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PWR DEBRIS TRANSPORT IN ICE CONDENSER CONTAINMENTS—PHENOMENA IDENTIFICATION AND RANKING TABLES (PIRTs)

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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 upon 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 actions 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 directly related 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 focuses on a specific containment design and accident scenario. Once the initial PIRT is completed, other containment designs and plant types can be considered, building upon the base of the original PIRT. PIRTs have previously been prepared for large dry containments and the results have been reported in a companion document (See Section 2 Ref. 2-2). For this PIRT, the panel identified the base configuration as a Westinghouse four-loop PWR with ice condenser

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 five components: (1) the containment upper compartment open area, (2) the containment lower compartment open area, excluding the potential pool in the bottom of the containment and the debris-generating zone-of-influence in the vicinity of the break; (3) the containment lower compartment structures; and (4) the containment floor upon which a liquid pool forms in the lower containment elevations, and (5) the ice condenser.

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, ten high-ranked processes/phenomena were identified. Pressure driven (bulk) flows in the containment lower compartment open areas move debris (advection) to the ice condenser. The dynamics of the pool developing on the containment floor, including agitation, serves to keep debris suspended and in movement. They also promote the disintegration of any calcium silicate insulation in the pool. Debris enters the pool by transport within liquid streams, primarily the flows associated with the melting ice. Steam and non-condensable flow pass into the ice condenser where essentially all the steam is condensed so that only noncondensables pass into the upper compartment. The steam melts ice. The resultant water flows backward into the containment lower compartment carrying debris that had passed into the ice condenser.

During the nearly 30-min post blowdown phase, five high-ranked processes/phenomena were identified. The large-scale flows associated with pool dyamics and agitation of the pool on the containment floor keep the smaller debris suspended in the pool. Calcium silicate fragments, erodes and disintegrates in the agitated pool. Both fiber and calcium silicate are subject to transport within the pool prior to sump activation. Heavier debris settles to the floor of the pool.

During the period of sump operation beginning at 30 min and continuing to 48 h, seven high-ranked processes/phenomena were identified, all of which occur in the pool on the containment floor. Pool thermal-hydraulic processes of importance were pool agitation by liquid streams still entering the pool from above and the associated pool dynamics leading to re-entrainment of debris that had settled 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 22 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 programs.

Blowdown Phase (0–40 s)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT LOWER COMPARTMENT OPEN AREAS	Thermal-hydraulic related	**Pressure driven flows (bulk flows)**	H
	Debris related	Advection	M
		Entrapment (space below ice condenser)	M
		Gravitational settling	M
CONTAINMENT STRUCTURES IN LOWER COMPARTMENT	Thermal-hydraulic related	Surface wetting (condensation, impact)	M
		Deluge (streaming)	M
	Debris related	Deluge (streaming) transport	M
		Inertial impaction	M/L/L/L
		Adhesion	M/L/L/L
CONTAINMENT FLOOR	Thermal-hydraulic related	**Pool agitation**	H
		Pool dynamics	H
	Debris related	**Entry via liquid transport**	H/H/H/L
		Reentrainment	M/M/M/L
		Disintegration	M/H/L/L
		Pool transport	M/M/M/L
		Entrapment	M
ICE CONDENSER	Thermal-hydraulic related	**Steam and noncondensable flow**	H
		Ice to liquid (melting)	H
		Liquid draindown	M
		Condensation	H
	Debris related	**Debris advection**	H/H/L/L
		Debris suspension	M/M/L/L
		Debris draining (downward)	H/H/L/L

① Multiple rankings appear, e.g., L/M/L/H (fibrous/calcium silicate/reflective metallic insulation/other) where the panel found it necessary to differentiate between debris types; H, M, L are High, Medium, and Low importance.

Post-Blowdown Phase (40 s–30 min)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT LOWER COMPARTMENT OPEN AREAS	Thermal-hydraulic related	None ranked H or M	
	Debris related	None ranked H or M	
CONTAINMENT STRUCTURES IN LOWER COMPARTMENT	Thermal-hydraulic related	Deluge (streaming)	L/M/L/L
	Debris related	Deluge transport	L/M/L/L
		Disintegration	L/M/L/L
CONTAINMENT FLOOR	Thermal-hydraulic related	Pool formation	M
		Pool agitation	**H**
		Pool flow dynamics	M/H/M/L
	Debris related	**Disintegration**	**L/H/L/L**
		Pool transport	**H/H/L/L**
		Settling	**H/H/L/L**
		Entrapment	M
ICE CONDENSER	Thermal-hydraulic related	Ice to liquid (melting)	M
		Condensation	M
	Debris related	None ranked H or M	

Post-Blowdown Phase (40 s–30 min)			
Component	Phenomenon type	Phenomenon	Rank ①
CONTAINMENT LOWER COMPARTMENT OPEN AREAS	Thermal-hydraulic related	None ranked H or M	
	Debris related	None ranked H or M	
CONTAINMENT STRUCTURES IN LOWER COMPARTMENT	Thermal-hydraulic related	None ranked H or M	
	Debris related	None ranked H or M	
CONTAINMENT FLOOR	Thermal-hydraulic related	**Pool agitation**	**H**
		Pool flow dynamics	**H**
	Debris related	**Sump induced flow**	**H**
		Reentrainment	**H**
		Disintegration	L/M/L/L
		Pool transport	**H/H/H/H**
		Sump induced overflow	**H**
		Adhesion	M
ICE CONDENSER	Thermal-hydraulic related	None ranked H or M	
	Debris related	None ranked H or M	

①: Multiple rankings appear, e.g., L/M/L/H (fibrous/calcium silicate/reflective metallic insulation/other) where the panel found it necessary to differentiate between debris types; H, M, L are High, Medium, and Low importance.

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:

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- 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 was the chairman of the counterpart boiling water reactor debris transport PIRT panel. Much of the structure and tables of the current document is 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. They are 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
NRC	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

CONTENTS

FIGURES

FIGURES (cont)

TABLES

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PRESSURIZED-WATER-REACTOR DEBRIS TRANSPORT IN ICE CONDENSER CONTAINMENTS—PHENOMENA IDENTIFICATION AND RANKING TABLES (PIRTS)

by

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

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 an ice condenser 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 modeled explicitly and accurately in code development and assessment efforts. The phenomena should be considered explicitly 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 program. 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, pressure-driven flows, steam and noncondensable flow, ice melting, condensation, debris advection, and debris draining phenomena were judged by the PIRT panel to be of high importance. During the post-blowdown phase, pool agitation, fragmentation/erosion/disintegration, pool transport, and settling phenomena were judged to be of high importance. During the sump operation phase, reentrainment, pool transport, sump-induced overflow, and precipitate formation phenomena were judged to be of high importance.

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1. INTRODUCTION

The United States 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 initial effort of the panel focused on large dry containments.[1-1] The remainder of this report collects and documents the findings of the PWR debris transport PIRT panel for ice condenser containments.

