greatest potential for causing screen blockage because of their low transport velocities when shredded."

3-32. M. E. Teske, A. H. Boschitsch, and T. B. Curbishley, "Zone of Destruction as Defined by Computational Fluid Dynamics," GE Report C.D.I. 96-01 (February 1996).

Three-dimensional computational fluid dynamics (CFD) calculations of constant pressure surfaces from pipe breaks are presented. The model has the usual limitations of jet-impingement envelope models; it does not address the initial blast or account for the impact of surrounding structures on jet expansion. Also, CFD calculations are not two phase. Finally, two pipe segments are always assumed parallel, so breaks near elbows are not covered.

3.3. Other

3-33. "Knowledge Base for Emergency Core Cooling System Recirculation Reliability," Nuclear Energy Agency Committee on the Safety of Nuclear Installations document NEA/CSNI/R (95)11, France (February 1996).

This report presents an excellent summary of debris-generation incidents, related experiments, and models. The report stresses the importance of blast as well as jet impingement loads. It emphasizes the difference between subcooled, saturated, and steam blowdown (see cited report Fig. 1.1). Steam blowdown provides the greatest penetration and the least expansion. Flashing blowdown provides the most expansion. Saturated blowdown provides the least thrust. Mineral wool is affected by initial blast, whereas fiberglass is affected by jet impingement.

Metal covers may be deformed or removed by the initial blast. Damage to calcium silicate, mostly by erosion, results in small particles (see cited report Table 1.1). The report discusses the applicability and limitations of the NRC cone model (Reg. Guide 1.82), sphere model (NUREG/CR-6224), stagnation pressure models including ABB empirical model for calcium silicate, CIIT eddy model, and jet-impingement models. It points out the importance of temperature aging, the tendency for steam-produced debris to have greater clogging potential than mechanically produced debris, and nonprototypic features of air-blast tests.

The focus of this effort was BWR plants, but some of the insights developed are useful for the PWR effort.

Debris generation: The major mechanisms for dislodging the material are the pressure wave associated with the pipe rupture, erosion by the fluid jet, and flow and pressure differences in narrow sections along the flow path. Models currently used to evaluate the amount of dislodged material are most applicable to flashing water. Steam jets produce destruction zones that are much narrower and much longer than jet produced by flashing water. The insulation type is a key parameter; mineral wool disintegrates more rapidly than fiberglass material under jet impact. Encapsulation of fibrous insulation in metallic jackets reduces the amount of debris generated. RMI is also destroyed by break flows, and the foils in the RMI can fragment into small pieces. Some of the test data examined are those from the HDR experiments, Marviken experiments, MIJIT tests, and the NRC-funded test at the Siemens Facility at Karlstein.

Drywell transport: Debris is transported through the drywell by blast forces, blowdown forces, and washdown. Some of the testing done to date has indicated retention factors that are contradictory (higher) than observed in the Barseback incident.

Suppression pool transport: Debris transport in the wetwell pool is controlled by sedimentation and resuspension, which are dependent on parameters like character of the debris materials and turbulence levels present. Aging has a strong affect on debris fibrous debris characteristics and accounts, in part, for the severity of the Barseback event; aged materials stayed suspended much longer than the new fibrous materials used in the tests upon which early guidance was based. Resuspension of previously settled debris due to turbulent pool motions may be a significant factor for fibrous debris.

Appendix D—the Barseback Incident: The rupture disc on a safety valve reached its setpoint of 3 MPa. The disc failed, and the resultant steam jet caused mineral wool insulation to be dislodged from the pipework located close to the safety relief valve. About 200 kg (440 lb_m) of dry insulation was installed to replace that which had blown away. The judgement is that 180–220 kg was dislodged. The NUREG-0897 Rev. 1 cone model, which is applicable between 8 and 15 MPa, estimates disintegration within 3 L/D at 3 MPa. The affected zone in Barseback was larger. Of the total amount of insulation debris generated, roughly half, or 100 kg, was estimated to have been transported to the suppression pool.

3-34. "Oconee Nuclear Station Emergency Sump Operability Evaluation," Oconee Nuclear Station document OSC-6827, Rev. 2. (Unapproved update).

This report contains some of the same material as in Ref. 4-13. However, there is some additional material by way of informal communication that is of interest. One is Attachment 7, "Loose Coating in the Containment Building Unit 2" dated January 21, 1997, authored by M. Salim. The informal memorandum discusses lose and flaking coating covering ~1200 ft^2. The coating used on the structural shell and liner plate were Prime coat Carbo Zinc11 and topcoat Phenoline 305 on concrete Carboline surfacer 195 prime coat and carboline 305 topcoat. The stated cause for the failure was that the film thickness was greater than designed and that resulted in delamination of the topcoat.

3-35. "Utility Resolution Guidance for ECCS Suction Strainer Blockage, Volume 2, Technical Support Documentation," Boiling Water Reactor Owners' Group document NEDO-32686-A (GE Nuclear Energy) (November 1996).

One volume of a four-volume set. Volume 2 contains two reference documents. The first is NRC Bulletin 96-03 and the second is a document titled "Testing of Alternate Strainers with Insulation Fiber and Other Debris." Pages 43–46 of the second document contains a description of various debris types used in the strainer blockage tests.

3-36. R. Kolbe and E. Gahan, "Survey of Insulation Used in Nuclear Power Plants and the Potential for Debris Generation," Sandia National Laboratories document SAND82-0927, NUREG/CR-2403, Sup. 1 (July 1982).

The report was published in July 1982. As of that date, the report summarizes the type and percentage of insulation in 8 plants (Millstone 2 [CE-PWR], St. Lucie Unit 1 [CE-PWR], Calvert Cliffs Units 1 and 2 [CE-PWR], Robert E. Ginna [W-PWR], Prairie Island Units 1 and 2 [W-PWR], Kewaunee [W-PWR], Haddam Neck [W-PWR], and H. B. Robinson [W-PWR]).

3-37. R. Reyer et. al., "Survey of Insulation Used in Nuclear Power Plants and the Potential for Debris Generation," Burns and Roe, Inc. document NUREG/CR-2403) (July 1982).

The report contains a good description of the different types of insulation found inside containments of commercial nuclear power plants. It provides actual inventories of insulation types and containment layout drawings for 11 plants as of the report date (July 1982). The report covers Crystal River 3 (B&W PWR), Oconee Unit 3 (B&W PWR), Midland Unit 2 (B&W PWR), Maine Yankee (CE PWR), Arkansas Unit 2 (CE PWR), Waterford Unit 3 (CE PWR), Salem Unit 1 (W PWR), Sequoyah Unit 2 (W PWR), McGuire Units 1&2 (W PWR), Cooper (GE BWR I), and WPPSS Unit 2 (GE BWR 2). Debris generation and sump blockage characterization are qualitative. Some assumptions seem questionable; for example, "any dislodged reflective insulation would sink to the floor of the containment if blown off the piping rather than be transportable to the emergency sump." This fails to acknowledge the small-sized metallic debris generated in tests such as those at Colorado Engineering Experiment Station, Inc.

4. PWR DEBRIS TRANSPORT PIRTS

Three PIRT tables are presented in this section, one each for the blowdown, post-blowdown, and sump operation phases of an LBLOCA scenario in a Westinghouse four-loop PWR with a dry ambient containment.

These PIRTs represent the informed judgment of the PIRT panel members regarding both the processes and phenomena that are expected to occur during the scenario, and the relative importance of those processes and phenomena. The importance of each process and phenomenon was evaluated relative to the primary evaluation criteria presented in Section 2.7, namely, the transport of debris mass generated within the containment during the initial blowdown of primary coolant into containment that is transported to the sump entrance.

Before embarking upon the ranking element of the PIRT effort, the panel summarized the behavior of four debris types during each of the three transient phases, i.e., blowdown, post blowdown, and sump operation. The three debris types discussed were fibrous, calcium silicate (Cal-Sil), and RMI. Descriptions of the insulation systems from which these debris types are created are found in Section 2.6. The results of the panel's discussions are summarized in Table 4-1.

4.1. Blowdown

The blowdown phase begins at the time of break initiation and continues until 40 s. A description of this phase is presented in Table 2-1. The PIRT for this time phase is provided in Table 4-2. The structure of the table is

- Column 1—Component in which phenomenon occurs. The components are described in Section 2.4 and Fig. 2-2.
- Column 2—General phenomenon type.
- Column 3—Higher-level system process with which the phenomenon is associated. These processes are described in Section 2.5.
- Column 4—Phenomena being ranked.
- Column 5—Cross-reference number for phenomenon description given in Table B-1 in Appendix B. Additional pictorial descriptions are provided in Figures B-1 through B-6, as cross referenced in Table B-1.
- Column 6—Phenomenon relative importance rank. The ranking scheme is described in Section 2.8.
- Column 7—Cross-reference number for ranking rationale given in Table C-1 in Appendix C.

4.2. Post Blowdown

The post-blowdown phase follows the blowdown phase and continues until 30 min following event initiation. A description of this phase is presented in Table 2-1. The PIRT for this time phase is provided in Table 4-3. The structure of this table is similar to Table 4-2, except that the phenomena descriptions are provided in Table B-2 and Figs. B-7 through B-12 in Appendix B. The ranking rationales are given in Table C-2 in Appendix C.

4.3. Sump Operation

The sump operation phase follows the post blowdown phase and continues until 48 h following event initiation. A description of this phase is presented in Table 2-1. The PIRT for this time phase is provided in Table 4-4. The structure of this table is similar to Table 4-2, except that the phenomena descriptions are provided in Table B-3 and Figs. B-13 through B-18 in Appendix B. The ranking rationales are given in Table C-2 in Appendix C.

4.4. PIRT Applicability to Other Dry Ambient Containments

The panel focused briefly on each of the dry ambient containment types tabulated in Section 2.1 with the objective of assessing the applicability of the PIRTs presented in Tables 4-2 through 4-4 to other dry ambient containments. The observations that follow are qualified by the limited time available for this effort, the large number of containments, and the rather general containment descriptions available. Nevertheless, the panel offers the following observations with reasonable confidence of their validity.

- The processes and phenomena listed in Tables 4-2 through 4-4 appear to be generally applicable to all dry ambient containments.

- The importance of each of the processes and phenomena listed in Tables 4-2 through 4-4 is somewhat dependent of the specific design of each containment type. The panel produced the following observations regarding plant-specific issues.

- The proximity of local agitation sources, primarily the break, to the sump is important. For example, in a number of plants there is a generally unobstructed path between the break location and the sump. This configuration has been described as an "exposed" sump. In other plants, shield walls or other obstacles may obstruct the direct path between the break location and the sump. This configuration has been described as a "remote" sump. Clearly, the break-sump orientation is important because flow exiting the break is an ongoing source of pool agitation that may keep debris suspended in the pool on the containment floor from the time the break occurs until the sump begins to operate.

- The number of spray trains, their location, and coverage may influence the relative importance of processes and phenomena.

- The separation of redundant sumps will influence the relative importance of processes and phenomena if the sumps are physically separated by 10 or more feet.

- Structures such as grated doors or other structures may entrap debris at an intermediate location and influence the relative importance of processes and phenomena.

In summary, the PIRTs presented in Tables 4-2 through 4-4 may be used as a tool to support plant-specific decision making about either the capabilities of analytical tools or the details of experimental test program if the focus is only on the identified processes and phenomena. However, if decisions are to be made based upon the phenomena rankings, a mini-PIRT effort should be conducted to ensure that the rankings apply to the specific facility or generate revised rankings that are specific to the given facility.

Table 4-1
PWR Debris Transport Behavior

Debris Type	Phase 1—Blowdown	Phase 2—Post Blowdown	Phase 3—Sump Operation
RMI			
Sheets	Knocked off; transport during initial blowdown; then settles	Little or no movement	Little or no movement
Small pieces	Settles and moves only in areas where liquid flow velocity exceeds threshold; some gravitational settling	Settling completed; liquid transport in areas were threshold velocity exceeded	Liquid transport in areas were threshold velocity exceeded
Calcium Silicate			
Chunks	Transport during initial blowdown; breaks into smaller pieces; some settling	Erosion; suspend in water; liquid transport	Erosion; suspend in water; liquid transport
Dust	Aerosol transport; dust to mud; adhere to surfaces	Subject to washdown; adheres to surfaces; suspend in water subject to scrubbing; liquid transport in water	Suspend in water; liquid transport
Individual fibers	Adhesion and settling	Subject to washdown; adheres to surfaces; suspend in water subject to scrubbing; liquid transport in water	Suspend in water; liquid transport
Fibrous			
Large pieces	Transport; settle	Little or no movement	Little or no movement
Chunks	Transport during initial blowdown; trapping, adhesion, settling	Partial washdown; liquid transport where threshold velocity exceeded; erosion, trapping	Agglomeration; liquid transport
Shreds	Transport during initial blowdown	Partial washdown; settling; liquid transport	Slowly settling; liquid transport
Particulate			
Dirt/dust	See Cal-Sil Dust	Same as cal-sil dust	Same as Cal-Sil dust
Paint chips	Transport during initial blowdown; start of gravitational settling	Settling completed; possible resuspension near streams entering pool; liquid transport only in areas where threshold velocity exceeded	Possible resuspension; liquid transport only in areas where threshold velocity exceeded.
Assumptions: Ignoring foreign materials and debris such as tape, clothing, pads, etc.; synergistic effects not accounted for.			

Table 4-2
PWR Debris Transport Blowdown Phase PIRT (0–40 s)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
Containment open areas	Thermal-hydraulic related	Gas/vapor transport	Pressure-driven flows (bulk flows)	P1-1	M	P1-1
			Fan-driven flows	P1-2	L	P1-2
			Spray-induced flows	P1-3	NA	P1-3
			Circulating flows	P1-4	L	P1-4
			Mixing (noncondensables)	P1-5	L	P1-5
			Localized flow field	P1-6	L	P1-6
			Turbulence	P1-7	L	P1-7
		Suspended-water transport (including gravitational settling)	Unflashed liquid flows	P1-8	L	P1-8
			Flashing of break liquid effluent	P1-9	L	P1-9
			Droplet interactions	P1-10	L	P1-10
			Condensation (droplet formation)	P1-11	L	P1-11
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P1-12	L	P1-12
			Film dynamics	P1-13	L	P1-13
	Debris related	Debris transport	Advection	P1-14	M	P1-14
			Agglomeration	P1-15	L	P1-15
		Debris depletion	Sweepout	P1-16	NA	P1-16
			Gravitational settling	P1-17	H	P1-17
			Condensation on particles	P1-18	L	P1-18
			Stephan flow (diffuseophoresis)	P1-19	L	P1-19
			Thermophoresis	P1-20	L	P1-20
Containment structures	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P1-21	L	P1-21
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P1-22	L	P1-22
			Surface wetting (condensation, impact)	P1-23	M	P1-23
			Film draining under gravity	P1-24	L	P1-24
			Deluge (streaming)	P1-25	L	P1-25

Table 4-2 (cont)
PWR Debris Transport Blowdown Phase PIRT (0–40 s)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
	Debris related	Debris transport	Resuspension	P1-26	L	P1-26
			Agglomeration	P1-27	L	P1-27
			Deluge (streaming) transport	P1-28	L	P1-28
			Film transport	P1-29	L	P1-29
			Runoff/reentrainment	P1-30	L	P1-30
			Disintegration	P1-31	L/L/-	P1-31
		Debris depletion	Entrapment	P1-32	M	P1-32
			Inertial impaction	P1-33	M/L/-	P1-33
			Turbulence-induced impaction	P1-34	L	P1-34
			Adhesion	P1-35	M/L/-	P1-35
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	P1-36	L	P1-36
			Heat transfer to structure	P1-37	L	P1-37
			Surface wetting (before pool formation)	P1-38	L	P1-38
			Streaming-induced pool dynamics	P1-39	L	P1-39
			Sheeting flow dynamics	P1-40	L/M/-	P1-40
	Debris related	Debris transport	Film transport	P1-41	L	P1-41
			Resuspension	P1-42	L	P1-42
			Sheet transport	P1-43	L/M/-	P1-43
		Debris depletion	Agglomeration in pool	P1-44	L	P1-44
			Adhesion	P1-45	L	P1-45
			Settling	P1-46	L	P1-46
			Impaction	P1-47	L	P1-47
			Entrapment by porous structures	P1-48	L/M/-	P1-48

Notes
①: See Appendix B for phenomena descriptions.
②: NA (not applicable) is entered when the phenomenon does not occur or is insignificant during the phase. Multiple rankings appear, e.g., L/M or L/H/L where the panel found it necessary to differentiate between debris types; the justification is provided in the applicable appendix (see Sections 4.1–4.3). The multiple rankings are, in order, for fibrous/cal-sil/RMI, respectively.
③: See Appendix C for ranking rationales.