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,[1-2] "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[1-3] and Regulatory Guide 1.82, Rev. 1.[1-4]

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 collection on, sump debris screens reduces the 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.[1-5] 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[1-6] and Regulatory Guide 1.82, Rev. 2.[1-7] 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 action 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 Andrechek, Westinghouse Electric Corporation (W);
- Dr. Brent E. Boyack, Los Alamos National Laboratory (LANL), 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[1-8, 1-9, 1-10] to its description as a generalized process.[1-11] 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 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 of 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, i.e., those that drive events. Plausible physical phenomena, 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 often can 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 then are ranked with respect to their influence on the primary evaluation criteria to establish PIRTs. Primary evaluation criteria (or criterion) normally are based on regulatory safety requirements such as those related to restrictions in fuel rods (peak clad temperature, hydrogen generation, etc.) and/or 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

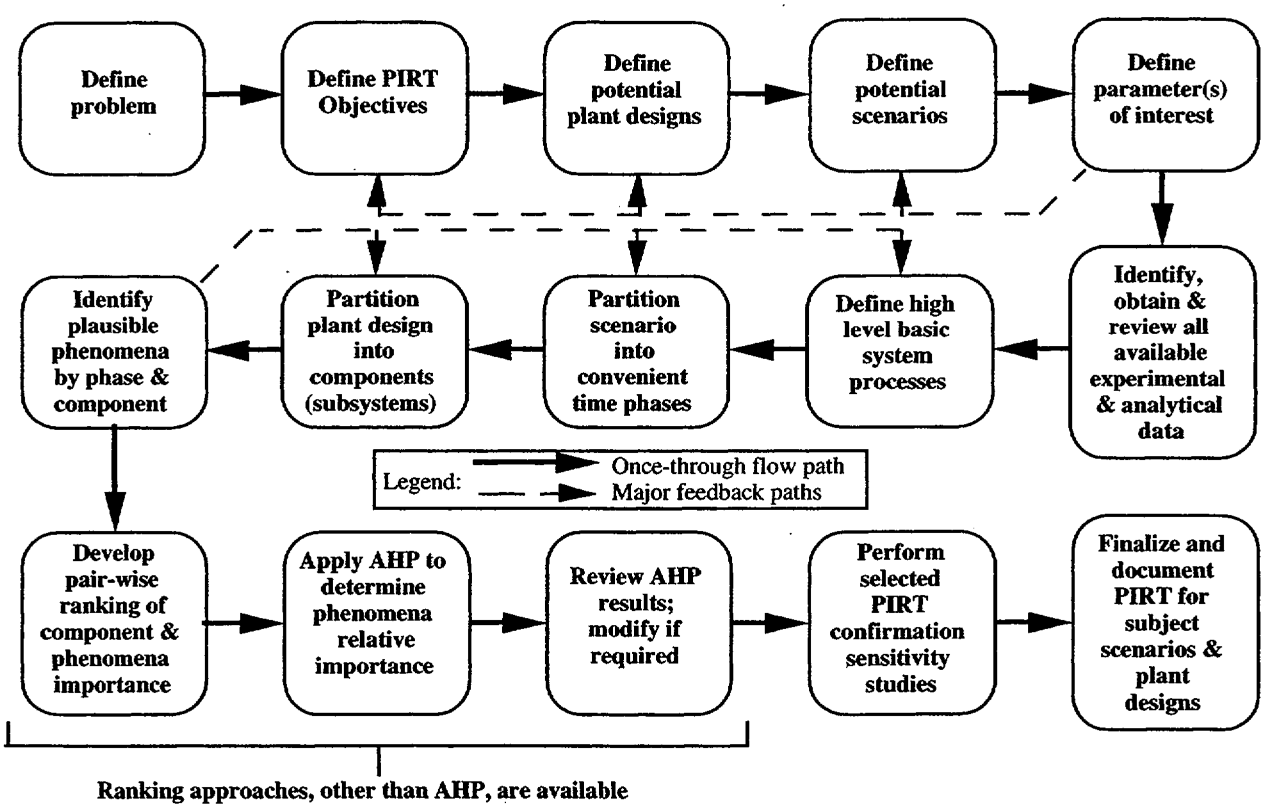

Fig. 1-1. Illustration of typical PIRT process.

investigated separately. 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 [AHP]), and selected calculations. The final product of applying 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 to help guide future NRC-sponsored analytical, experimental, and modeling efforts conducted as part of the GSI-191 study.

1.5. References

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1-10. 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).

1-11. 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. The plant and containment designs selected for the PWR debris transport PIRT effort are discussed in Section 2.1. A description of an ice condenser containment and its performance following a LOCA is described in Section 2.2. The accident scenario selected for the PWR debris transport PIRT is discussed in Section 2.3. 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 2.4. 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 2.5. 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 2.8. Finally, the ranking scale used by the PIRT panel must be explicitly defined, as done in Section 2.9.

2.1. Selected Plant and Containment

There are many 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. This effort has been completed, and a report has been prepared.[2-2] The applicability of the PIRT prepared for a W four-loop plant with dry ambient containment to other plants with large dry and subatmospheric containments was evaluated and reported by the panel.[2-2] The remaining containments to be considered were of the ice condenser variety. All such containments in the US are associated with W plants. The panel did not focus on a specific W four-loop plant.* The design considered in the PIRT effort included ice condenser containment, nonsafety-grade fan coolers, and containment sprays.

2.2. Ice Condenser Containment Description

The following information is from Refs. 2-3 and 2-4. The ice condenser containment is characterized by both components and performance that significantly impact debris transport following a large cold-leg (CL)-break LOCA. The containment building for a reactor equipped with a W ice-condenser containment system is composed of three compartments (see Fig. 2-1). The lower or upstream compartment contains the reactor and its coolant system; this portion of the containment has a volume of ~7800 m^3. The upper-containment volume acts as a receiver to contain the noncondensable gas (air) forced out of the lower compartment by steam in the event of a break in the reactor containment system; this portion of the containment has a volume of ~18,500 m^3. The upper and lower compartments are separated by an operating deck that ensures a low-leakage barrier between them. Enclosures above the operating deck over the steam generators and pressurizer complete the barrier. The only path for leakage between the upper and lower compartments is 0.2 m^2 of known deck leakage. This path is used to return spray water from the upper to the lower compartment. With this configuration, essentially all energy released in a LOCA would be directed into the ice condenser, which serves as the third, or transfer, compartment. This compartment is arranged similar to a heat exchanger to condense the steam and conduct the air and other noncondensables from the lower containment volume into the upper volume during such an accident.

*In most respects, the selected plant is representative of all ice condenser plants. However, the selected plant does have lower-compartment sprays, and these are not typical of most ice condenser plants. Therefore, the phenomena and importance ranks reported in Section 4 for sprays in the lower compartment are not generally applicable.