Table 4-3
PWR Debris Transport Post-Blowdown Phase PIRT (40 s–30 min)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
Containment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P2-1	L	P2-1
			Fan-driven flows	P2-2	L	P2-2
			Spray-induced flows	P2-3	L	P2-3
			Circulating flows	P2-4	L	P2-4
			Localized flow field	P2-5	L	P2-5
			Turbulence	P2-6	L	P2-6
			Plume	P2-7	L	P2-7
			Thermal stratification	P2-8	NA	P2-8
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P2-9	L	P2-9
			Falling condensate	P2-10	L	P2-10
			Droplet motions	P2-11	H	P2-11
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P2-12	L	P2-12
	Debris related	Debris transport	Advection	P2-13	L	P2-13
			Agglomeration	P2-14	L	P2-14
		Debris depletion	Sweepout	P2-15	H	P2-15
			Gravitational settling	P2-16	M	P2-16
			Condensation on particles	P2-17	M	P2-17
			Stephan flow (diffuseophoresis)	P2-18	L	P2-18
			Thermophoresis	P2-19	L	P2-19
Containment structures	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P2-20	L	P2-20
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P2-21	L	P2-21
			Surface pooling	P2-22	L/H/L	P2-22
			Film draining under gravity	P2-23	L	P2-23
			Deluge (streaming)	P2-24	L	P2-24
			Surface draining	P2-25	H	P2-25
			Condensation	P2-26	L	P2-26

Table 4-3 (cont)
PWR Debris Transport Post-Blowdown Phase PIRT (40 s–30 min)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
	Debris related	Debris transport	Resuspension	P2-27	L	P2-27
			Agglomeration	P2-28	L	P2-28
			Deluge transport	P2-29	H	P2-29
			Film related transport	P2-30	M	P2-30
			Reentrainment	P2-31	L	P2-31
			Disintegration	P2-32	M/H/L	P2-32
		Debris depletion	Entrapment	P2-33	H	P2-33
			Inertial impaction	P2-34	L	P2-34
			Turbulent impaction	P2-35	L	P2-35
			Adhesion	P2-36	M	P2-36
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation④	P2-37	H	P2-37
			Evaporation	P2-38	L	P2-38
			Heat transfer to structure	P2-39	L	P2-39
			Pool agitation	P2-40	H	P2-40
			Pool flow dynamics	P2-41	H	P2-41
	Debris related	Debris transport	Entry via film transport	P2-42	H	P2-42
			Entry via vapor transport	P2-43	L	P2-43
			Entry via liquid transport	P2-44	H	P2-44
			Reentrainment	P2-45	L	P2-45
			Disintegration	P2-46	L/H/L	P2-46
			Pool transport	P2-47	H	P2-47
		Debris depletion	Agglomeration in pool	P2-48	L	P2-48
			Adhesion	P2-49	L	P2-49
			Settling	P2-50	H	P2-50
			Entrapment by porous structures	P2-51	M	P2-51

Notes
①: See Appendix B for phenomena descriptions.
②: NA (not applicable) is entered when the phenomenon does not occur or is insignificant during the phase. Multiple rankings appear where the panel found it necessary to differentiate between debris types; the justification is provided in the applicable appendix (see Sections 4.1–4.3). The rankings are, in order, for fibrous/cal-sil/RMI, respectively.
③: See Appendix C for ranking rationales.
④ This phenomenon creates the pool height for the sump operation phase (Table 4-4) and the pool height determines the magnitude of the induced pool velocity field following sump activation.

Table 4-4
PWR Debris Transport Sump Operation Phase PIRT (30 min–48 h)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
Containment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P3-1	L	P3-1
			Fan-driven flows	P3-2	L	P3-2
			Spray-induced flows	P3-3	L	P3-3
			Circulating flows	P3-4	L	P3-4
			Localized flow field	P3-5	L	P3-5
			Turbulence	P3-6	L	P3-6
			Plume	P3-7	L	P3-7
			Thermal stratification	P3-8	NA	P3-8
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P3-9	L	P3-9
			Falling condensate	P3-10	L	P3-10
			Droplet motions	P3-11	L	P3-11
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P3-12	L	P3-12
	Debris related	Debris transport	Advection	P3-13	L	P3-13
			Agglomeration	P3-14	L	P3-14
		Debris depletion	Sweepout	P3-15	L	P3-15
			Gravitational settling	P3-16	L	P3-16
			Condensation on particles	P3-17	L	P3-17
			Stephan flow (diffuseophoresis)	P3-18	L	P3-18
			Thermophoresis	P3-19	L	P3-19
Containment structures	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P3-20	L	P3-20
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P3-21	L	P3-21
			Surface pooling	P3-22	L	P3-22
			Film draining under gravity	P3-23	L	P3-23
			ECCS (streaming) deluge	P3-24	L	P3-24
			Surface draining	P3-25	L/M/L	P3-25
			Condensation	P3-26	L	P3-26

Table 4-4 (cont)
PWR Debris Transport Sump Operation Phase PIRT (30 min–48 h)

Component	Phenomenon type	System-level process	Phenomenon	Description ①	Rank ②	Ranking rationale③
	Debris related	Debris transport	Resuspension	P3-27	L	P3-27
			Agglomeration	P3-28	L	P3-28
			Deluge transport	P3-29	L/M/L	P3-29
			Film-related transport	P3-30	L/M/L	P3-30
			Reentrainment	P3-31	L	P3-31
			Disintegration	P3-32	L/M/L	P3-32
		Debris depletion	Entrapment	P3-33	H	P3-33
			Inertial impaction	P3-34	L	P3-34
			Turbulent impaction	P3-35	L	P3-35
			Adhesion	P3-36	L	P3-36
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	P3-37	L④	P3-37
			Evaporation	P3-38	L	P3-38
			Heat transfer to structure	P3-39	L	P3-39
			Pool agitation	P3-40	H	P3-40
			Pool flow dynamics	P3-41	M	P3-41
			Sump-induced flow	P3-42	H	P3-42
	Debris related	Debris transport	Entry via film transport	P3-43	L/M/L	P3-43
			Entry via vapor transport	P3-44	L	P3-44
			Entry via liquid transport	P3-45	L/M/L	P3-45
			Reentrainment	P3-46	H	P3-46
			Disintegration	P3-47	L/M/L	P3-47
			Pool transport⑤	P3-48	H	P3-48
		Debris depletion	Agglomeration in pool	P3-49	M/L/L	P3-49
			Adhesion	P3-50	L	P3-50
			Settling	P3-51	M	P3-51
			Precipitate formation	P3-52	L	P3-52
			Sump-induced overflow	P3-53	H	P3-53
			Debris-created flow obstructions	P3-54	M	P3-54

Notes

①: See Appendix B for phenomena descriptions.

②: NA (not applicable) is entered when the phenomenon does not occur or is insignificant during the phase. Multiple rankings appear, e.g., L/M or L/H/L where the panel found it necessary to differentiate between debris types; the justification is provided in the applicable appendix (see Sections 4.1–4.3). The multiple rankings are, in order, for fibrous/cal-sil/RMI, respectively.

③: See Appendix C for ranking rationales.

④ See note 4, Table 4-3 for details.

⑤ The initial debris distribution at the start of this phase is very important, i.e., debris will move toward the sump only if the flow velocity at the location of the debris exceeds the movement threshold velocity associated with each debris type.

APPENDIX A

MEMBERS OF THE PWR DEBRIS TRANSPORT PIRT PANEL

T. S. Andreychek

Timothy S. Andreychek is an Advanced Technical Engineer with Westinghouse Electric Company, LLC. He obtained his B. S. and M. S. degrees in Mechanical Engineering, and his M. S. in Industrial Engineering from the University of Pittsburgh. Mr. Andreychek has over 26 years of experience in the nuclear field, all of it with Westinghouse. He is currently a technical lead in the Containment and Radiological Analysis group. During his tenure with Westinghouse, Mr. Andreychek has been responsible for the conduct of proprietary ECCS heat-transfer tests for PWRs, thermal design and testing of reactor internals for liquid metal reactors, and LOCA analyses for PWRs. Mr. Andreychek has also worked extensively with Westinghouse's advanced reactor design, the AP600. He was responsible for the design of tests to demonstrate the operability of passive safeguards systems and the reduction and analysis of data from those tests, and he participated in developing the analysis methodology to demonstrate the performance of the passive containment cooling system for the AP600. Mr. Andreychek also has participated in the performance of Individual Plant Evaluations and Individual Plant External Event Evaluations.

B. E. Boyack

Brent E. Boyack is Chairman of the PWR Debris Transport PIRT Panel. He is a registered professional engineer. He obtained his B. S. and M. S. in Mechanical Engineering from Brigham Young University. He obtained his Ph.D. in Mechanical Engineering from Arizona State University in 1969. Dr. Boyack has been on the staff of the Los Alamos National Laboratory for 18 years; he is currently the leader of the software development team, continuing the development, validation, and application of the Transient Reactor Analysis Code (TRAC). Dr. Boyack has over 30 years experience in the nuclear field. He has been extensively engaged in accident analysis efforts, including design basis and severe accident analyses of light water, gas-cooled, and heavy-water reactors; reactor safety code assessments and applications; safety assessments; preparation of safety analysis reports; and independent safety reviews. He chaired the MELCOR and CONTAIN independent peer reviews and was a member of the Code Scaling, Applicability, and Uncertainty or CSAU technical program group. He has participated in numerous PIRT panels. He has over 70 journal and conference publications, and is an active member of the American Nuclear Society.

P. Griffith

Peter Griffith is a retired professor of Mechanical Engineering from Massachusetts Institute of Technology (MIT). He received his B. S. in

Mechanical Engineering from New York University in 1950, his M. S. in Mechanical Engineering from the University of Michigan, and his Sc.D. from MIT in 1956. He taught at MIT until 1997. He has consulted on thermal hydraulics and nuclear safety for a wide variety of companies, including Westinghouse, General Electric, Babcock and Wilcox, and a variety of other nuclear component suppliers. He has also consulted for a variety of government agencies including the NRC, Department of Energy, and several national laboratories including Oak Ridge, Argonne, Los Alamos, the Idaho National Engineering Laboratory, and Brookhaven. He served on the original PIRT panel for the LBLOCA that ultimately led to a relaxing of the Appendix K licensing requirements. He also served on the SBLOCA PIRT Panel, the AP600 SBLOCA PIRT Panel, and the Direct Containment Heating PIRT Panel. He is the author or co-author of about 100 papers in heat transfer, two-phase flow, and reactor safety.

F. E. Haskin

F. Eric Haskin is a registered professional engineer and a consultant to the nuclear industry and national laboratories. He obtained his B. S. in Nuclear Engineering in 1966 and his Ph.D. in Nuclear Engineering in 1971 from Kansas State University. Dr. Haskin's interests include accident progression and consequence modeling, quantitative risk assessment, and uncertainty analysis. He was a Research Professor in the Department of Chemical and Nuclear Engineering at the University of New Mexico from 1990 through 1998. He developed and teaches a course titled Perspectives on Reactor Safety for the US NRC. From 1979 to 1989, Dr. Haskin managed numerous severe-accident and space-nuclear-power research projects at Sandia National Laboratories. He supervised the development of the MELCOR, MACCS, and NUREG-1150 uncertainty analysis codes. From 1973 to 1980, Dr. Haskin served as Mechanical/Nuclear Engineering Supervisor for Bechtel in Ann Arbor. He was a Visiting Assistant Professor of Nuclear Engineering at the University of Arizona from 1971 to 1973.

J. Tills

Jack Tills is a registered professional engineer and a consultant to the US NRC and the national laboratories. He obtained his B. S. in Nuclear Engineering in 1968 from the University of Wisconsin and his M. S. in Nuclear Engineering in 1972 from the US Air Force Institute of Technology. Mr. Tills has 30 years of experience in numerical computations and analyses in the areas of heat transfer, thermal hydraulics, aerosol behavior, thermal stress analysis, and nuclear radiation transport. He has obtained his experience in the fields of nuclear reactor safety analysis, reactor design, and nuclear weapon effects. Mr. Tills has performed numerous severe accident studies of nuclear reactor containments using the US NRC sponsored CONTAIN computer code. Most recently, Mr. Tills has been involved in coauthoring a state-of-the-art report on containment thermal hydraulics and hydrogen distribution for the NEA

Committee on the Safety of Nuclear Installations (CSNI) and qualifying the CONTAIN code as a DBA licensing code for the US NRC. In these efforts, Mr. Tills has facilitated the development of PIRTs for various containment accident scenarios. Mr. Tills is president of Jack Tills and Associates, Inc., a New Mexico small business engineering consulting firm started in 1983. He is a member of the American Nuclear Society and the National Society of Professional Engineers.

APPENDIX B

PHENOMENA DESCRIPTIONS FOR PWR DEBRIS TRANSPORT PIRTS

This appendix provides the description for each phenomenon appearing in Tables 4-2 through 4-4. The description for each process or phenomenon arising during the blowdown phase of the accident scenario is presented in Table B-1. The description for each process or phenomenon arising during the post blowdown phase of the accident scenario is presented in Table B-2. The description for each process or phenomenon arising during the sump operation phase of the accident scenario is presented in Table B-3.

The reference numbers in the first column of each table are those presented in the corresponding PIRT tables, i.e., Table C-1 corresponds to Table 4-2 in Section 4, Table C-2 corresponds to Table 4-3, and Table C-3 corresponds to Table 4-4.

Reference is made to figures in the fourth column of each table. The figures for each phase of the scenario are found in this appendix following the phenomena description table for that phase of the accident scenario.

Table B-1
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (page 1 of 4)
(Reference number relates to entry in Table 4-2 in the report main body)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-1	Pressure-driven flows (bulk flows)	Net (macroscopic) flow characteristics of the containment atmosphere.	B-1
P1-2	Fan-driven flows	Moderate-sized (macroscopic) flows driven by the containment fans.	B-1
P1-3	Spray-induced flows	Flows resulting from the falling liquid droplets from the containment sprays.	B-1
P1-4	Circulating flows	Moderate-sized (macroscopic) flows driven by the pressure-driven flows.	B-1
P1-5	Steam/noncondensable mixing	Mixing (or stratification) of noncondensable gases in the containment atmosphere (N2 or air) with the two-phase break effluent.	B-1
P1-6	Localized flow field	Flow direction and/or velocities that differ from the bulk (net) atmosphere flow characteristics due to localized geometries.	B-1
P1-7	Turbulence	Local fluid vortexes or flow eddies created by flow around obstacles.	B-1
P1-8	Unflashed liquid flows	Flow of break fluid that does not flash but continues as a liquid stream.	B-1
P1-9	Flashing of break liquid effluent	Phase transformation (liquid–vapor) due to expansion across choked break plane.	B-1
P1-10	Droplet interactions	Mechanical interactions between suspended water droplets due to diffusion, settling, or any other process causing relative motion.	B-1
P1-11	Droplet formation via condensation	Phase transformation (vapor–liquid) as steam cools during its motion through the containment atmosphere creating nucleation-size water droplets.	B-1
P1-12	Condensation on structures	Heat and mass transfer from steam in the containment atmosphere to surfaces of containment structures associated with steam condensing on cooler structures.	B-1
P1-13	Film dynamics	The interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces, including interfacial shear, surface instability and droplet reentrainment.	B-1
P1-14	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-2
P1-15	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-2

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (page 2 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-16	Sweepout	Transport of debris through the containment by liquid droplets from the containment spray system.	B-2
P1-17	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-2
P1-18	Condensation on particles	Heat and mass transfer from steam in the containment atmosphere to surfaces of suspended debris particles with steam condensing onto particle surface.	B-2
P1-19	Stephan flow (diffusiophoresis)	Transport of debris particles toward deposition surfaces due to concentration gradients of atmosphere contents (dominated by steam concentration gradients created by condensation on containment structures).	B-2
P1-20	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-2
P1-21	Heat transfer	Cooling of containment atmosphere due to heat transfer to structures.	B-3
P1-22	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-3
P1-23	Surface wetting (condensation, impact)	Formation of a liquid film on structure surfaces due to condensation of steam from the atmosphere or impaction of water droplets onto structure surfaces.	B-3
P1-24	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-3
P1-25	Deluge (streaming)	Large flow rate of liquid effluent from a break in the reactor coolant system onto containment structures, or from sprays when activated.	B-3
P1-26	Resuspension	Reentrainment of debris previously deposited on structure surfaces into the atmosphere flow stream due to local fluid/structure shear forces.	B-4
P1-27	Agglomeration	Mechanical interaction among debris particles on structure surfaces (i.e., within a liquid film) by which two or more small particles combine to form a larger conglomerate particle.	B-4