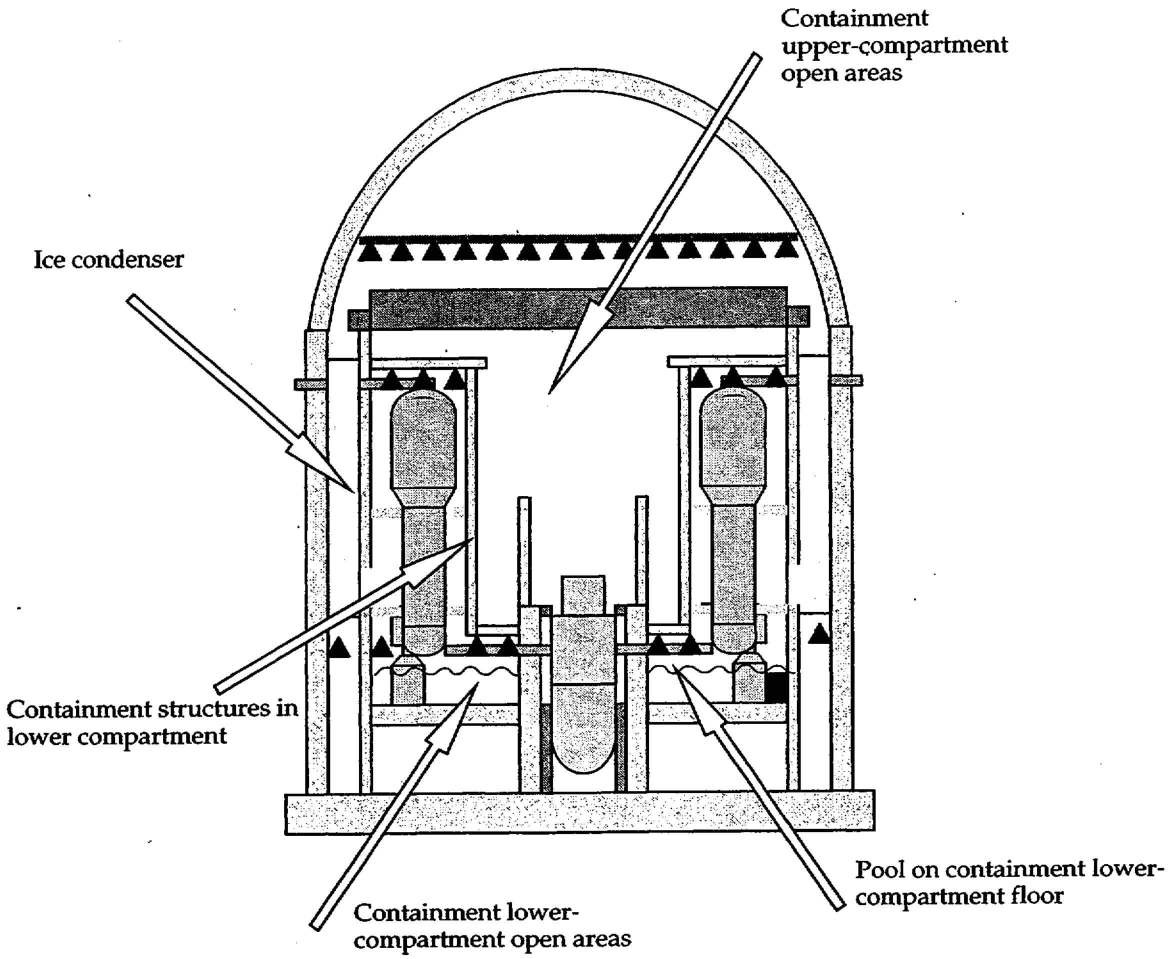

Fig. 2-1. Component partitioning of PWR ice condenser containment.

The ice condenser extends as a partial annulus around ~300° of the periphery of the reactor containment building. In a typical installation, the overall cavity is 24 m high and 4 m wide. The ice, in granulated form <0.3 cm thick, is contained in perforated-metal baskets, each 30.5 cm in diameter. The ice bed is ~14.5 m high and holds more than 1.1 million kg of borated ice. The baskets are stacked in columns to provide suitable flow channels through and between them for passage of steam and air. A structural framework supports the baskets. The ice condenser consists of 24 identical modules or bays, each of which holds 81 basket columns in an array of 9 radial and 9 circumferential rows. The bottom rows of supporting frames and platform sections form a lower void space into which the 24 4.9-m^2 inlet doors can open through ports in the crane wall.

If a reactor coolant pipe breaks in the upstream compartment, energy is released into the lower (upstream) containment atmosphere in the form of steam and water. The resulting pressure increase acts as a driving force to open the inlet doors for flow into the ice condenser. Air in the lower compartment at the time of the accident is forced through the ice condenser and into the upper compartment. Steam from the break follows. Because of the efficiency of the ice in condensing steam, essentially no steam flows out of the ice-condenser compartment. Therefore, the major factor that determines the upper containment maximum pressure is the compression effect resulting from the displacement of air into the upper (downstream) compartment. The containment pressure is reduced in a matter of minutes to a low value after blowdown is complete because the ice condenser rapidly condenses the remaining steam in the lower compartment.

Long-term decay heat removal is provided by spray systems. Because a large amount of ice would remain following the initial reactor coolant blowdown, the spray system is designed to condense steam at a rate equivalent to reactor core residual heat removal at a time when essentially all of the ice is melted. This occurs at ~2 h.

2.3. 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, 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 when 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. These sequences were not selected by the PIRT panel 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 with ice condenser containment is found in Fig. 2-2.

2.4. Scenario Phases

The CL LBLOCA identified in Section 2.3 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.