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (page 3 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-28	Deluge (streaming)-related transport	Relocation of debris from containment structures due to interactions with the deluge of liquid from recirculation pipe breaks or sprays.	B-4
P1-29	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity.	B-4
P1-30	Runoff/reentrainment	Resuspension of debris on structure surfaces into the flow stream as liquid films drain off of structures.	B-4
P1-31	Debris fragmentation	Breakup of relatively large pieces of debris into smaller particles that can be reentrained into the flow stream due to fluid shear created (for example) by locally high flow velocities at constricted flow areas.	B-4
P1-32	Entrapment	Retention of debris in areas having insufficient flow velocity.	B-4
P1-33	Inertial Impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-4
P1-34	Turbulent impaction	Capture of debris on structural surfaces due to turbulent eddies	B-4
P1-35	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-4
P1-36	Pool formation	Creation of a pool of water on the containment floor sufficiently deep to allow overflow into the sump due to the accumulation of water from all sources higher in the containment (e.g., film drainage, droplet settling).	B-5
P1-37	Heat transfer to structure	Heat transfer between water on containment floor and bounding structures.	B-5
P1-38	Surface wetting (before pool formation)	Wetting of containment floor due to steam condensation or settling of suspended water droplets.	B-5
P1-39	Streaming-induced pool dynamics	Agitation of the pool by liquid streams falling or draining from above.	B-5
P1-40	Sheeting flow dynamics	Multidimensional flow patterns and velocities within the sheet of water on the containment floor; includes free-surface (vertical) velocity profile and turbulent mixing (circulation) flows.	B-5
P1-41	Film transport	Introduction of debris into the developing pool by watering draining down vertical surfaces	B-6

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (page 4 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-42	Resuspension	Reentrainment of debris into the atmospheric flow stream from the containment floor due to high shear forces at the surface of the floor.	B-6
P1-43	Sheet transport	Debris movement within the sheet of water developing into a pool on the basemat floor.	B-6
P1-44	Agglomeration in pool	Mechanical interaction among debris particles in the pool of water on the floor by which two or more small particles combine to form a larger conglomerate particle.	B-6
P1-45	Adhesion	Permanent retention of debris particles on the containment floor due to mechanical interactions with a rough surface or other forces.	B-6
P1-46	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-6
P1-47	Impaction	Capture of debris on the surface of the containment floor (or water pool) due to inertial deposition.	B-6
P1-48	Entrapment by porous structures	Retention of debris against porous blocking structures such as grated doors.	B-6

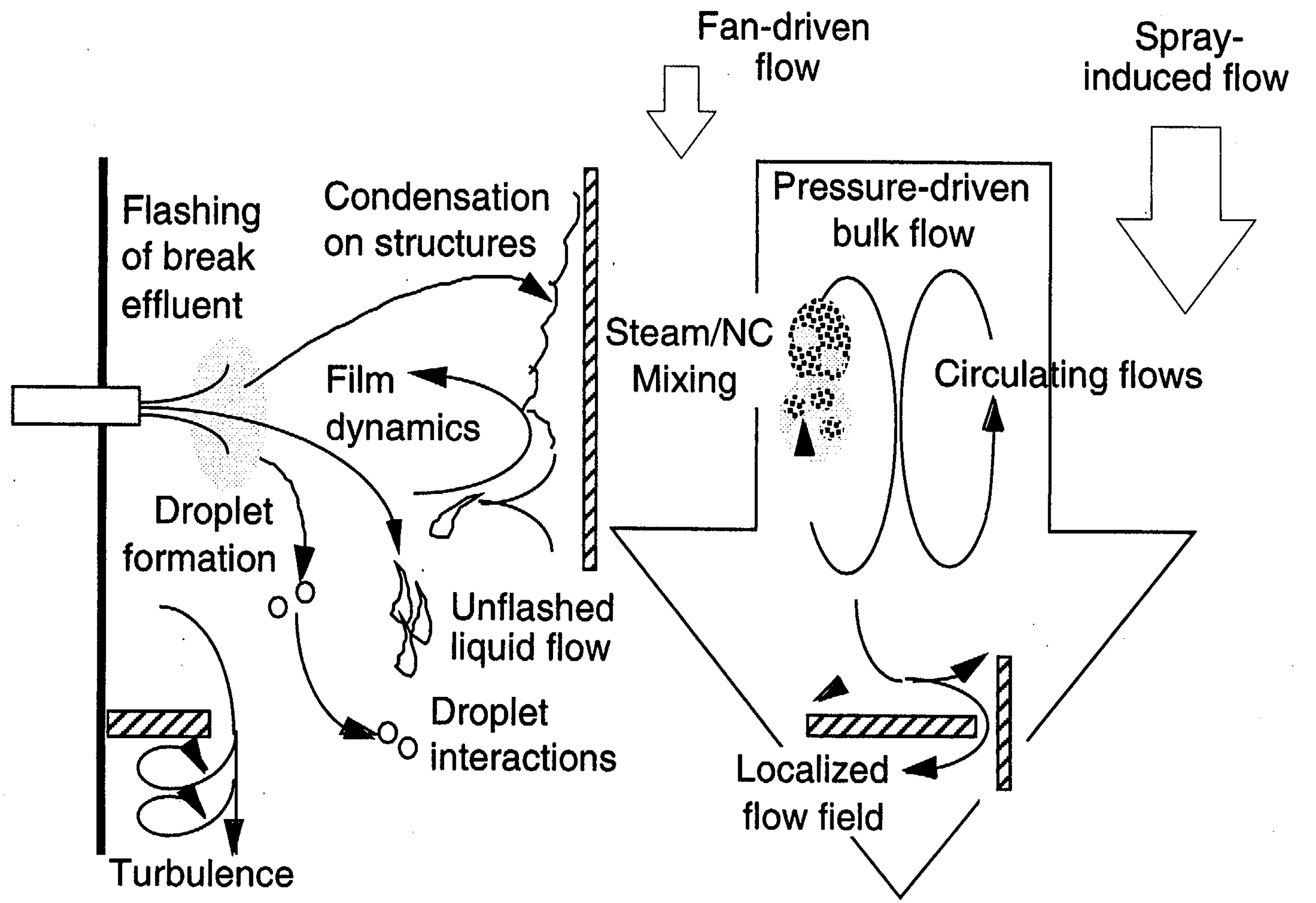

Fig. B-1. Thermal-hydraulic processes in PWR containment open areas during the blowdown phase of a CL LBLOCA.

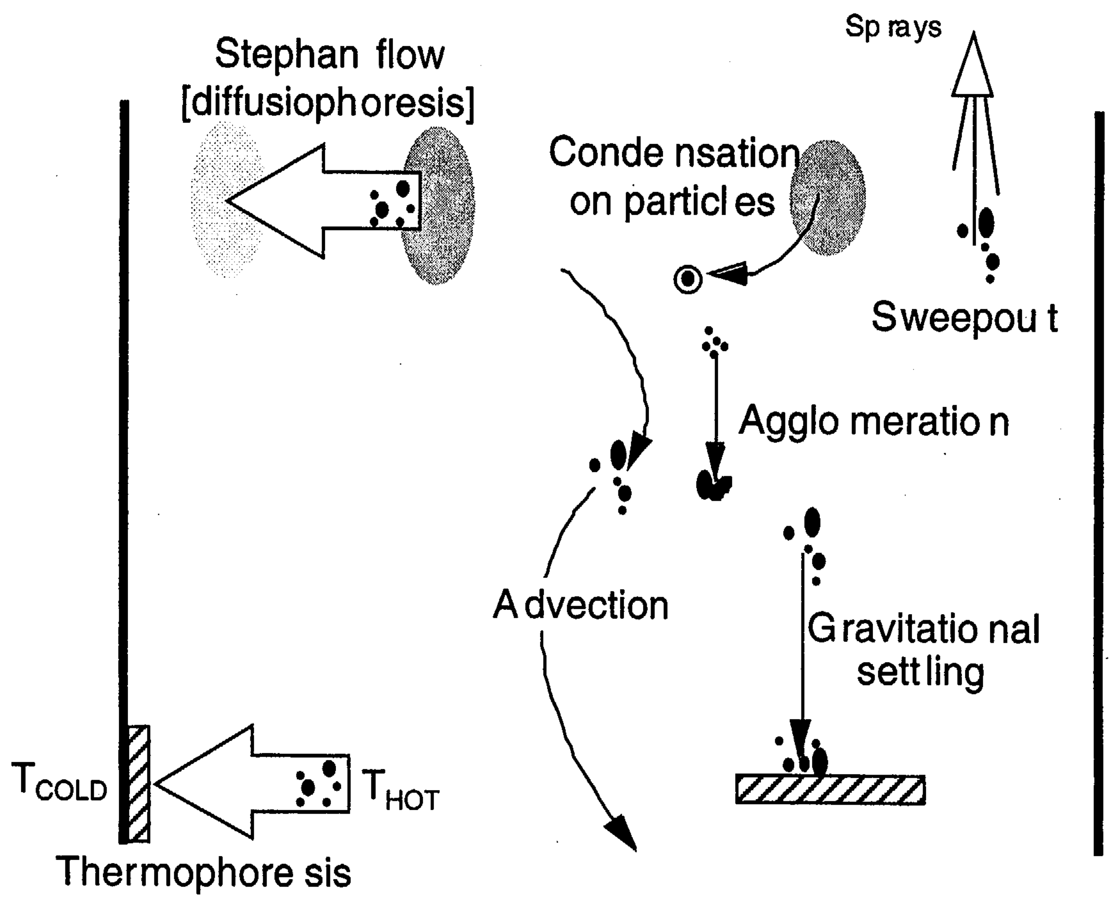

Fig. B-2. Transport/deposition processes for debris in containment open areas during the blowdown phase of a CL LBLOCA.

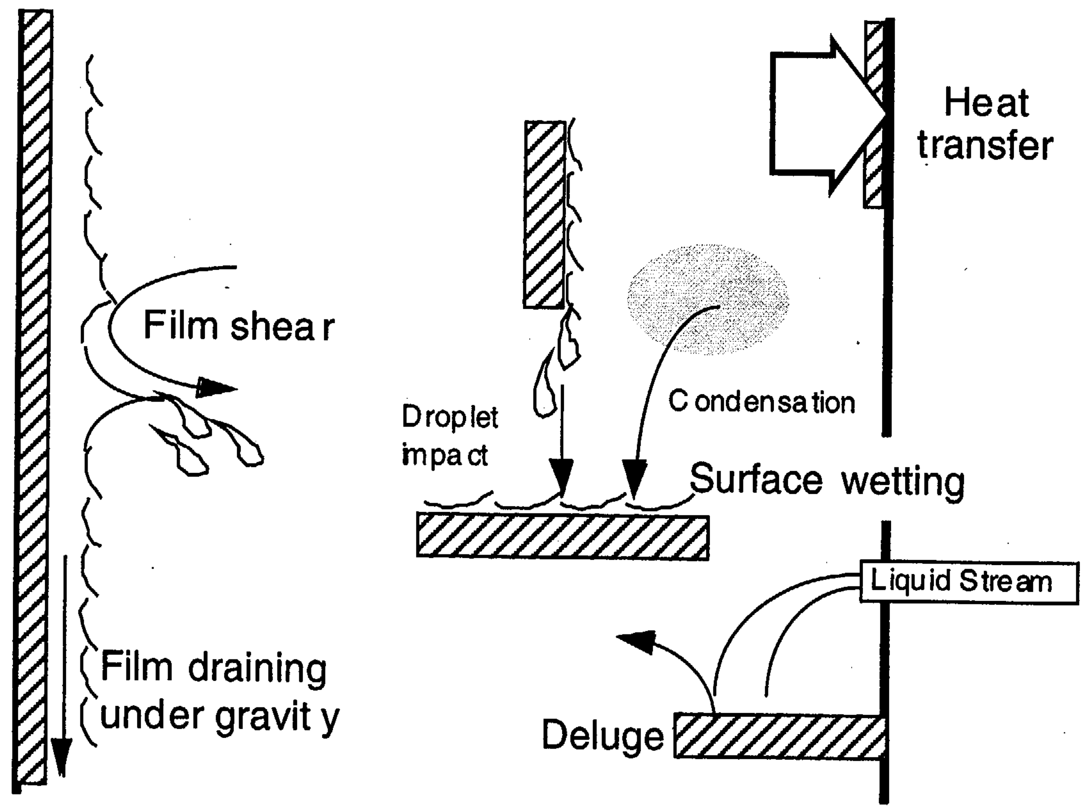

Fig. B-3. Thermal-hydraulic processes on containment structures during the blowdown phase of a CL LBLOCA.

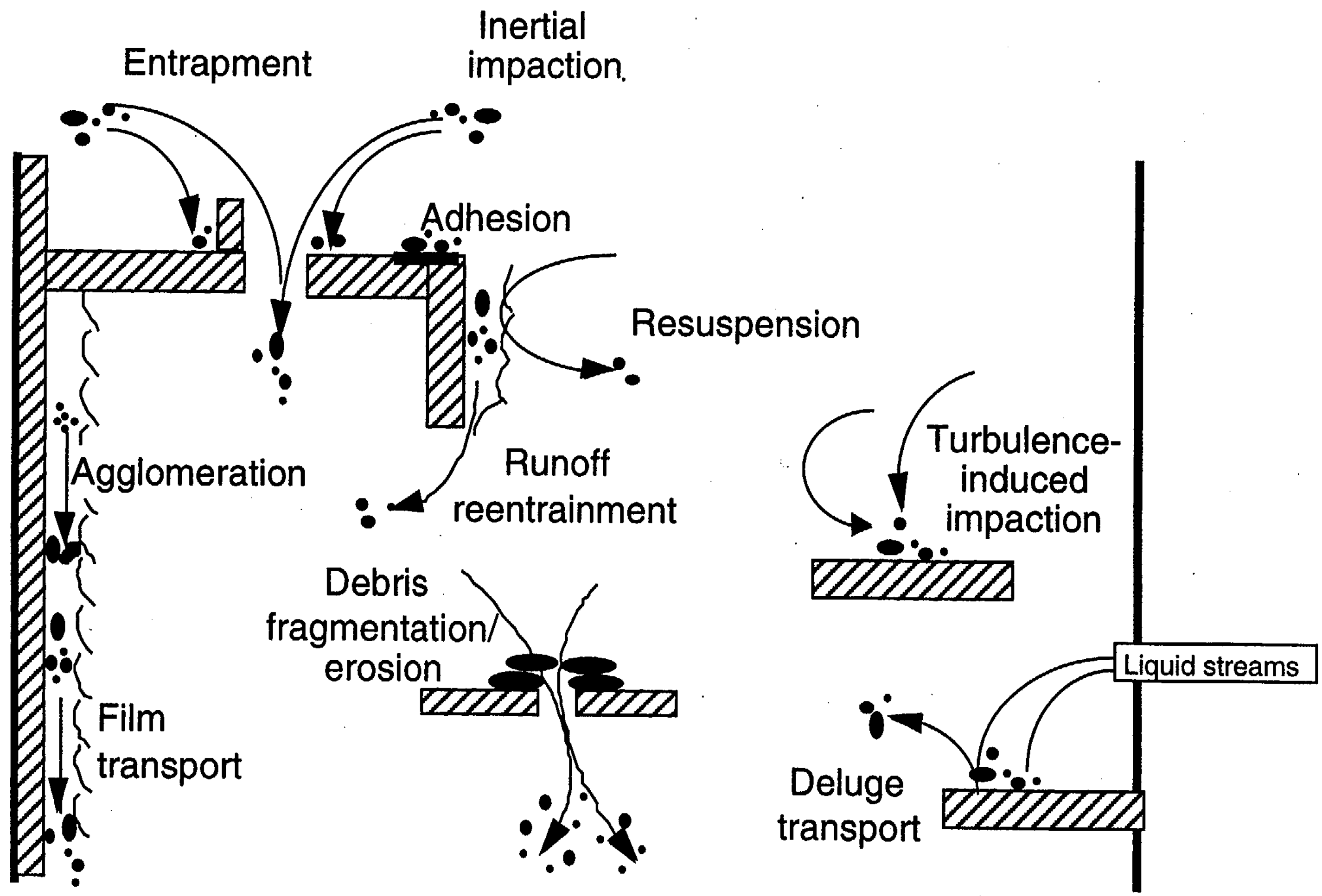

Fig. B-4. Transport/deposition processes for debris on containment structures during the blowdown phase of a CL LBLOCA.