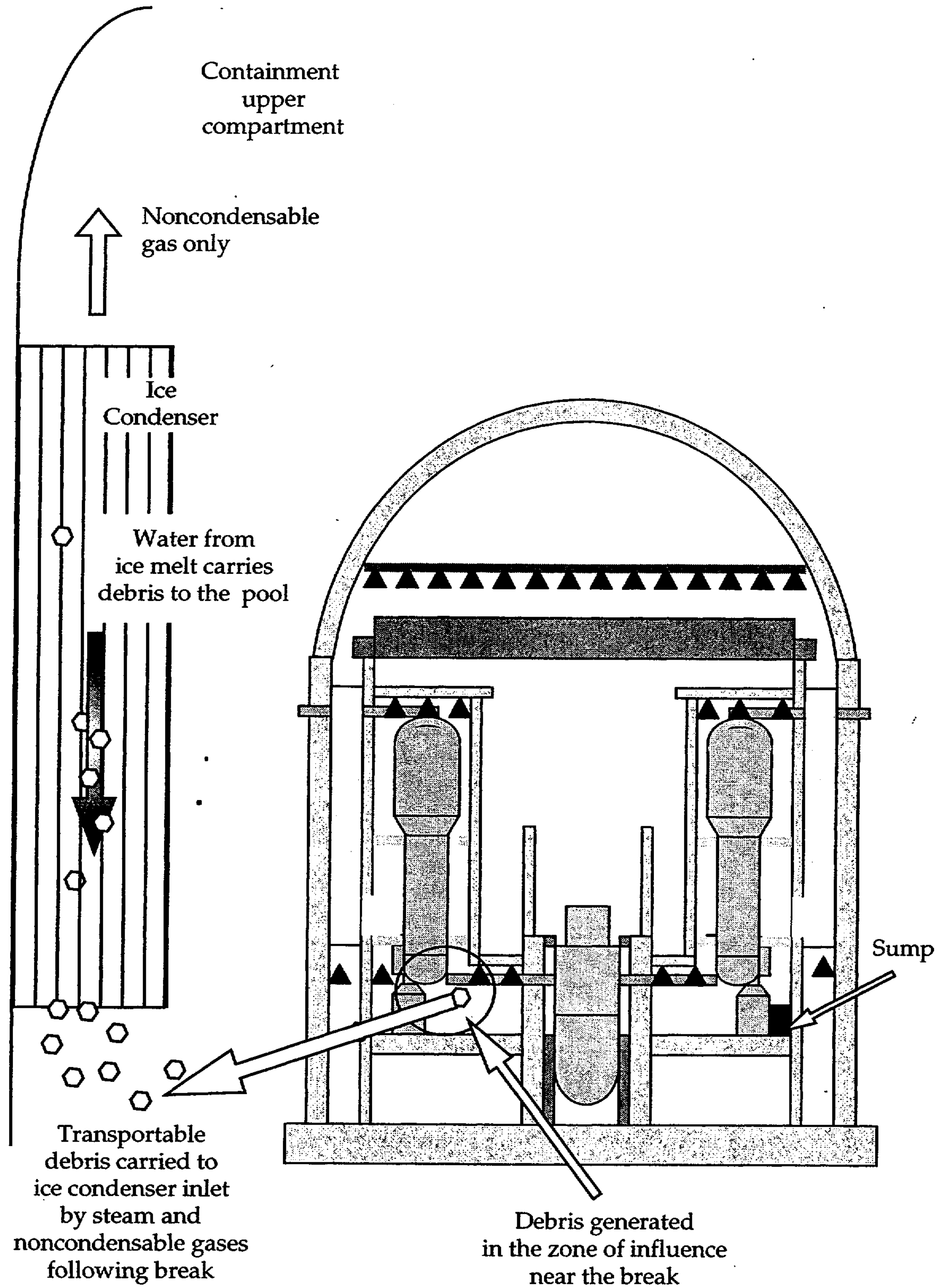

Fig. 2-2. Break location in a W four-loop plant with ice condenser containment.

Table 2-1
Description of Scenario Phases

Phase	Time Interval (s)	Description
1 Blowdown	0–40	• Coolant is exhausted as a two-phase mixture from the Nuclear Steam Supply System (NSSS) into the containment lower compartment until the end of this phase. • In-containment structural elements and NSSS components are wetted by the break coolant. • Debris is generated by the exhaust of two-phase coolant through the break into the lower-compartment open areas. Debris generation ends after ~10 s. Generated debris includes insulation on affected NSSS components and piping, containment and structural coatings, and particulate debris. • The two-phase break flow pushes air through the ice condenser followed by steam; essentially all steam is condensed in the ice condenser, and only noncondensable gases and water exhaust into the upper compartment. After the initial air flow, the velocity of gas exiting the ice condenser into the upper compartment is low. • An initial pressure peak in subcompartments of the lower compartment occurs early; it is terminated within ~3 s as steam condenses in the ice condenser. The upper-compartment pressure raises less rapidly; it closely tracks the lower-compartment pressure by 10 s. • Transportable debris is carried to and through the ice condenser doors; smaller debris is swept into the ice condenser. Heavier debris, e.g., RMI, falls to the floor after its initial transport. • Water from the melting ice and condensed steam drain downward into the lower compartment, returning debris within the ice condenser to the lower compartment. • Liquid begins to accumulate on the lower compartment floor. The pool forms rapidly as water from the ice condenser comes into the lower compartment.
2 Post Blowdown	40–1800	• For a CL break, water is exhausted out the vessel-side of the break and steam is exhausted out of the steam generator side of the break. For an HL break, water is exhausted out the vessel side of the break. Energetics associated with this phase are small compared with the blowdown phase. • Agitation in the lower compartment is driven by injection flow spilling from the break and is at much lower levels than during the blowdown phase. • Steam from the break enters the ice condenser and condenses, melting more ice and returning more water to the lower compartment. An ice bed exists throughout the entire phase. • Containment recirculation fans begin to operate, establishing air flow from the containment upper compartment to the lower compartment and through the ice condenser back into the containment upper compartment. • Safety injection and containment sprays are initiated from the refueling water storage tank (RWST).

Table 2-1 (cont)
Description of Scenario Phases

Phase	Time Interval (s)	Description
2 (cont) Post Blowdown	40–1800	• The upper-compartment sprays collect and drain through limited drain pathways into the lower compartment. The lower-compartment sprays (specific feature of the D. C. Cook plant only) 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 water flow from the ice condenser, break flow, and spray water draining from the upper compartment. Pool energetics are strongest where the water enters the pool and diminish with distance and depth. • RWST level decreases, switchover from RWST injection to sump recirculation occurs at ~1800 s. Both containment spray and core coolant are drawn from the sump.
3 Sump Operation	1800 s–48 h	• Operation of containment spray and ECCS in the recirculation mode drawing suction from the containment sump begins. • The remaining ice in the ice condenser is melted ~2 h after LOCA initiation. • Containment pressure and temperature continue to decrease unit ice bed melt-out (occurs at ~2 h). Containment pressure increases immediately following ice bed melt-out, then again decreases as decay heat continues to decrease. • Pool flow fields are established with pool dynamics dominated by the directed flows to the sump(s). • The pool maximum height is reached. • Recirculation to the core via the sump continues. • Containment sprays continue until termination criteria are reached (>1,000,0000 s for D. C. Cook). • RHR spray is initiated and continues until termination criteria are reached (>1,000,0000 s for D. C. Cook). • Directed flows in the pool to the sump decrease in proportion to the decreased demands for sump flow with termination of the containment and RHR sprays. • The containment recirculation fans continue to operate. • For a CL break, steam and water continue to exit from opposite ends of the break. For an HL break, liquid continues to exit from the vessel side of the break. • Washdown and transport of debris to the pool from the upper compartment continue as long as containment and RHR spray are provided.

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

2.5. Containment Partitions (Components)

The PWR Debris Transport PIRT panel benefited from previous work[2-5] that provided insights regarding a consistent framework for partitioning the containment into the components pictorially illustrated in Fig. 2-1 and described below.

- Containment upper-compartment, open area: the free-flow area in the upper (downstream) compartment as described in Section 2.2.
- Containment lower-compartment, open area: the free-flow area in the lower (upstream) compartment as described in Section 2.2, excluding the potential pooling of the bottom of the lower compartment and the debris-generating zone of influence (ZOI) in the vicinity of the break.
- Containment lower-compartment structures: all solid boundaries and barriers to the flow stream, including NSSS components, containment walls, pipes, cabinets, walls, grates, beams, component supports, and cable trays.
- Containment floor: the area where a liquid pool will form in the lower-containment elevations.
- Ice condenser: the ice-condenser structures from the inlet doors to the exit of the ice condenser in the containment upper-compartment open area.

Boundary Conditions

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

The first of these is 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., (1) insulation on pipes and NSSS components and (2) the containment and component coatings. The ZOI concept was documented during the BWR debris transport study.[2-6] The phenomena and processes occurring in this volume are the subject of a separate but related PWR Debris Sources PIRT.[2-7] The panel considered 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 considered all processes and phenomena in the containment floor area that could transport liquid and debris to the sump screens. These 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.

2.6. System-Level Processes

During the preparation of an earlier BWR debris transport PIRT,[2-5] 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, also have been used for the current PWR debris transport PIRT effort.

1. Gas/vapor transport—flow of noncondensables and steam through free-stream paths and around structures.
2. Suspended water transport—flow of liquid through free-stream paths and around structures.
3. Water depletion/accumulation/surface transport—capture, storage, and flow of liquid on the surface of containment internal structures.
4. Debris transport—flow of debris through free-stream paths and around structures, including transport via gas/vapor, liquid films, and pool surfaces and within pools.
5. 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. B-1 through B-18 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.

2.7. 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 2.3. Five sources of debris were considered by the panel: (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 provided only 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. 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 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 normally is 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.

2.8. 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 on a single parameter, *the fraction of debris mass generated during the initial blowdown period within the ZOI that is transported to the sump entrance.*

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

2.9. 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 also should be considered in any experimental programs.

- Low = The phenomena or process has little 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.

2.10. References

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

2-2. B. E. Boyack, T. Andreychek, P. Griffith, F. E. Haskin, and J. Tills, "PWR Debris Transport in Dry Ambient Containments–Phenomena Identification and Ranking Tables (PIRTs)," Los Alamos National Laboratory document LA-UR-99-3371, Rev. 1 (July 1999).

2-3. S. J. Weems, W. G. Lyman, and P. B. Haga, "The Ice-Condenser Reactor Containment System," *Nuclear Safety* **11**, No. 3, 215–222 9 (May–June 1970).

2-4. N. J. Liparulo, C. G. Tinkler, and J. A. George, "The Ice-Condenser System for Containment Pressure Suppression," *Nuclear Safety* **17**, No. 6, 710–721 (November–December 1976).

2-5. 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).

2-6. 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) (Sec. 3.4).

2-7. 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).

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 large quantity 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 included 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 fiber-glass 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 1000 kg/m^3 (soaked through). The more superheat there is in the steam, the more insulation that is transported because the insulation that is generated is not as wet.

3-2. "NUKON Blowdown Tests," 35947-2F, Owens/Corning Fiberglass (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 three to five 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 Heissdampfreaktor

(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 source 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 a 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 p. 13 of the source report in which the size distribution of the generated debris was characterized. Between 15% and 20% of the initial material was lost.

3-4. D. Brocard, "Buoyancy, Transport, and Head Loss of Fibrous Reactor Insulation," NUREG/CR-2982 (SAND82-7205), U.S. Nuclear Regulatory Commission (Sandia National Laboratories), Washington, DC (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 the screen. The one RMI sample (20 x 20 x 8 cm^3 with six 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 10x 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 NUREG/CR-3616 (ARL-124-83/M398F) (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 and 0.15 m/s (2.4 and 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, of 6.1 to 15.2 cm/s (0.2 to 0.5 ft/s). Thicker foils (0.008 in.) transported at higher velocities, of 12.2 to 23.4 cm/s (0.4 to 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 NUREG/CR-3170 (SAND83-7008)(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 and 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," RVE 92-202, ABB Atom (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 (Fig. 7 in the source 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 entry.

3-8. M. Gustafsson, "Block I—Transport of Insulation in the Reactor Containment—Test Results," 92-07528, OKG (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. A total of 200 kg of insulation material was placed on a drywell floor, and the sprays started. At the end of the test, 189 kg remained in the drywell, and 11 kg was 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," NT34/95/e32, Siemens AG—Power Generation Group (July 1995).

The test objective was to measure the amount and size distribution of insulation debris generated during a simulated double-ended guillotine break from RMI with a 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 between 175 and 200 kg/s. Initial weight of panels 2A and 2B was 16.50 kg. The weight of the "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 document STUK-YTO-TR 73 (July 1994).

This report documents experiments investigating the transport and clogging properties of MRI 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). Settling velocities were between 0.04 and 0.08 m/s (1.6 and 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 began at ~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 source report Table 1, p. 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 indicated 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, ~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 increased the settling time only 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.), Nunn, Colorado (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 conclusions were reached: (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 <0.10 in. to >1.0 in.

Six air-impact tests on NUKON insulation also were conducted. Results were compared with the NUREG/CR-0897-described destruction zone formed by a 90° cone extending seven nozzle diameters from the exhaust nozzle. Less than 30% (by weight) of NUKON base wool in the seven-nozzle-diameter zone was fragmented into small, easily transported pieces. The pipe on 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 source 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.), Nunn, Colorado (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 was 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 <0.10 in. to >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.), Nunn, Colorado (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. outer-diameter pipe. The insulation is fabricated in two halves, and a pair of latches hold 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 were 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 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 source report, Fig. 4, p. 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 was observed and recorded. The flow was further increased in increments of 0.008 m/s (0.9 in./s) until all of the material had been transported. One case of interest was for an isolated 3.5-in.-square x 0.125-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 document (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 losses determined from the debris contents of slurries were as much as five times the wear losses 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," M-93/60, Studsvik Material (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 source report, Fig. 1, p. 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 the nozzle to the 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 p. 6). The side impact was perpendicular to the axis of the insulation, whereas front impact was parallel to it.

3-22. D. Williams, "Measurements on the Sink Rate and Submersion Time for Fibrous Insulation," Illinois Institute of Technology (sponsored by Transco Products, Inc.) document ITR-93-02N (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 the 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 absorbed into the material. 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 on 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," ABB Atom AB document CRC/KC/LR-93/3238 (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. J. H. Mueller, "Containment Sump Zone of Influence for Coatings," Zion Nuclear Station document 22S-B-040M-002, Rev. 2 (Attachment A) (January 1997), letter 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 for a total system flow rate of 9000 gpm. 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 ≤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 Carbozinc 11 having a specific gravity of 5.6 and thickness of 3.0 mil 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), New York, New York (October 1984).

Comanche Peak is a Westinghouse four-loop plant with a large dry containment. There are some helpful figures (see source 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. If the reactor coolant, RWST, accumulators, and miscellaneous water inventories are considered, the maximum water level is 817.5 ft and the minimum water level is 814.8 ft.

The containment spray system is shown in source report Fig. 5.3-1. There are four spray zones, and 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 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 of 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 0.125 in. 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 probably will 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.