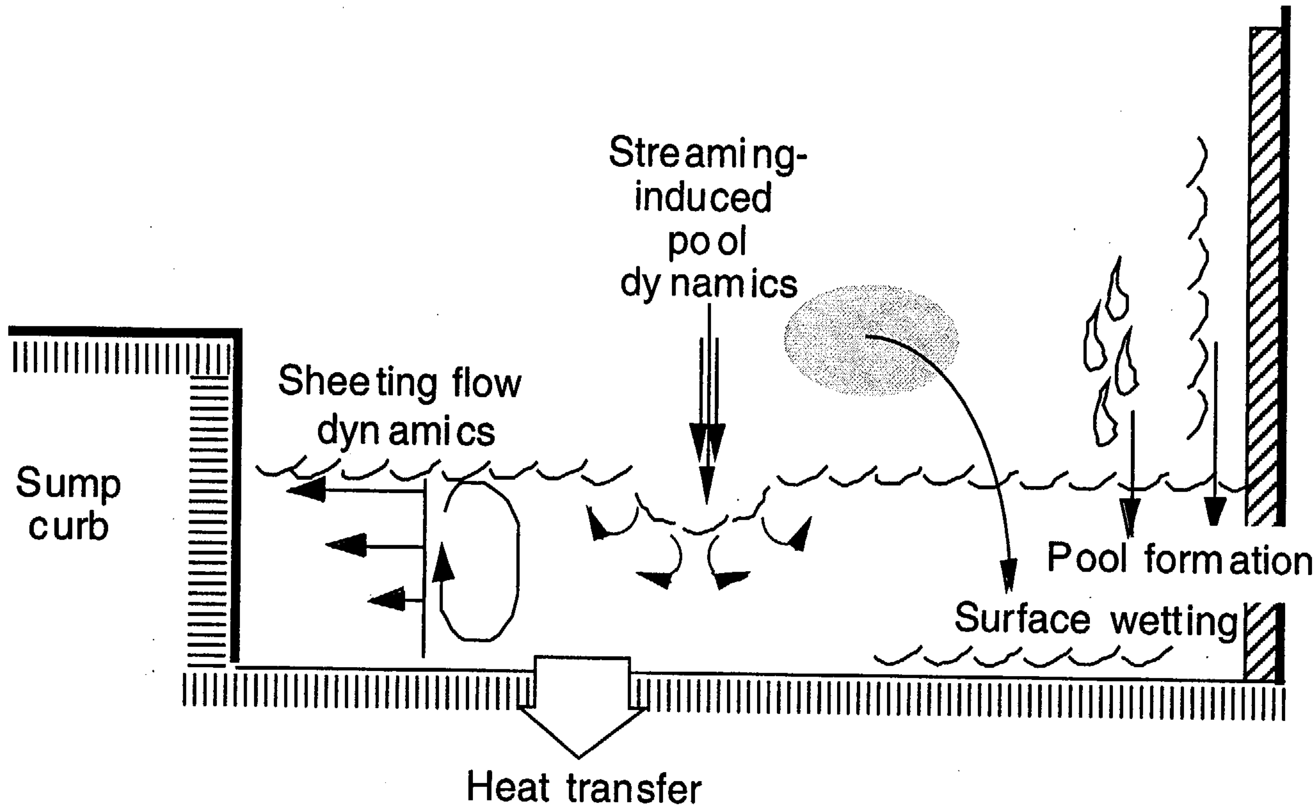

Fig. B-5. Thermal-hydraulic processes on the basemat floor during the blowdown phase of a CL LBLOCA.

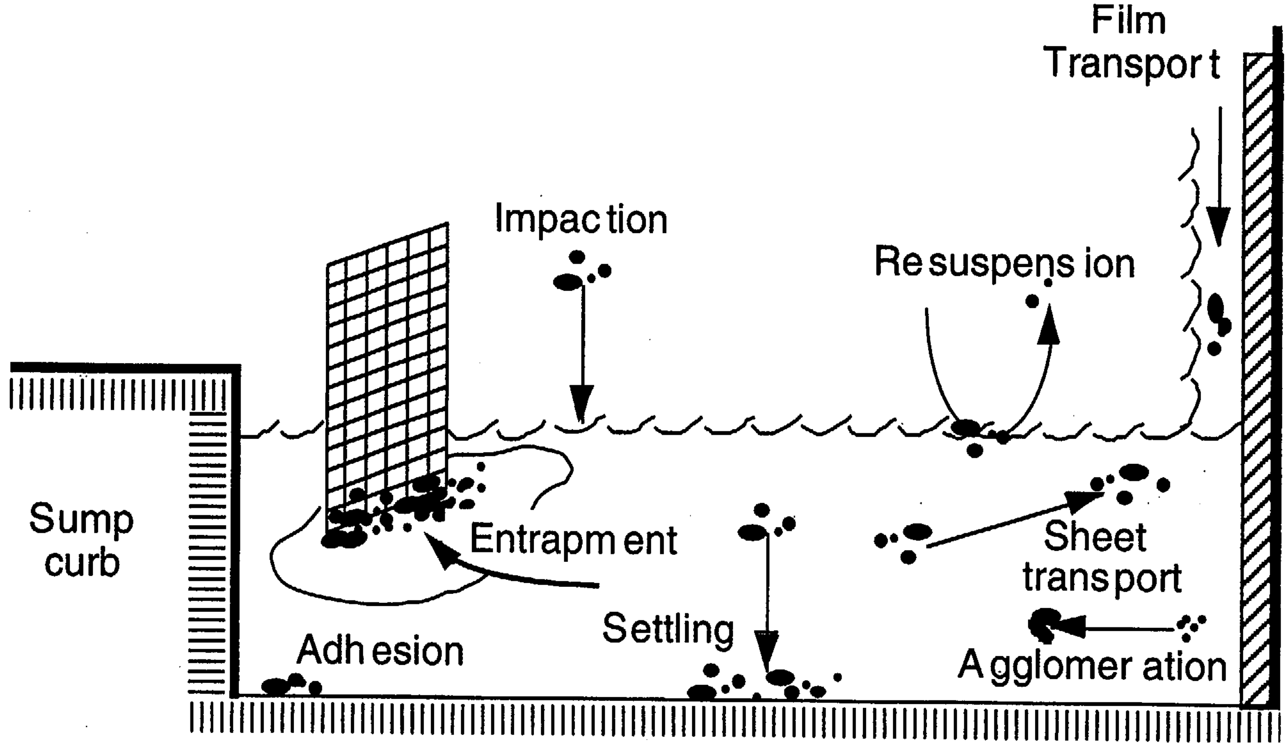

Fig. B-6. Transport/deposition processes for debris on the basemat floor during the blowdown phase of a CL LBLOCA.

Table B-2
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (page 1 of 4)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-1	Steam flow	Vapor entering containment from vessel and pump sides of cold-leg break.	B-7
P2-2	Fan-driven flow	Containment flow fields created by operation of the fan-cooling system.	B-7
P2-3	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-7
P2-4	Circulating flows	Localized flows driven by buoyancy or other forces.	B-7
P2-5	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-7
P2-6	Turbulence	Turbulent fluid motions within the containment.	B-7
P2-7	Plume	Centralized local upflow in containment.	None
P2-8	Thermal stratification	Formation of vertical temperature gradient in the containment.	None
P2-9	Unflashed liquid flow	Liquid entering containment from vessel side of the cold-leg break.	B-7
P2-10	Falling condensate	Liquid falling under gravitational force after condensing on fan coolers.	B-7
P2-11	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-7
P2-12	Condensation on structures	Macroscopic effects include containment pressure reduction due to reduction in vapor volume fraction. Local effects include development of liquid films that migrate downward on vertical structures.	B-7
P2-13	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-8
P2-14	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-8
P2-15	Sweepout	Capture by airborne liquid.	B-8

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (page 2 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-16	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-8
P2-17	Condensation on particles	Heat and mass transfer from steam in the containment atmosphere to surfaces of suspended debris particles with steam condensing onto particle surface.	B-8
P2-18	Stephan flow (diffuseophoresis)	Transport of debris particles toward deposition surfaces due to concentration gradients of atmosphere contents (dominated by steam concentration gradients created by condensation on containment structures).	B-8
P2-19	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-8
P2-20	Heat transfer	Transfer of heat from containment atmosphere to walls by convection.	B-9
P2-21	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-9
P2-22	Surface pooling	Buildup of water layers on horizontal or inclined surfaces	B-9
P2-23	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-9
P2-24	Deluge (streaming)	Large flow rate of liquid effluent from ECCS onto containment structures.	B-9
P2-25	Surface draining	Movement of liquid streams from higher elevations to lower elevations	B-9
P2-26	Condensation	Phase transformation (vapor-liquid) as steam cools during its motion through the containment atmosphere, e.g., on structures.	B-9
P2-27	Resuspension into flow stream	Reentrainment of debris previously deposited on structure surfaces into the atmosphere flow stream due to local fluid/structure shear forces.	B-10
P2-28	Agglomeration	Mechanical interaction among debris particles on structure surfaces (i.e., within a liquid film) by which two or more small particles combine to form a larger conglomerate particle.	B-10

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (page 3 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-29	Deluge transport	Relocation of debris from containment structures due to interactions with the deluge of liquid from the ECCS and spray system.	B-10
P2-30	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity. Also called "washdown."	B-10
P2-31	Runoff/reentrainment	Resuspension of debris on structure surfaces into the atmosphere flow stream as liquid films drain off of structures.	B-10
P2-32	Disintegration	Breakup of relatively large pieces of debris into smaller particles that can be reentrained into the flow stream caused by the impact of falling liquid streams from the break, fan coolers, and liquid draining off surfaces.	B-8
P2-33	Entrapment	Capture of debris in local structural "pooling points," i.e., locations that allow the accumulation and storage of draining condensate and associated transported debris.	B-10
P2-34	Inertial impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-10
P2-35	Turbulent impaction	Capture of debris particles driven to structure surfaces by turbulence	B-10
P2-36	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-10
P2-37	Pool formation	Creation of a pool of water on the containment floor (due to accumulation of water from all sources higher in the containment, e.g., film drainage, droplet settling) sufficiently deep to allow flow into the sump upon switching to sump recirculation.	B-11
P2-38	Evaporation	Transformation of pool liquid to vapor at the pool surface.	B-11
P2-39	Heat transfer to structure	Heat transfer between water on the containment floor and bounding structures.	B-11
P2-40	Pool agitation	Agitation of the pool by liquid streams falling or draining from above.	B-11
P2-41	Pool flow dynamics	Multidimensional flow patterns and velocities within the pool of water on the containment floor; includes increasing pool height, circulating flows, and turbulent mixing flows.	B-11

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (page 4 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-42	Entry via film transport	Introduction of debris into the pool on the containment floor as draining films containing debris from vertical surfaces enter the pool.	B-12
P2-43	Entry via vapor transport	Introduction of debris into the pool on the containment floor by vapor flows moving to the pool or direct settling or sweepout to the pool.	B-12
P2-44	Entry via liquid transport	Introduction of debris into the pool on the containment floor as draining liquid streams containing debris from horizontal surfaces enter the pool.	B-12
P2-45	Reentrainment	Movement of debris off the basemat floor and into higher elevations of the pool.	B-12
P2-46	Disintegration	Breakup of relatively large pieces of debris in the pool into smaller particles due to tumbling action and inertial impact of liquid streams, e.g., liquid draining from higher elevations.	B-12
P2-47	Pool Transport	Prior to sump activation, directed flows exist near the entry location of falling liquid streams, which transport debris in the pool.	B-12
P2-48	Agglomeration	Mechanical interaction among debris particles on the containment floor by which two or more small particles combine to form a larger conglomerate particle.	B-12
P2-49	Adhesion	Permanent retention of debris particles on the basemat surface due to mechanical interactions with a rough surface or other forces.	B-12
P2-50	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-12
P2-51	Entrapment by porous structures	Retention of debris against porous blocking structures such as grated doors.	B-12

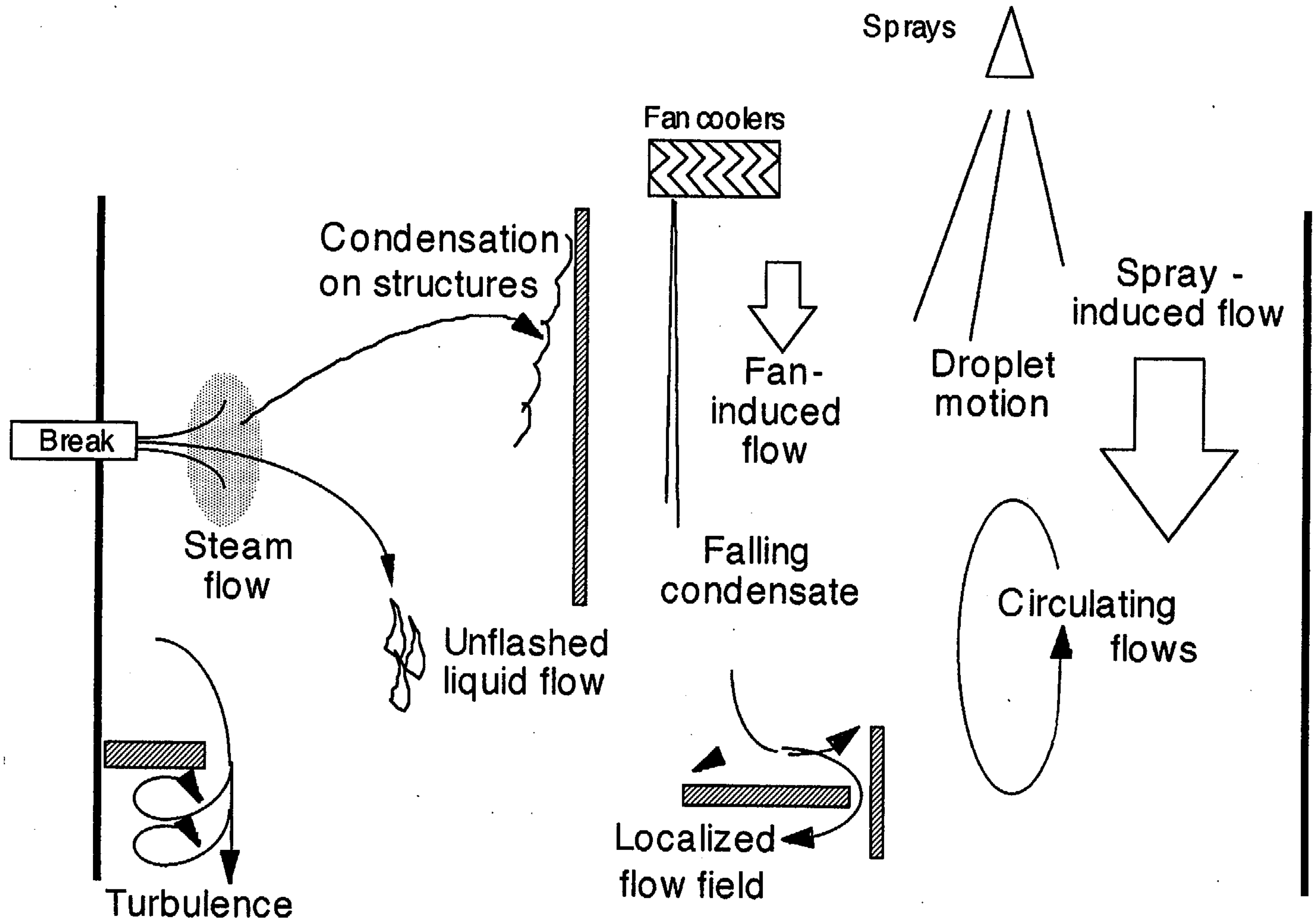

Fig. B-7. Thermal-hydraulic processes in PWR containment open areas during the post-blowdown phase of a CL LBLOCA.