The 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 the tank). Tables of corrosion mass with time are presented for aluminum and zinc. Corrosion products for aluminum and zinc 1 day after event initiation are estimated to be 262.6. lb for the former and 761.9 lb for the latter (see source report Tables 4 and 5 for time-dependent corrosion estimates). It is estimated that 90% to 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. (prepared for GE Nuclear Energy) document CDI Report No. 96-01 (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," U.S. Nuclear Regulatory Commission (Sandia National Laboratories) document NUREG/CR-2913 (SAND82-1935) (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 of pressure and 70°C subcooled liquid to 0.75 or greater quality. The model displays in a series of tables and charts within the source report, target load, and pressure distributions as a function of vessel (or break) conditions. The high-pressure and high-temperature fluid that exits 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 NUREG/CR-3394, SAND83-7116, 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 ZOI, and three 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, (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 source 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 the 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 source 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 jets 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 also is 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) to those 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 such as character of the debris materials and turbulence levels present. Aging has a strong effect 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 on 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 judgment is that 180 to 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," OSC-6827, Rev. 2. (Unapproved update).

See 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 Carbozinc 11 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, which 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 (GE Nuclear Energy) document NEDO-32686-A (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 contain 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," U.S. Nuclear Regulatory Commission (Sandia National Laboratories) document NUREG/CR-2403, Sup. 1 (SAND82-0927) (July 1982).

The report was published in July 1982. As of that date, the report summarizes the type and percentage of insulation in eight 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," U.S. Nuclear Regulatory Commission (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 and 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; e.g., "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 W four-loop PWR with ice-condenser 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 2.8, 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 on 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 2.7. 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 2.5 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 2.6.
- 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 Figs. B-1 through B-7, as cross-referenced in Table B-1.
- Column 6—Phenomenon relative importance rank. The ranking scheme is described in Section 2.9.
- 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-8 through B-14 in Appendix B, and 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-15 through B-21 in Appendix B, and the ranking rationales are given in Table C-2 in Appendix C.

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	Movement toward ice condenser and into ice condenser. Subsequent washout possible, followed by settling where flow velocities sufficiently low	Settling completed; liquid transport in areas where threshold velocity exceeded	Liquid transport in areas where threshold velocity exceeded
Cal-Sil			
Chunks	Transport to and into ice condenser during initial blowdown; breaks into smaller pieces; subsequent washout possible	Erosion; suspend in water; liquid transport	Erosion; suspend in water; liquid transport
Dust	Aerosol transport to and into ice condenser; dust to mud; adheres to surfaces. subsequent washout possible	Subject to washdown; adheres to surfaces; suspend in water subject to scrubbing; liquid transport in water	Suspend in water; liquid transport
Individual fibers	Transport to and into ice condenser; adhesion; subsequent washout possible	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 toward ice condenser during initial blowdown; then settles	Little or no movement	Little or no movement
Chunks	Transport to and into ice condenser during initial blowdown, followed by trapping, and adhesion but subsequent washout possible	Partial washdown; liquid transport where threshold velocity exceeded; erosion, trapping	Agglomeration; liquid transport
Shreds	Transport to and into ice condenser during initial blowdown, followed by trapping, and adhesion but subsequent washout possible	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 to and into ice condenser during initial blowdown, followed by trapping, and adhesion but subsequent washout possible	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, and pads; synergistic effects with foreign materials 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 Upper-compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Pressure-driven flows (bulk flows)	P1-1	L	P1-1
			Fan-driven flows (nonsafety)	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	NA	P1-8
			Flashing of break liquid effluent	P1-9	NA	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	L	P1-14
			Agglomeration	P1-15	L	P1-15
		Debris depletion	Sweepout	P1-16	L	P1-16
			Gravitational settling	P1-17	L	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 lower-compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Pressure driven flows (bulk flows)	P1-21	H	P1-21
			Fan-driven flows (nonsafety)	P1-22	L	P1-22
			Circulating flows	P1-23	L	P1-23
			Mixing (noncondensables)	P1-24	L	P1-24
			Localized flow field	P1-25	L	P1-25
			Turbulence	P1-26	L	P1-26
		Suspended-water transport (including gravitational settling)	Unflashed liquid flows	P1-27	L	P1-27
			Flashing of break liquid effluent	P1-28	L	P1-28
			Droplet interactions	P1-29	L	P1-29
			Condensation (droplet formation)	P1-30	L	P1-30
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P1-31	L	P1-31
			Film dynamics	P1-32	L	P1-32

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
Containment lower-compartment open areas (cont)	Debris related	Debris transport	Advection	P1-33	M	P1-33
			Agglomeration	P1-34	L	P1-34
		Debris depletion	Entrapment (space below ice condenser)	P1-35	M	P1-35
			Gravitational settling	P1-36	M	P1-36
			Condensation on particles	P1-37	L	P1-37
			Stephan flow (diffuseophoresis)	P1-38	L	P1-38
			Thermophoresis	P1-39	L	P1-39
Containment structures in lower compartment	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P1-40	L	P1-40
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P1-41	L	P1-41
			Surface wetting (condensation, impact)	P1-42	M	P1-42
			Film draining under gravity	P1-43	L	P1-43
			Deluge (streaming)	P1-44	M	P1-44
	Debris related	Debris transport	Resuspension	P1-45	L	P1-45
			Agglomeration	P1-46	L	P1-46
			Deluge (streaming) transport	P1-47	M	P1-47
			Film transport	P1-48	L	P1-48
			Runoff/reentrainment	P1-49	L	P1-49
			Disintegration	P1-50	L	P1-50
		Debris depletion	Inertial impaction	P1-51	M/L/L/L	P1-51
			Turbulence-induced impaction	P1-52	L	P1-52
			Adhesion	P1-53	M/L/L/L	P1-53
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	P1-54	L	P1-54
			Heat transfer to structure	P1-55	L	P1-55
			Pool agitation	P1-56	H	P1-56
			Pool dynamics	P1-57	H	P1-57

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
Containment floor (cont)	Debris related	Debris transport	Entry via film transport	P1-58	L/L/L/L	P1-58
			Entry via vapor transport	P1-59	L/L/L/L	P1-59
			Entry via liquid transport	P1-60	H/H/H/L	P1-60
			Reentrainment	P1-61	M/M/M/L	P1-61
			Disintegration	P1-62	M/H/L/L	P1-62
			Pool transport	P1-63	M/M/M/L	P1-63
		Debris depletion	Agglomeration in pool	P1-64	L	P1-64
			Adhesion	P1-65	L	P1-65
			Settling	P1-66	L	P1-66
			Impaction	P1-67	L	P1-67
			Entrapment	P1-68	M	P1-68
Ice condenser	Thermal-hydraulic related	Gas/vapor transport	Steam and noncondensable flow	P1-69	H	P1-69
		Liquid transport (including gravitational settling)	Ice to liquid (melting)	P1-70	H	P1-70
			Liquid draindown	P1-71	M	P1-71
		Water-surface transport depletion/accumulation	Condensation	P1-72	H	P1-72
	Debris related	Debris transport	Debris advection (into ice condenser)	P1-73	H/H/H/L	P1-73
			Debris suspension	P1-74	M/M/L/L	P1-74
			Debris draining (downward)	P1-75	H/H/H/L	P1-75
			Debris carry through (exit)	P1-76	L/L/L/L	P1-76
			Debris liftoff (interior)	P1-77	L/L/L/L	P1-77
		Debris depletion	Debris deposition (interior)	P1-78	L/L/L/L	P1-78