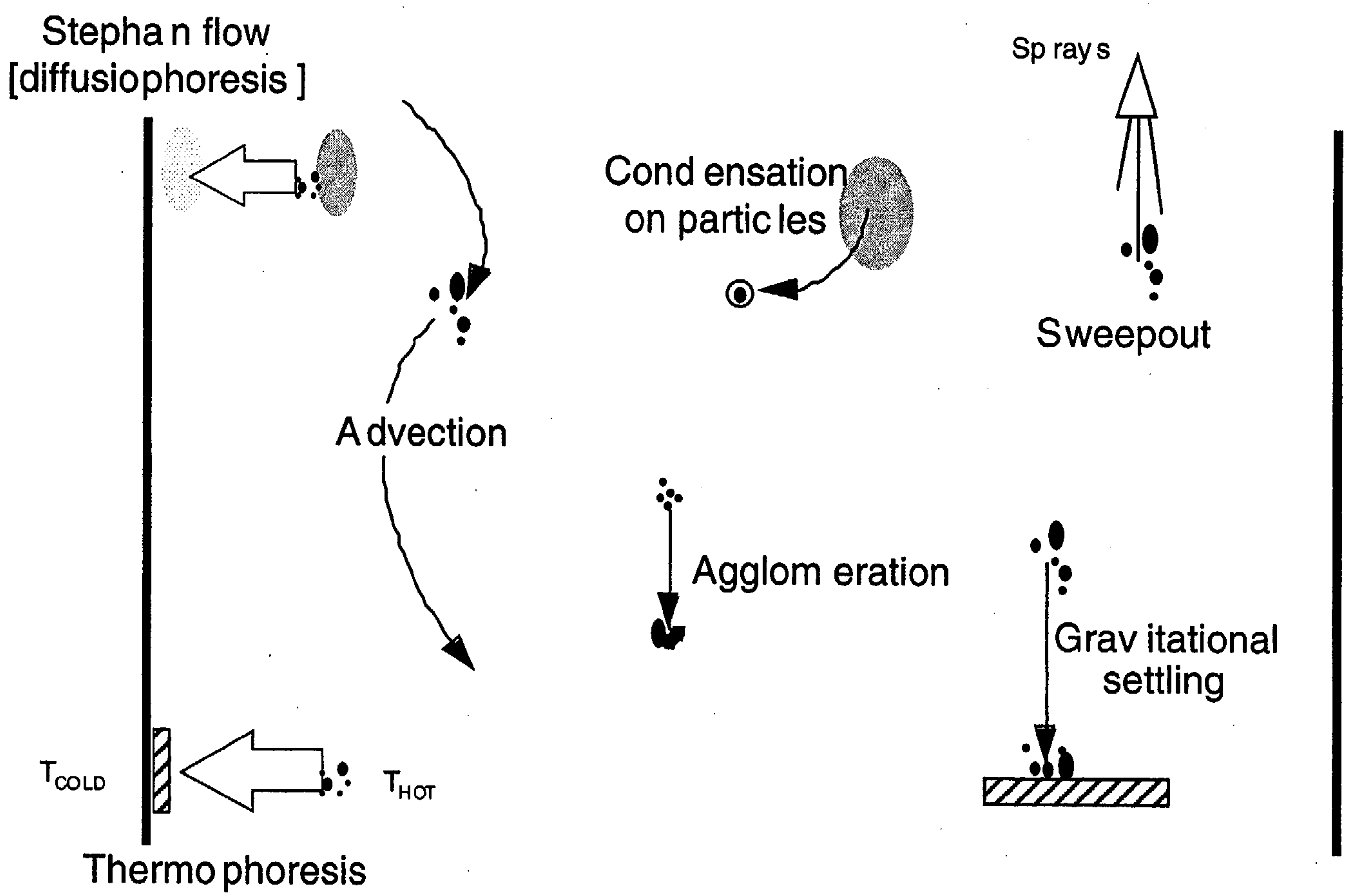

Fig. B-8. Transport/deposition processes for debris in containment open areas during the post-blowdown phase of a CL LBLOCA.

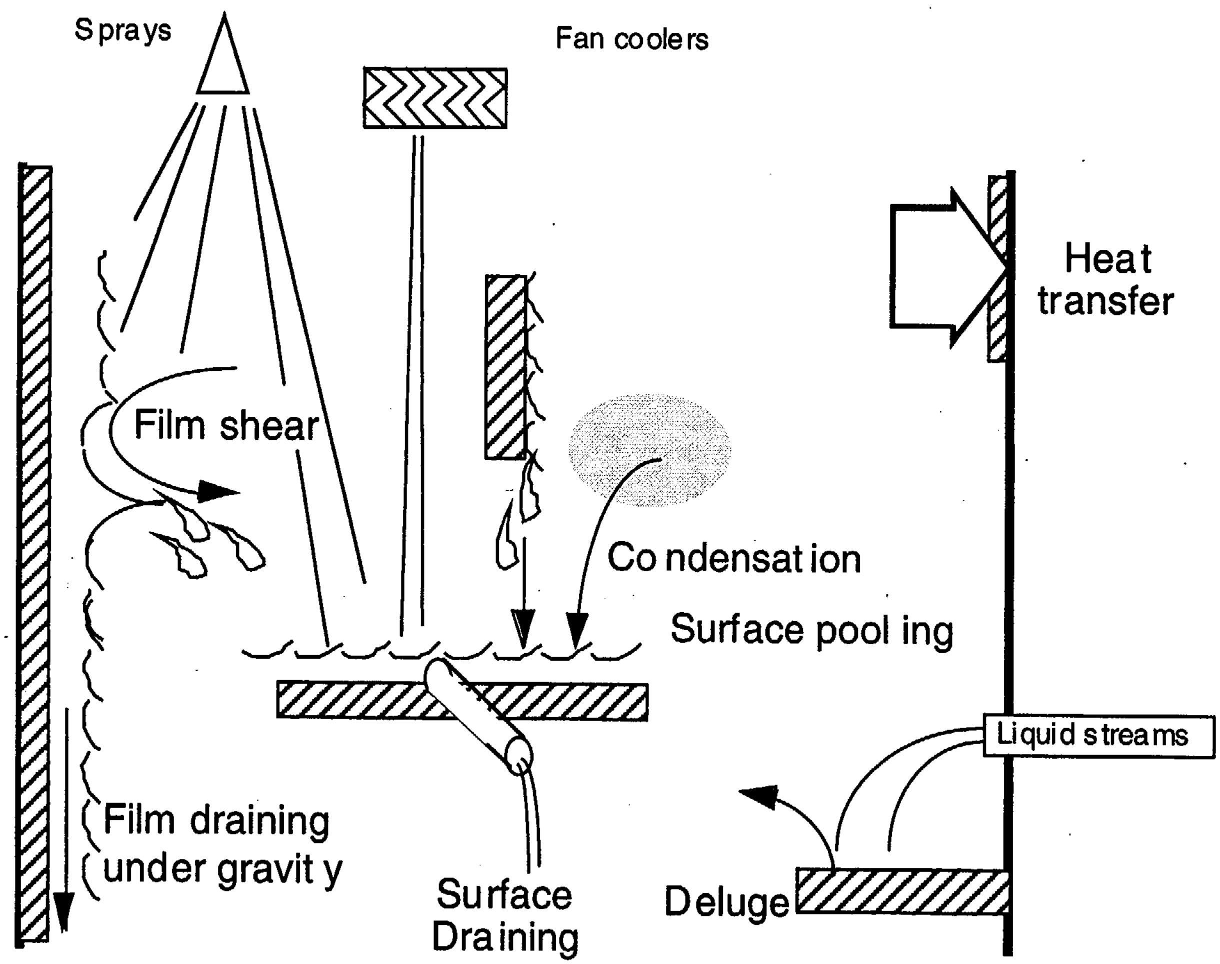

Fig. B-9. Thermal-hydraulic processes on containment structures during the post-blowdown phase of a CL LBLOCA.

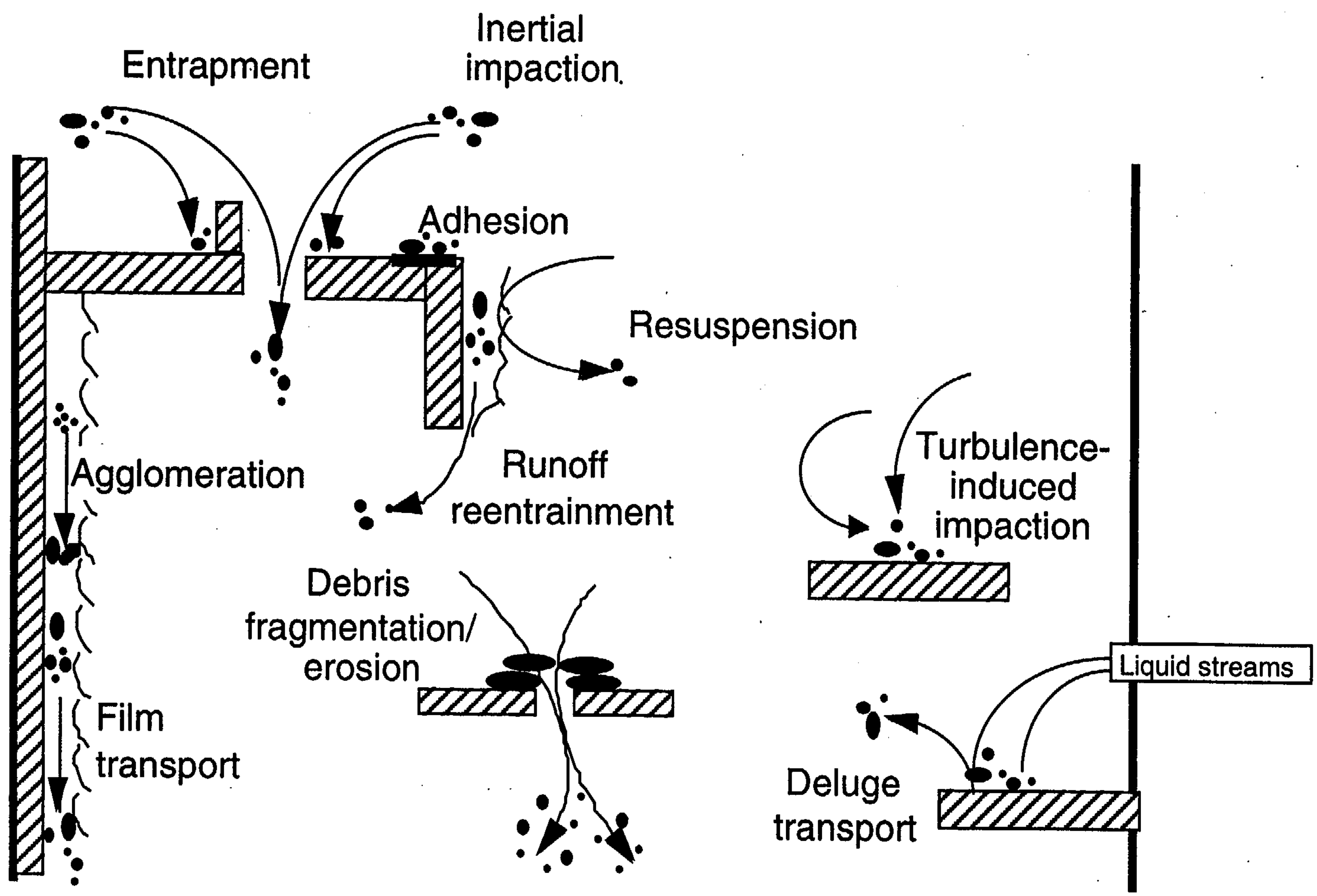

Fig. B-10. Transport/deposition processes for debris on containment structures during the post-blowdown phase of a CL LBLOCA.

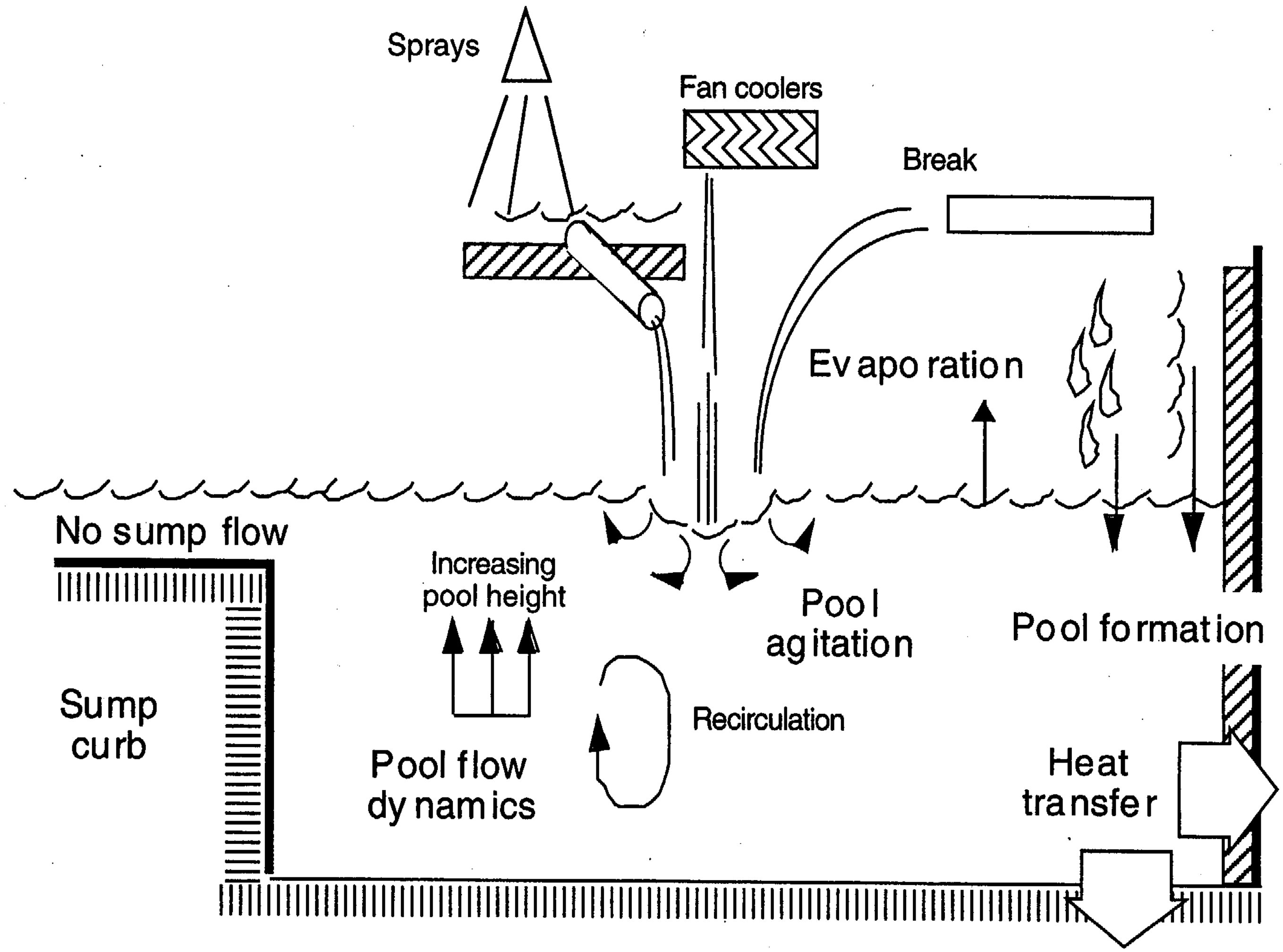

Fig. B-11. Thermal-hydraulic processes on the basemat floor during the post-blowdown phase of a CL LBLOCA.

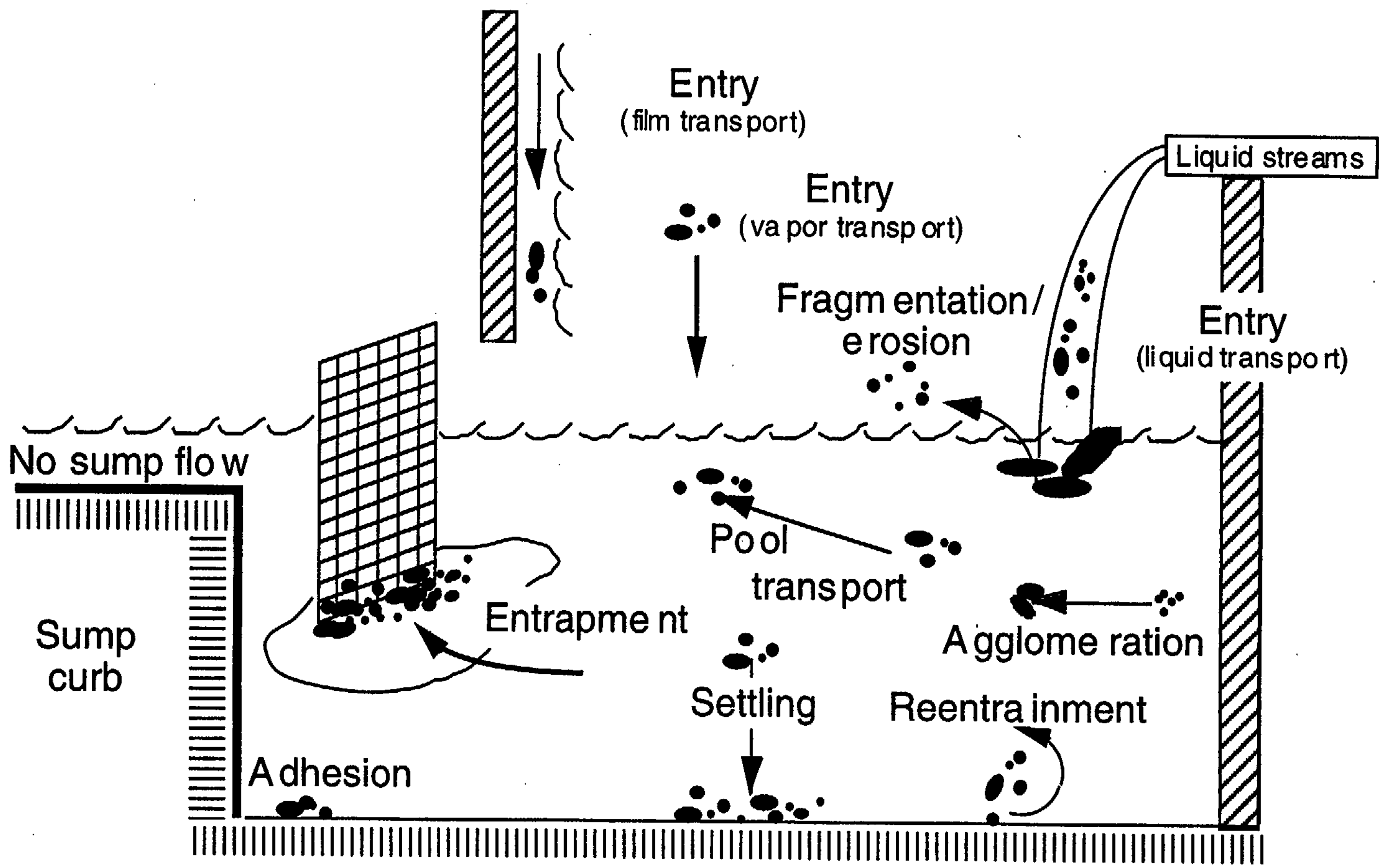

Fig. B-12. Transport/deposition processes for debris on the basemat floor during the post-blowdown phase of a CL LBLOCA.