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/L/H (fibrous/Cal-Sil/RMI/other) 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); H, M, and L are High, Medium, and Low importance.
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 upper compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P2-1	L	P2-1
			Fan-driven flows (non-safety)	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
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P2-7	L	P2-7
			Falling condensate	P2-8	L	P2-8
			Droplet motions	P2-9	L	P2-9
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P2-10	L	P2-10
	Debris related	Debris transport	Advection	P2-11	L	P2-11
			Agglomeration	P2-12	L	P2-12
		Debris depletion	Sweepout	P2-13	L	P2-13
			Gravitational settling	P2-14	L	P2-14
			Condensation on particles	P2-15	L	P2-15
			Stephan flow (diffuseophoresis)	P2-16	L	P2-16
			Thermophoresis	P2-17	L	P2-17
Containment lower-compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P2-18	L	P2-18
			Fan-driven flows	P2-19	L	P2-19
			Spray-induced flows	P2-20	L	P2-20
			Circulating flows	P2-21	L	P2-21
			Localized flow field	P2-22	L	P2-22
			Turbulence	P2-23	L	P2-23
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P2-24	L	P2-24
			Falling condensate	P2-25	L	P2-25
			Droplet motions	P2-26	L	P2-26
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P2-27	L	P2-27

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
Containment lower-compartment open areas (cont)	Debris related	Debris transport	Advection	P2-28	L	P2-28
			Agglomeration	P2-29	L	P2-29
		Debris depletion	Sweepout	P2-30	L	P2-30
			Gravitational settling	P2-31	L	P2-31
			Condensation on particles	P2-32	L	P2-32
			Stephan flow (diffuseophoresis)	P2-33	L	P2-33
			Thermophoresis	P2-34	L	P2-34
Containment structures in lower compartment	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P2-35	L	P2-35
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P2-36	L	P2-36
			Film draining under gravity	P2-37	L	P2-37
			Deluge (streaming)	P2-38	L/M/L/L	P2-38
			Condensation	P2-39	L	P2-39
	Debris related	Debris transport	Resuspension	P2-40	L	P2-40
			Agglomeration	P2-41	L	P2-41
			Deluge transport	P2-42	L/M/L/L	P2-42
			Film related transport	P2-43	L	P2-43
			Runoff/reentrainment	P2-44	L	P2-44
			Disintegration	P2-45	L/M/L/L	P2-45
		Debris depletion	Entrapment	P2-46	L	P2-46
			Inertial impaction	P2-47	L	P2-47
			Turbulent impaction	P2-48	L	P2-48
			Adhesion	P2-49	L	P2-49
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	P2-50	M	P2-50
			Heat transfer to structure	P2-51	L	P2-51
			Pool agitation	P2-52	H	P2-52
			Pool flow dynamics	P2-53	M/H/M/L	P2-53

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
Containment floor (cont)	Debris related	Debris transport	Entry via film transport	P2-54	L	P2-54
			Entry via vapor transport	P2-55	L	P2-55
			Entry via liquid transport	P2-56	L	P2-56
			Reentrainment	P2-57	L	P2-57
			Disintegration	P2-58	L/H/L/L	P2-58
			Pool transport	P2-59	H/H/L/L	P2-59
		Debris depletion	Agglomeration in pool	P2-60	L	P2-60
			Adhesion	P2-61	L	P2-61
			Settling	P2-62	H/H/L/L	P2-62
			Entrapment	P2-63	M	P2-63
Ice condenser	Thermal-hydraulic related	Gas/vapor transport	Steam and noncondensable flow	P2-64	L	P2-64
		Liquid transport (including gravitational settling)	Ice to liquid (melting)	P2-65	M	P2-65
			Liquid draindown	P2-66	L	P2-66
		Water-surface transport depletion/accumulation	Condensation	P2-67	M	P2-67
	Debris related	Debris transport	Debris advection (into ice condenser)	P2-68	NA	P2-68
			Debris suspension	P2-69	NA	P2-69
			Debris draining (downward)	P2-70	L/L/L/L	P2-70
			Debris carry through (exit)	P2-71	NA	P2-71
			Debris liftoff (interior)	P2-72	L/L/L/L	P2-72
		Debris depletion	Debris deposition (interior)	P2-73	NA	P2-73

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/L/H (fibrous/calcium silicate/reflective metallic insulation/other) 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); H, M, L are High, Medium, and Low importance.
③: See Appendix C for ranking rationales.

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 upper-compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P3-1	L	P3-1
			Fan-driven flows (non-safety)	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
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P3-7	L	P3-7
			Falling condensate	P3-8	L	P3-8
			Droplet motions	P3-9	L	P3-9
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P3-10	L	P3-10
	Debris related	Debris transport	Advection	P3-11	L	P3-11
			Agglomeration	P3-12	L	P3-12
		Debris depletion	Sweepout	P3-13	L	P3-13
			Gravitational settling	P3-14	L	P3-14
			Condensation on particles	P3-15	L	P3-15
			Stephan flow (diffuseophoresis)	P3-16	L	P3-16
			Thermophoresis	P3-17	L	P3-17
Containment lower-compartment open areas	Thermal-hydraulic related	Gas/vapor transport	Steam flow	P3-18	L	P3-18
			Fan-driven flows	P3-19	L	P3-19
			Spray-induced flows	P3-20	L	P3-20
			Circulating flows	P3-21	L	P3-21
			Localized flow field	P3-22	L	P3-22
			Turbulence	P3-23	L	P3-23
		Suspended water transport (including gravitational settling)	Unflashed liquid flows	P3-24	L	P3-24
			Falling condensate	P3-25	L	P3-25
			Droplet motions	P3-26	L	P3-26
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	P3-27	L	P3-27