Table B-3
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (page 1 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-1	Steam flow	Vapor entering containment from vessel and pump sides of CL break.	B-13
P3-2	Fan-induced flow	Containment flow fields created by operation of the fan cooling system.	B-13
P3-3	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-13
P3-4	Circulating flows	Localized flows driven by buoyancy or other forces.	B-13
P3-5	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-13
P3-6	Turbulence	Turbulent fluid motions within the containment.	B-13
P3-7	Plume	Centralized local upflow in containment.	None
P3-8	Thermal stratification	Formation of vertical temperature gradient in the containment.	None
P3-9	Unflashed liquid flow	Liquid entering containment from vessel side of CL break.	B-13
P3-10	Falling condensate	Liquid falling under gravitational force after condensing on fan coolers.	B-13
P3-11	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-13
P3-12	Condensation on structures	Macroscopic effects include containment pressure reduction due to reduction in vapor volume fraction. Local effects include development of liquid films, which migrate downward on vertical structures.	B-13
P3-13	Debris advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-14
P3-14	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-14
P3-15	Sweepout	Capture by airborne liquid.	B-14
P3-16	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-14

Table B-3
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (page 2 of 5)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-17	Condensation on particles	Heat and mass transfer from steam in the containment atmosphere to surfaces of suspended debris particles with steam condensing onto particle surface.	B-14
P3-18	Stephan flow (diffuseophoresis)	Transport of debris particles toward deposition surfaces due to concentration gradients of atmosphere contents (dominated by steam concentration gradients created by condensation on containment structures).	B-14
P3-19	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-14
P3-20	Heat transfer	Transfer of heat from containment atmosphere to walls by convection.	B-15
P3-21	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-15
P3-22	Surface pooling	Buildup of water layers on horizontal or inclined surfaces	B-15
P3-23	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-15
P3-24	Deluge (streaming)	Large flow rate of liquid effluent from ECCS onto containment structures.	B-15
P3-25	Surface draining	Movement of liquid streams from higher elevations to lower elevations.	B-15
P3-26	Condensation	Phase transformation (vapor-liquid) as steam cools during its motion through the containment atmosphere, e.g., on structures.	B-15
P3-27	Resuspension into flow stream	Reentrainment of debris previously deposited on structure surfaces into the atmosphere flow stream due to local fluid/structure shear forces.	B-16
P3-28	Agglomeration	Mechanical interaction among debris particles on structure surfaces (i.e., within a liquid film) by which two or more small particles combine to form a larger conglomerate particle.	B-16

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (page 3 of 5)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-29	Deluge transport	Relocation of debris from containment structures due to interactions with the deluge of liquid from ECCS.	B-16
P3-30	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity.	B-16
P3-31	Runoff/reentrainment	Resuspension of debris on structure surfaces into the atmosphere flow stream as liquid films drain off of structures.	B-16
P3-32	Disintegration	Breakup of relatively large pieces of debris into smaller particles that can be reentrained into the flow stream due to the impact of falling liquid streams from the break, fan coolers, and liquid draining off surfaces.	B-14
P3-33	Entrapment	Capture of debris in local structural "pooling points," i.e., locations that allow the accumulation and storage of draining condensate and associated transported debris.	B-16
P3-34	Inertial impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-16
P3-35	Turbulence impaction	Capture of debris particles driven to structure surfaces by turbulence.	B-16
P3-36	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-16
P3-37	Pool formation	Creation of a pool of water on the containment floor (due to accumulation of water from all sources higher in the containment e.g., film drainage, droplet settling) sufficiently deep to allow flow into the sump upon switching to sump recirculation.	B-17
P3-38	Evaporation	Transformation of pool liquid to vapor at the pool surface.	B-17
P3-39	Heat transfer to structure	Heat transfer between water on the containment floor and bounding structures.	B-17
P3-40	Pool agitation	Agitation of the pool by liquid streams falling or draining from above.	B-17

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (page 4 of 5)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-41	Pool flow dynamics	Multidimensional flow patterns and velocities within the pool of water on the containment floor; includes increasing pool height, circulating flows, and turbulent mixing flows.	B-17
P3-42	Sump-induced flow	Following sump activation, a directed flow is established toward the sump.	B-17
P3-43	Entry via film transport	Introduction of debris into the pool on the containment floor as draining films containing debris enter the pool.	B-18
P3-44	Entry via vapor transport	Capture of debris on the surface of the containment floor pool due to inertial impaction.	B-18
P3-45	Entry via liquid transport	Introduction of debris into the pool on the containment floor as draining liquid streams containing debris enter the pool.	B-18
P3-46	Reentrainment	Movement of debris residing off the basemat floor and into higher elevations of the pool.	B-18
P3-47	Debris fragmentation	Breakup of relatively large pieces of debris on the containment floor (pool surface) into smaller particles due to inertial impact of liquid streams., e.g., liquid draining from higher elevations.	B-18
P3-48	Pool transport	Debris will be transported toward the sump by the directed flow established following sump activation.	B-18
P3-49	Agglomeration	Mechanical interaction among debris particles on the containment floor by which two or more small particles combine to form a larger conglomerate particle.	B-18
P3-50	Adhesion	Permanent retention of debris particles on the basemat surface due to mechanical interactions with a rough surface or other forces.	B-18
P3-51	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-18

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (page 5 of 5)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-52	Precipitate formation	Containment walls and equipment in some PWRs use protective coatings consisting of a zinc primer and a topcoat. Upon prolonged exposure to borated water in the basemat pool, a precipitate may form from the reaction of the borated water and any exposed zinc primer, either while still on walls or equipment or on paint chips that were created within the ZOI during the blowdown and subsequently washed into the basemat pool.	B-18
P3-53	Sump-induced overflow	Transport of suspended debris over the sump curb and to the trash rack/debris screen. In addition to the sump curb, the buildup of ramp-like debris beds at the base of the curb must be considered for their impact on flow patterns and debris transport.	B-18
P3-54	Entrapment	An obstacle created during the scenario by the accumulation of debris at a given location that serves to divert flow from the path it would normally follow if the obstacle did not exist.	B-18

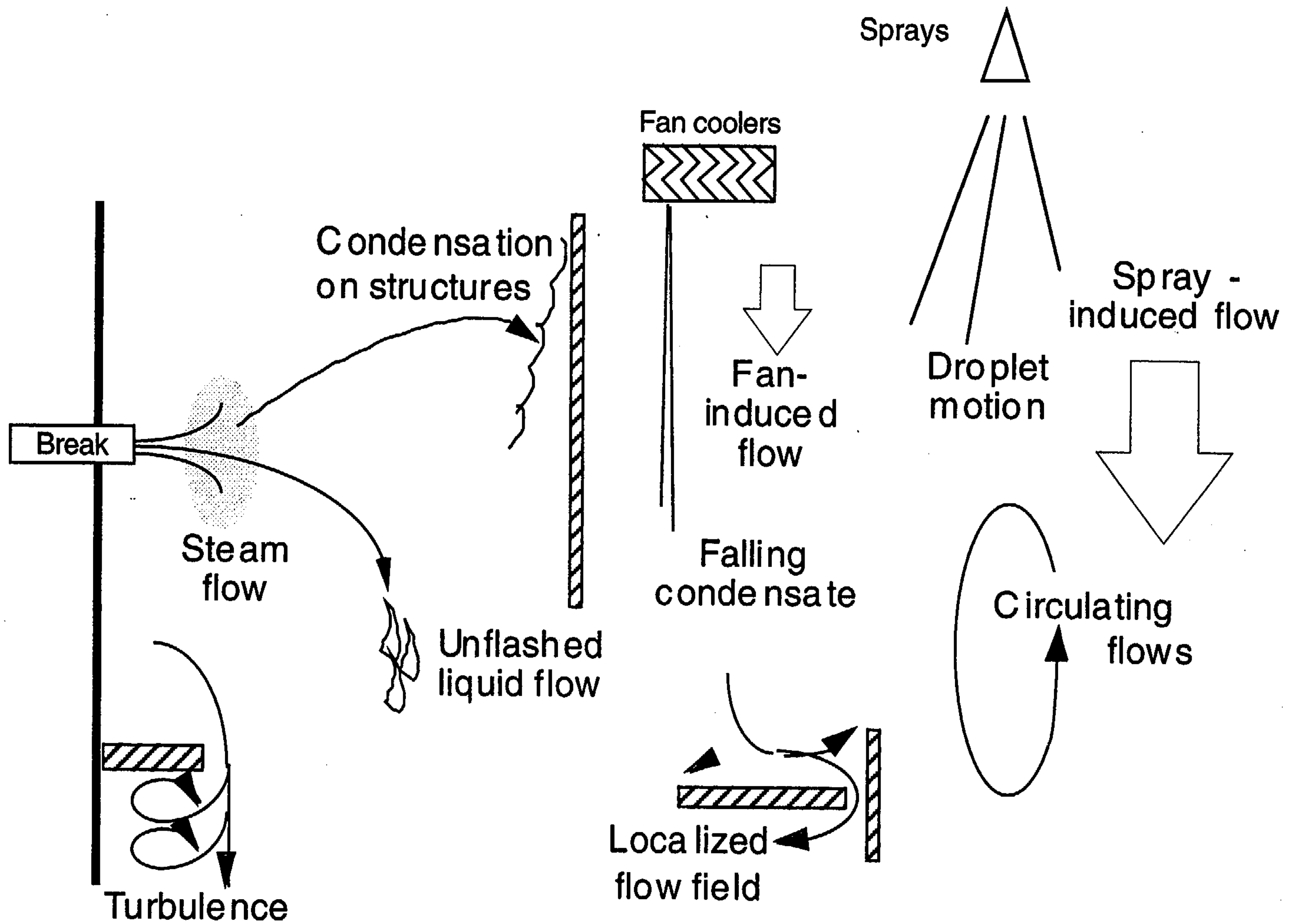

Fig. B-13. Thermal-hydraulic processes in PWR containment open areas during the sump-operation phase of a CL LBLOCA.

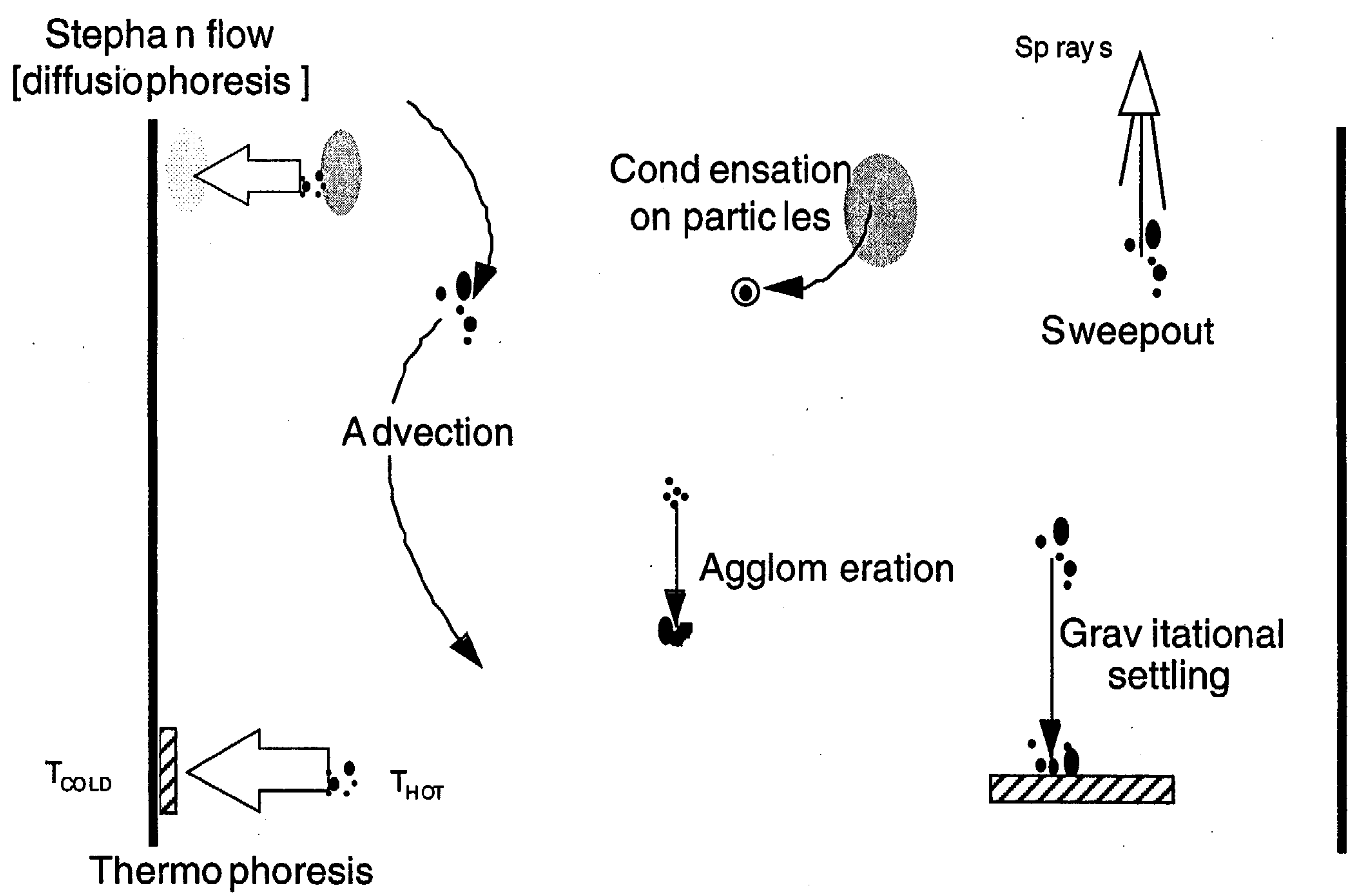

Fig. B-14. Transport/deposition processes for debris in containment open areas during the sump-operation phase of a CL LBLOCA.

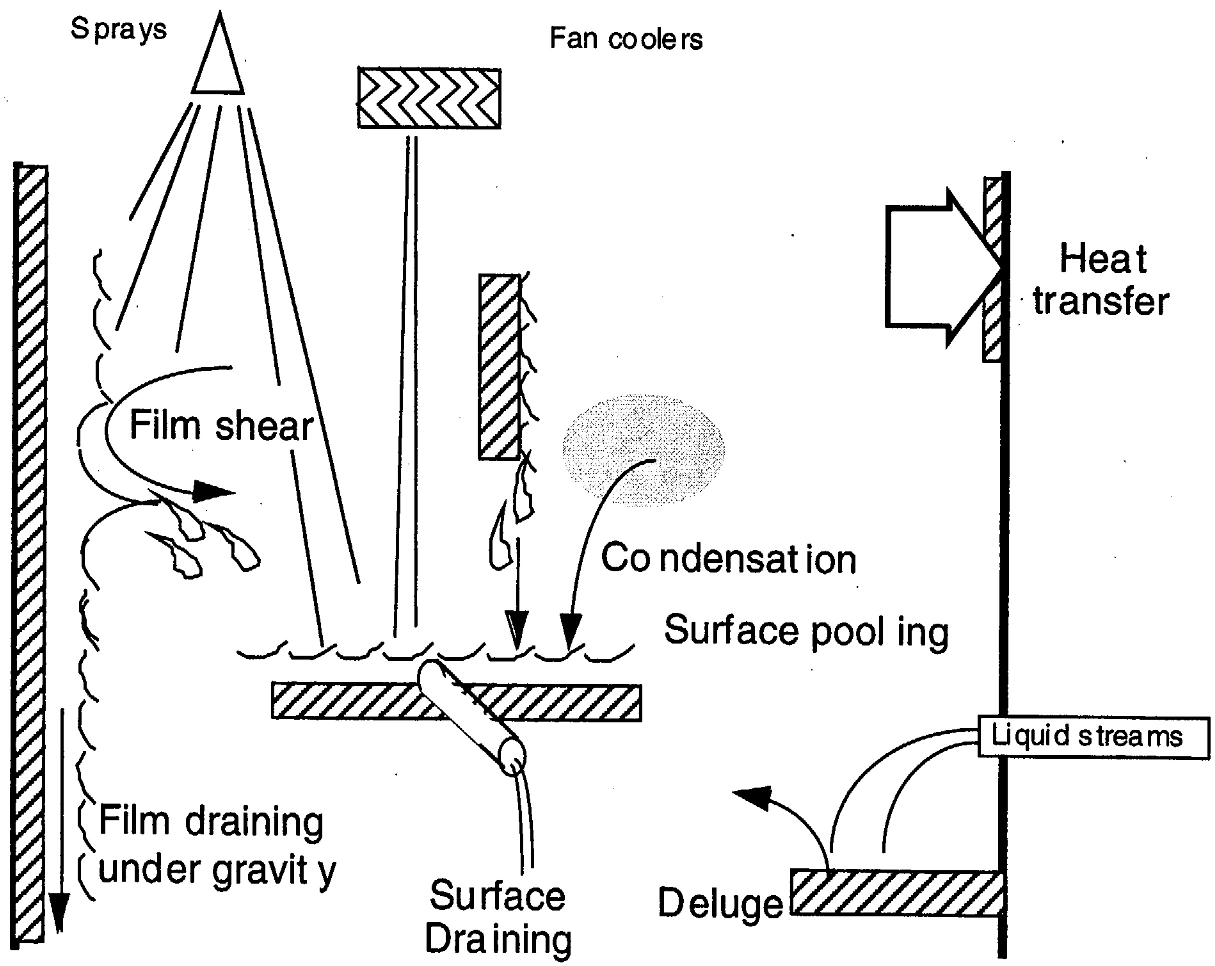

Fig. B-15. Thermal-hydraulic processes on containment structures during the sump-operation phase of a CL LBLOCA.

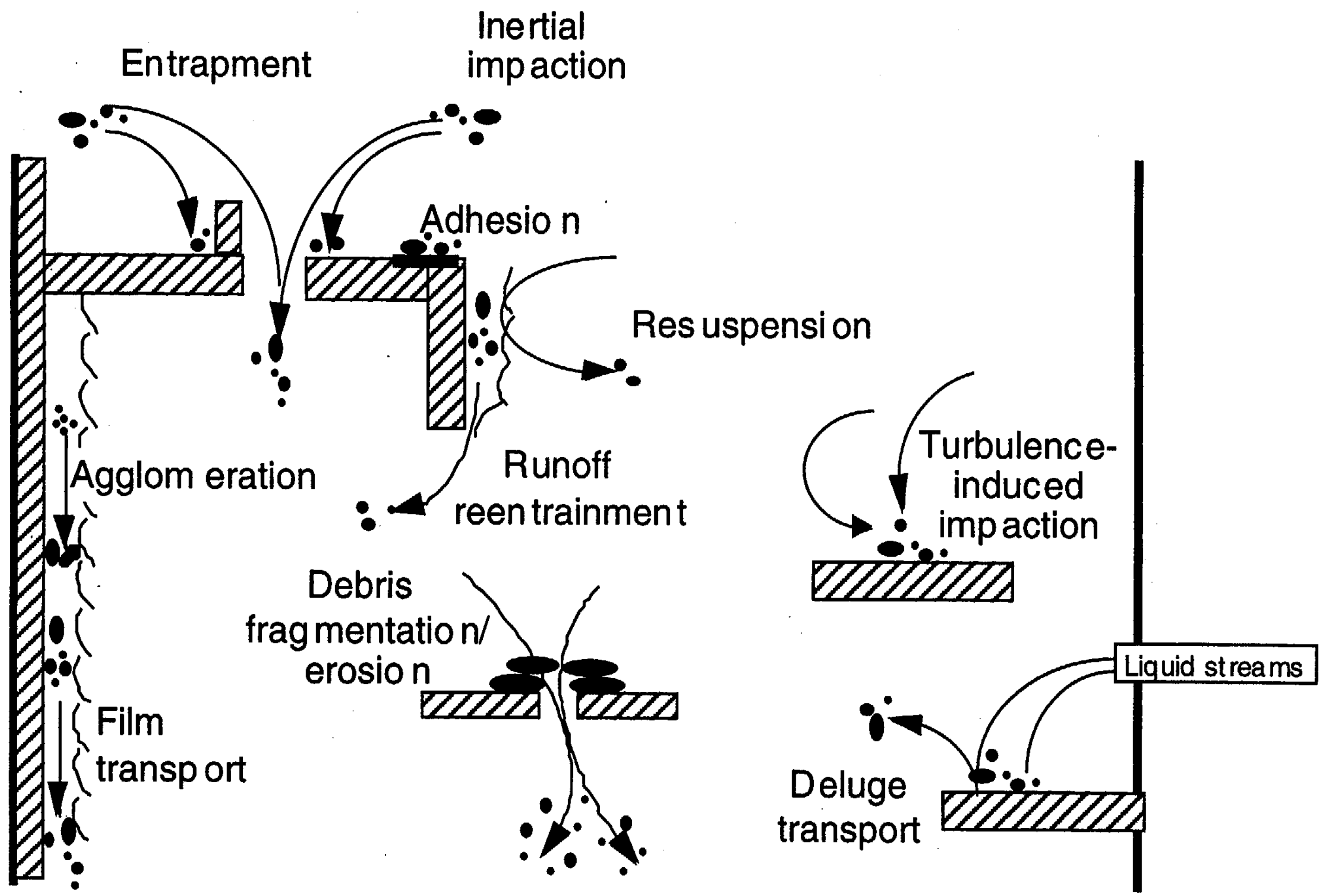

Fig. B-16. Transport/deposition processes for debris on containment structures during the sump-operation phase of a CL LBLOCA.

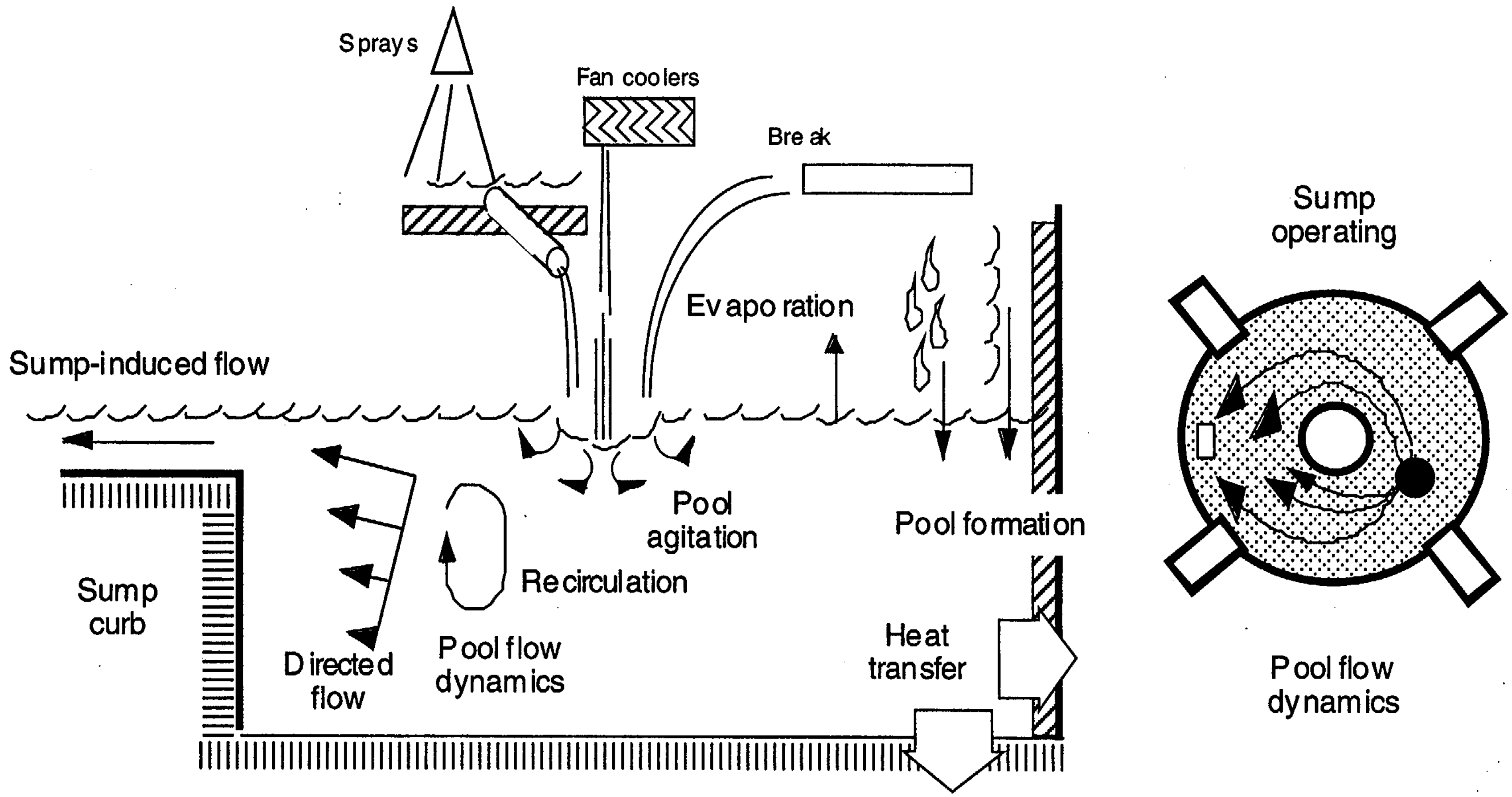

Fig. B-17. Thermal-hydraulic processes on the basemat floor during the sump-operation phase of a CL LBLOCA.

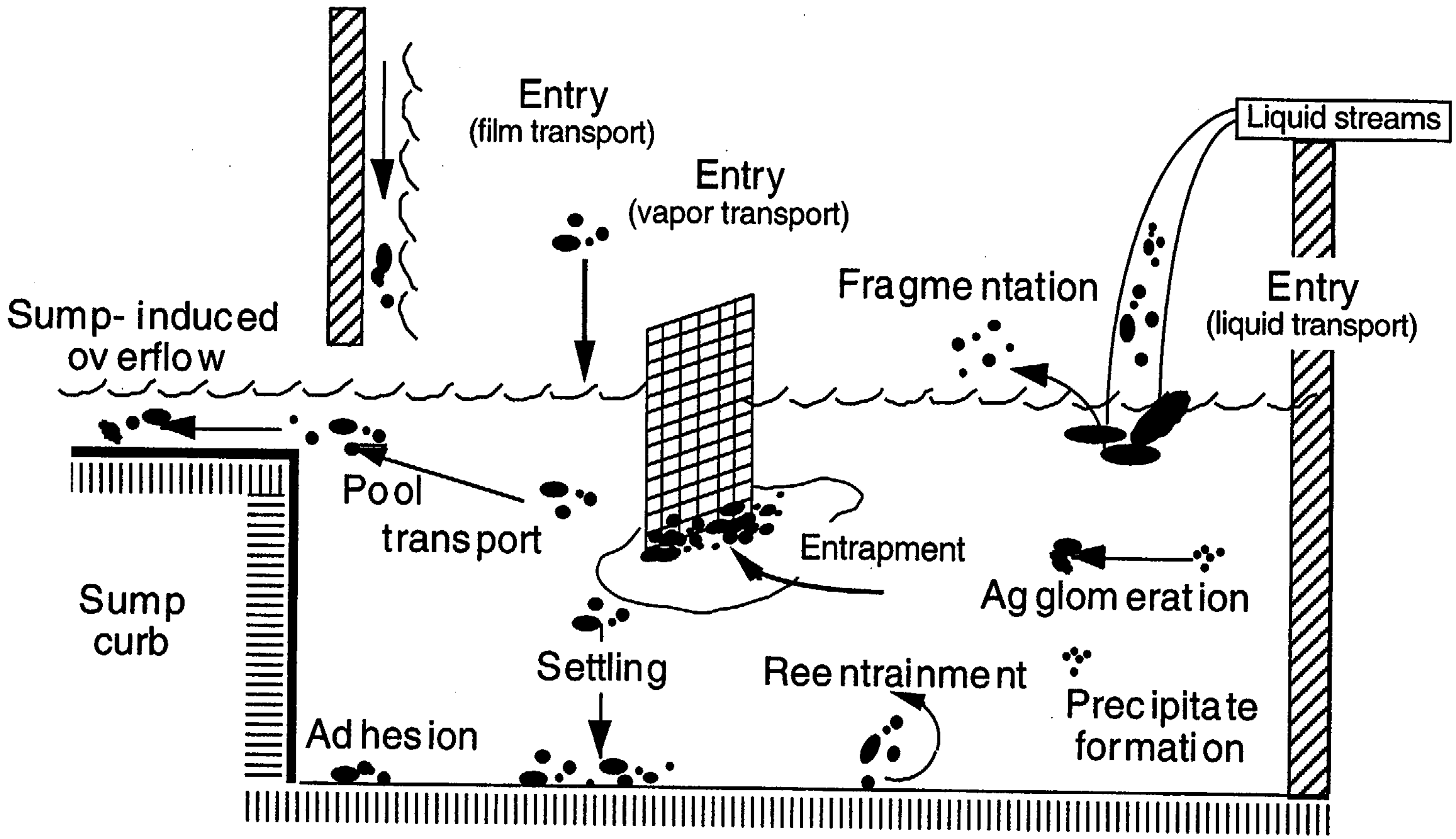

Fig. B-18. Transport/deposition processes for debris on the basemat floor during the sump-operation phase of a CL LBLOCA.

APPENDIX C

RANKING RATIONALES FOR PWR DEBRIS TRANSPORT PIRTS

This appendix provides the rationale for each of the importance ranks appearing in Tables 4-2 through 4-4. The rationale for each process or phenomenon arising during the blowdown phase of the accident scenario is presented in Table C-1. The rationale for each process or phenomenon arising during the post blowdown phase of the accident scenario is presented in Table C-2. The rationale for each process or phenomenon arising during the sump operation phase of the accident scenario is presented in Table C-3.

The reference numbers in the first column of each table are those presented in the corresponding PIRT tables, i.e., Table C-1 corresponds to Table 4-2 in Section 4, Table C-2 corresponds to Table 4-3, and Table C-3 corresponds to Table 4-4.

Reference is made to figures in the fourth column of each table. The figures are found in Appendix B.

Table C-1
Ranking Rationales for PWR Debris Transport during Blowdown Phase PIRT (page 1 of 3)
(Reference number relates to entry in Table 4-2 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-1	Pressure-driven flows (bulk flows)	Bulk flows produce circumstances in which debris depletion by trapping, impaction and adhesion can occur.	B-1
P1-2	Fan-driven flows	Created flow field is remote from the ZOI.	B-1
P1-3	Spray-induced flows	Sprays not activated until near the end of this phase.	B-1
P1-4	Circulating flows	Secondary flows have only a minor effect on debris movement and depletion.	B-1
P1-5	Steam/nonble mixing	Little or no impact on debris movement or depletion during this phase.	B-1
P1-6	Localized flow field	Secondary flows through and around structures have only a minor effect on debris movement and depletion.	B-1
P1-7	Turbulence	Turbulent flows through and around structures have only a minor effect on debris movement and depletion.	B-1
P1-8	Unflashed liquid flows	Amount of liquid available to affect debris movement and depletion during this phase is small.	B-1
P1-9	Flashing of break liquid effluent	Amount of liquid available to affect debris movement and depletion during this phase is small.	B-1
P1-10	Droplet interactions	Little or no impact on debris movement or depletion during this phase.	B-1
P1-11	Droplet formation via condensation	Little or no impact on debris movement or depletion during this phase.	B-1
P1-12	Condensation on structures	Little or no impact on debris movement or depletion during this phase.	B-1
P1-13	Film dynamics	Little or no impact on debris movement or depletion during this phase.	B-1
P1-14	Advection	Can lead to debris movement and/or depletion as debris is transported and distributed (see P1-1).	B-2
P1-15	Agglomeration	Little agglomeration during period of high velocities and agitation.	B-2
P1-16	Sweepout	Sprays not activated until near the end of this phase (see P1-3).	B-2

Table C-1 (cont)
Ranking Rationales for PWR Debris Transport during Blowdown Phase PIRT (page 2 of 3)
(Reference number relates to entry in Table 4-2 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-17	Gravitational settling	Primary depletion mechanism during this phase for large and heavy debris.	B-2
P1-18	Condensation on particles	Little or no impact on debris movement or depletion during this phase.	B-2
P1-19	Stephan flow (diffusiophoresis)	Little or no impact on debris movement or depletion during this phase.	B-2
P1-20	Thermophoresis	Little or no impact on debris movement or depletion during this phase.	B-2
P1-21	Heat transfer	Little or no impact on debris movement or depletion during this phase.	B-3
P1-22	Film shear	Little or no impact on debris movement or depletion during this phase.	B-3
P1-23	Surface wetting (condensation, impact)	Debris impacting surfaces will not adhere unless the surface is wet.	B-3
P1-24	Film draining under gravity	Little or no impact on debris movement or depletion during this phase.	B-3
P1-25	Deluge (streaming)	Little or no impact on debris movement or depletion during this phase.	B-3
P1-26	Resuspension	Little or no impact on debris movement or depletion during this phase.	B-4
P1-27	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-4
P1-28	Deluge (streaming) transport	Little deluge flow during blowdown phase (break flow only).	B-4
P1-29	Film transport	Little or no impact on debris movement or depletion during this phase.	B-4
P1-30	Runoff/reentrainment	Little or no impact on debris movement or depletion during this phase.	B-4
P1-31	Disintegration	Fiber: Small amount of additional fragmentation outside the ZOI during this phase. Cal-Sil: Small amount of additional fragmentation outside the ZOI during this phase.	B-2
P1-32	Entrapment	Moderate amount of material captured in dead-end areas or otherwise entrapped.	B-4
P1-33	Inertial Impaction	Fiber: Moderate amount of debris depletion occurs on wet surfaces. Other: Little or no impact on debris movement or depletion during this phase.	B-4

Table C-1 (cont)
Ranking Rationales for PWR Debris Transport during Blowdown Phase PIRT (page 3 of 3)
(Reference number relates to entry in Table 4-2 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-34	Turbulence-related impaction	Turbulent microscale effect is small for all debris types.	B-4
P1-35	Adhesion	Fiber: Moderate amount of debris depletion occurs on wet surfaces. Other: Little or no impact on debris movement or depletion during this phase.	B-4
P1-36	Pool formation	Little or no impact on debris movement or depletion during this phase.	B-5
P1-37	Heat transfer to structure	Little or no impact on debris movement or depletion during this phase.	B-5
P1-38	Surface wetting (before pool formation)	Little or no impact on debris movement or depletion during this phase.	B-5
P1-39	Streaming-induced pool dynamics	Little or no impact on debris movement or depletion during this phase.	B-5
P1-40	Sheeting flow dynamics	All but RMI: Little or no impact on debris movement or depletion during this phase. RMI: The potential exists during this phase for sweeping large pieces of RMI to locations where they might cluster to form potential flow blockages, e.g., grated doors preventing personnel access near and below the reactor vessel during reactor operation.	B-5
P1-41	Film transport	Little or no impact on debris movement or depletion during this phase.	B-6
P1-42	Resuspension	Little or no impact on debris movement or depletion during this phase.	B-6
P1-43	Sheet transport	All but RMI: Little or no impact on debris movement or depletion during this phase. RMI: The potential exists during this phase for sweeping large pieces of RMI to locations where they might cluster to form potential flow blockages, e.g., grated doors preventing personnel access near and below the reactor vessel during reactor operation (see P1-39).	B-6
P1-44	Agglomeration in pool	Little or no impact on debris movement or depletion during this phase.	B-6
P1-45	Adhesion	Little or no impact on debris movement or depletion during this phase.	B-6
P1-46	Settling	Little or no impact on debris movement or depletion during this phase.	B-6
P1-47	Impaction	Little or no impact on debris movement or depletion during this phase.	B-6
P1-48	Entrapment by porous structures	Moderate potential for large pieces of RMI to be entrapped at doorways (see P1-39).	B-6

Table C-2
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 1 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-1	Steam flow	Velocity decreasing; most of the debris subject to steam transport moved during the blowdown phase.	B-7
P2-2	Fan-induced flow	Flow velocities are low relative to those in the blowdown phase when most debris was airborne; most of the debris subject to advection was transported during the blowdown phase.	B-7
P2-3	Spray-driven flow	Flow velocities are low relative to those in the blowdown phase when most debris was airborne; most of the debris subject to advection was transported during the blowdown phase.	B-7
P2-4	Circulating flows	Flow velocities are low relative to those in the blowdown phase when most debris was airborne; most of the debris subject to advection was transported during the blowdown phase.	B-7
P2-5	Localized flow field	Flow velocities are low relative to those in the blowdown phase when most debris was airborne; most of the debris subject to advection was transported during the blowdown phase.	B-7
P2-6	Turbulence	Flow velocities are low relative to those in the blowdown phase when most debris was airborne; most of the debris subject to advection was transported during the blowdown phase.	B-7
P2-7	Plume	Not present in any significant degree with sprays and fan coolers operating.	None
P2-8	Thermal stratification	Not present in any significant degree with sprays and fan coolers operating.	None
P2-9	Unflashed liquid flow	Insignificant source of liquid for debris sweepout compared with sprays.	B-7
P2-10	Falling condensate	Insignificant source of liquid for debris sweepout compared with sprays.	B-7

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 2 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-11	Droplet motion	Thermal-hydraulic component of debris sweepout (see P2-15).	B-7
P2-12	Condensation on structures	Structures wetted during blowdown phase; little or no additional impact on debris movement or depletion during this phase.	B-7
P2-13	Advection	Containment atmosphere flows much smaller than during the blowdown phase. Most debris depletion and/or movement are via sweepout by the droplets injected by the containment spray system.	B-8
P2-14	Agglomeration	Little or no impact on debris movement or depletion during this phase. Sweepout is the dominant mechanism for removal of suspended debris from the containment atmosphere.	B-8
P2-15	Sweepout	Dominant mechanism for removal of suspended debris from the containment atmosphere.	B-8
P2-16	Gravitational settling	The containment configuration considered by the panel featured containment sprays in the dome but nowhere else. For this configuration, settling in spaces below lower flows was judged to be of moderate importance.	B-8
P2-17	Condensation on particles	Moderate impact on movement or depletion of fine debris during this phase. Sweepout is the dominant mechanism for removal of suspended debris from the containment atmosphere.	B-8
P2-18	Stephan flow (diffuseophoresis)	Little or no impact on debris movement or depletion during this phase.	B-8
P2-19	Thermophoresis	Little or no impact on debris movement or depletion during this phase.	B-8
P2-20	Heat transfer	Little or no impact on debris movement or depletion during this phase.	B-9
P2-21	Film shear	Little or no impact on debris movement or depletion during this phase.	B-9

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 3 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-22	Surface pooling	Fibrous: Little or no impact on debris movement or depletion or change in the character of the debris during this phase. Cal-Sil: Pieces will disintegrate in water pools and become more transportable. Other: Little or no impact on debris movement or depletion during this phase.	B-9
P2-23	Film draining under gravity	Little or no impact on debris movement or depletion during phase.	B-9
P2-24	Deluge (streaming)	Little or no impact on debris movement or depletion during this phase. Of secondary importance relative to the movement of debris from accumulation and draining of water flows from the containment sprays, which wash down a much larger fraction of the containment surfaces.	B-9
P2-25	Surface draining	Dominant mechanism for transporting fibrous and Cal-Sil debris to lower levels in the containment and ultimately to the containment floor.	B-9
P2-26	Condensation	Amount of liquid accumulating on surface through condensation is small relative to the amount of liquid deposited by the containment sprays.	B-9
P2-27	Resuspension into flow stream	Little or no impact on debris movement or depletion during this phase.	B-10
P2-28	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-10
P2-29	Deluge transport	Dominant mechanism for transporting fibrous and Cal-Sil debris to lower levels in the containment and ultimately to the containment floor.	B-10

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 4 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-30	Film-related transport	A moderate amount of debris may be on vertical surfaces and subject to transport.	B-10
P2-31	Runoff/reentrainment	Little or no impact on debris movement or depletion during this phase.	B-10
P2-32	Disintegration	Fibrous: Moderate fiber breakup has been observed in BWR testing when fiber is exposed to prolonged deluge by liquid streams. Cal-Sil: Water erodes and disintegrates Cal-Sil creating a mud-like substance that is subject to breakdown into fine particles and further transport. Other: Little additional fragmentation expected during this phase.	B-8
P2-33	Entrapment	Dominant mechanism for debris depletion as debris settles on horizontal surfaces in areas where either stagnant or low velocity liquid resides.	B-10
P2-34	Inertial impaction	Little or no impact on debris movement or depletion during this phase.	B-10
P2-35	Turbulence impaction	Little or no impact on debris movement or depletion during this phase.	B-10
P2-36	Adhesion	Adhesion to structures in the containment during the process of liquid transport to lower levels is a depletion mechanism of moderate importance.	B-10
P2-37	Pool formation	Liquid approaching the containment floor in discrete streams creates the pool and influences the distribution of debris in the pool.	B-11
P2-38	Evaporation	Little or no impact on debris movement or depletion during this phase.	B-11

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 5 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-39	Heat transfer to structure	Little or no impact on debris movement or depletion during this phase.	B-11
P2-40	Pool agitation	This is the major phenomenon for determining the location of debris at the time of sump activation.	B-11
P2-41	Pool flow dynamics	The importance of pool dynamics is the greatest when the pool depths are small and decreases as the pool depth increases.	B-11
P2-42	Entry via film transport	Dominant process for debris transport along vertical surfaces to the containment floor; debris-bearing liquid may move to the containment floor by alternatively moving along vertical and horizontal surfaces (see P2-44).	B-12
P2-43	Entry via vapor transport	The primary process for debris transport to the containment floor during this phase is via liquid streams and not through the containment atmosphere.	B-12
P2-44	Entry via liquid transport	Dominant process for debris transport along horizontal or slightly inclined surfaces to the containment floor; debris-bearing liquid may move to the containment floor by alternatively moving along vertical and horizontal surfaces (see P2-42).	B-12
P2-45	Reentrainment	May be some reentrainment when pool depth is small but little is expected when pool height is greater.	B-12
P2-46	Disintegration	Fibrous: Little or no change in the character of the fiber during this phase. Cal-Sil: Pieces will disintegrate in water pools and become more transportable. Other: Little or no impact on debris movement or depletion during this phase.	B-12

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (page 6 of 6)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-47	Pool transport	Liquid streams entering the pool distribute both debris in the stream and debris already in the pool near the entry point, thereby strongly influencing the debris distribution that will exist at the time of sump startup.	B-12
P2-48	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-12
P2-49	Adhesion	The horizontal flow velocity in the pool at the containment floor is small during this phase, particularly late in the phase when the pool height is large. Settling is the dominant depletion mechanism.	B-12
P2-50	Settling	Dominant mechanism for debris depletion during this phase.	B-12
P2-51	Entrapment by porous structures	Moderate potential for further entrapment of fibrous and particulate debris on the large pieces of RMI previously trapped at doorways during the blowdown phase (see P1-48).	B-12

Table C-3
Ranking Rationales for PWR Debris Transport during Sump Operation Phase PIRT (page 1 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-1	Steam flow	Processes in the containment open areas have little or no impact on debris movement or depletion during this last phase of the scenario. Essentially all transportable debris has moved during the blowdown and post blowdown phases.	B-13
P3-2	Fan-induced flow	Same as P3-1.	B-13
P3-3	Spray-induced flow	Same as P3-1.	B-13
P3-4	Circulating flows	Same as P3-1.	B-13
P3-5	Localized flow field	Same as P3-1.	B-13
P3-6	Turbulence	Same as P3-1.	B-13
P3-7	Plume	Same as P3-1.	None
P3-8	Thermal stratification	Same as P3-1.	None
P3-9	Unflashed liquid flow	Same as P3-1.	B-13
P3-10	Falling condensate	Same as P3-1.	B-13
P3-11	Droplet motion	Same as P3-1.	B-13
P3-12	Condensation on structures	Same as P3-1.	B-13
P3-13	Debris advection	Same as P3-1.	B-14
P3-14	Agglomeration	Same as P3-1.	B-14
P3-15	Sweepout	Same as P3-1.	B-14
P3-16	Gravitational settling	Same as P3-1.	B-14
P3-17	Condensation on particles	Same as P3-1.	B-14
P3-18	Stephan flow (diffuseophoresis)	Same as P3-1.	B-14
P3-19	Thermophoresis	Same as P3-1.	B-14

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump Operation Phase PIRT (page 2 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-20	Heat transfer	Processes related to the containment structures have little or no impact on debris movement or depletion during this last phase of the scenario. Essentially all transportable debris has moved to the containment floor during the previous phases.	B-15
P3-21	Film shear	Same as P3-20.	B-15
P3-22	Surface pooling	Same as P3-20.	B-15
P3-23	Film draining under gravity	Same as P3-20.	B-15
P3-24	ECCS deluge	Same as P3-20.	B-15
P3-25	Surface draining	Fibrous: Same as P3-20. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-20.	B-15
P3-26	Condensation	Same as P3-20.	B-15
P3-27	Resuspension into flow stream	Same as P3-20.	B-16
P3-28	Agglomeration	Same as P3-20.	B-16
P3-29	Deluge transport	Fibrous: Same as P3-20. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-20.	B-16
P3-30	Film-related transport	Fibrous: Same as P3-20. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-20.	B-16
P3-31	Runoff/reentrainment	Same as P3-20.	B-16

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump Operation Phase PIRT (page 3 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-32	Fragmentation	Fibrous: Same as P3-20. Cal-Sil: Erosion and dissolving processes continues as long as the containment sprays operate (taken as two hours from scenario initiation). Other: Same as P3-20.	B-14
P3-33	Entrapment	Some plants have grated doors (chainlink) on the steam-generator compartments. There may be other entrapment sites. See related comments for P1-40, P1-43, P1-48, and P2-33.	B-16
P3-34	Inertial impaction	Same as P3-20.	B-16
P3-35	Turbulence impaction	Same as P3-20.	B-16
P3-36	Adhesion	Same as P3-20.	B-16
P3-37	Pool formation	The pool inflows and outflows (sump flow) are balanced and there is no further increase in pool height.	B-17
P3-38	Evaporation	This process has little or no impact on debris movement or depletion during this last phase of the scenario.	B-17
P3-39	Heat transfer to structure	Fibrous: Same as P3-38.	B-17
P3-40	Pool agitation	Some debris will remain suspended by the agitation of streams entering the pool from above.	B-17
P3-41	Pool flow dynamics	Debris transport could be influenced by pool dynamics.	B-17
P3-42	Sump-induced flow	Dominant mechanism for debris transport to the sump.	B-17
P3-43	Entry via film transport	Fibrous: Same as P3-38. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-38.	B-18
P3-44	Entry via vapor transport	Fibrous: Same as P3-38.	B-18

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump Operation Phase PIRT (page 4 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-45	Entry via liquid transport	Fibrous: Same as P3-38. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-38.	B-18
P3-46	Reentrainment	Once the sump pumps begin to operate, debris residing within some region of influence near the pump will be lifted from the containment floor to a position higher in the pool where it will be more susceptible to transport to the sump.	B-18
P3-47	Debris fragmentation	Fibrous: Same as P3-38. Cal-Sil: Process of moderate importance as long as erosion and dissolving processes of Cal-Sil continue (see P3-32). Other: Same as P3-38.	B-18
P3-48	Pool transport	Dominant mechanism for debris transport to the sump.	B-18
P3-49	Agglomeration	Fibrous: Smaller fibers will overtake and collect with larger fibers. Cal-Sil: Same as P3-38. Other: Same as P3-38.	B-18
P3-50	Adhesion	Same as P3-38.	B-18
P3-51	Settling	Will continue over an extended period of time to deplete debris as it moves into areas in which the velocity decreases below the threshold for transport.	B-18
P3-52	Precipitate formation	The amount of precipitate formed during the interval defined by this phase is small. However, over a much longer period of time, precipitate formation could form more transportable debris that could subsequently combine with fibrous, Cal-Sil, RMI, or coatings debris.	B-18

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump Operation Phase PIRT (page 5 of 5)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-53	Sump-induced overflow	The process by which debris is carried over a curb and to the sump screen or trashrack.	B-18
P3-54	Entrapment	Debris that is moving to the sump but enters a region of lower flow velocity, e.g., as the flow moves from a constricted to an open area, will settle to the floor and no longer move to the sump.	None