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
Containment lower compartment open areas (cont)	Debris related	Debris transport	Advection	P3-28	L	P3-28
			Agglomeration	P3-29	L	P3-29
		Debris depletion	Sweepout	P3-30	L	P3-30
			Gravitational settling	P3-31	L	P3-31
			Condensation on particles	P3-32	L	P3-32
			Stephan flow (diffuseophoresis)	P3-33	L	P3-33
			Thermophoresis	P3-34	L	P3-34
Containment structures in lower compartment	Thermal-hydraulic related	Gas/vapor transport	Heat transfer	P3-35	L	P3-35
		Water-surface transport depletion/accumulation/ (implied surface orientation)	Film shear	P3-36	L	P3-36
			Film draining under gravity	P3-37	L	P3-37
			Deluge (streaming)	P3-38	L/L/L/L	P3-38
			Condensation	P3-39	L	P3-39
	Debris related	Debris transport	Resuspension	P3-40	L	P3-40
			Agglomeration	P3-41	L	P3-41
			Deluge transport	P3-42	L/L/L/L	P3-42
			Film-related transport	P3-43	L	P3-43
			Runoff/reentrainment	P3-44	L	P3-44
			Disintegration	P3-45	L/L/L/L	P3-45
		Debris depletion	Entrapment	P3-46	L	P3-46
			Inertial impaction	P3-47	L	P3-47
			Turbulent impaction	P3-48	L	P3-48
			Adhesion	P3-49	L	P3-49
Containment floor	Thermal-hydraulic related	Water-surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	P3-50	L	P3-50
			Heat transfer to structure	P3-51	L	P3-51
			Pool agitation	P3-52	H	P3-52
			Pool flow dynamics	P3-53	H	P3-53
			Sump-induced flow	P3-54	H	P3-54

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
Containment floor (cont)	Debris related	Debris transport	Entry via film transport	P3-55	L	P3-55
			Entry via vapor transport	P3-56	L	P3-56
			Entry via liquid transport	P3-57	L	P3-57
			Reentrainment	P3-58	H	P3-58
			Disintegration	P3-59	L/M/L/L	P3-59
			Pool transport④	P3-60	H/H/H/H	P3-60
			Sump-induced overflow	P3-61	H	P3-61
		Debris depletion	Agglomeration in pool	P3-62	L	P3-61
			Adhesion	P3-63	M	P3-62
			Settling	P3-64	L	P3-63
			Precipitate formation	P3-65	L	P3-64
			Entrapment	P3-66	L	P3-66
Ice condenser	Thermal-hydraulic related	Gas/vapor transport	Steam and noncondensable flow	P3-67	L	P3-67
		Liquid transport (including gravitational settling)	Ice to liquid (melting)	P3-68	L	P3-68
			Liquid draindown	P3-69	L	P3-69
		Water-surface transport depletion/accumulation	Condensation	P3-70	L	P3-70
	Debris related	Debris transport	Debris advection (into ice condenser)	P3-71	NA	P3-71
			Debris suspension	P3-72	NA	P3-72
			Debris draining (downward)	P3-73	L	P3-73
			Debris carry through (exit)	P3-74	NA	P3-74
			Debris liftoff (interior)	P3-75	L	P3-75
		Debris depletion	Debris deposition (interior)	P3-76	NA	P3-76

Notes
①: See Appendix B for phenomenon descriptions.
②: NA is entered when the phenomena does not occur or is insignificant during the phase. Multiple rankings appear, e.g., L/M/L/H (fibrous/Cal-Sil/RMI/other) 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); H, M, and L are High, Medium, and Low importance.
③: See Appendix C for ranking rationales.
④: 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. Andrechek

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 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 also has 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 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 of 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 (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 USNRC, Department of Energy, and several national laboratories, including Oak Ridge, Argonne, LANL, 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 USNRC. 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 USNRC-sponsored CONTAIN computer code. Most recently, Mr. Tills has been involved in co-authoring a state-of-the-art report on containment thermal hydraulics and hydrogen distribution for the Nuclear Energy Agency's Committee on the Safety of Nuclear Installations (CSNI) and qualifying the CONTAIN code as a design-basis-accident licensing code for the USNRC. 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 B-1 corresponds to Table 4-2 in Section 4, Table B-2 corresponds to Table 4-3, and Table B-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 (p. 1 of 6)
(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 (N_2 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

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (p. 2 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
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
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-1
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-1
P1-21	Pressure-driven flows (bulk flows)	See P1-1.	B-1
P1-22	Fan-driven flows	See P1-2.	B-1
P1-23	Circulating flows	See P1-4.	B-1
P1-24	Steam/noncondensable mixing	See P1-5.	B-1
P1-25	Localized flow field	See P1-6.	B-1
P1-26	Turbulence	See P1-7.	B-1
P1-27	Unflashed liquid flows	See P1-8.	B-1
P1-28	Flashing of break liquid effluent	See P1-9.	B-1
P1-29	Droplet interactions	See P1-10.	B-1
P1-30	Droplet formation via condensation	See P1-11.	B-1
P1-31	Condensation on structures	See P1-12.	B-2
P1-32	Film dynamics	See P1-13.	B-2

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (p. 3 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-33	Advection	See P1-14	B-2
P1-34	Agglomeration	See P1-15	
P1-35	Entrapment (space below ice condenser)	Debris is in a space in which fluid velocities are very low, permitting the debris to settle to the floor.	
P1-36	Gravitational settling	See P1-17	B-2
P1-37	Condensation on particles	See P1-18	B-2
P1-38	Stephan flow (diffusiophoresis)	See P1-19	B-2
P1-39	Thermophoresis	See P1-20	B-2
P1-40	Heat transfer	Cooling of containment atmosphere due to heat transfer to structures.	B-3
P1-41	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-3
P1-42	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
P1-43	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-3
P1-44	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
P1-45	Resuspension	Reentrainment of debris previously deposited on structure surfaces into the atmospheric flow stream due to local fluid/structure shear forces.	B-4
P1-46	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
P1-47	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
P1-48	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity.	B-4
P1-49	Runoff/reentrainment	Resuspension of debris on structure surfaces into the flow stream as liquid films drain off of structures.	B-4

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (p. 4 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-50	Disintegration	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
P1-51	Inertial impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-4
P1-52	Turbulent impaction	Capture of debris on structural surfaces due to turbulent eddies.	B-4
P1-53	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-4
P1-54	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
P1-55	Heat transfer to structure	Heat transfer between water on containment floor and bounding structures.	B-5
P1-56	Pool agitation	Agitation of the pool by liquid streams falling or draining from above.	B-5
P1-57	Pool 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
P1-58	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-6
P1-59	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-6
P1-60	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-6
P1-61	Reentrainment	Movement of debris off the basemat floor and into higher elevations of the pool.	B-6
P1-62	Disintegration	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-6

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (p. 5 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-63	Pool transport	Before sump activation 30 min after accident initiation, nondirected flows exist that create the potential for transport of suspended debris in the pool.	B-6
P1-64	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
P1-65	Adhesion	Permanent retention of debris particles on the containment floor due to mechanical interactions with a rough surface or other forces.	B-6
P1-66	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-6
P1-67	Impaction	Capture of debris on the surface of the containment floor (or water pool) due to inertial deposition.	B-6
P1-68	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-6
P1-69	Steam and noncondensable flow	The movement of steam resulting from the pipe break and noncondensable gases existing in containment at the time of the break. Immediately following the break, the flow is directed from the containment lower compartments through the ice condenser and into the containment upper compartment.	B-7
P1-70	Ice to liquid (melting)	Ice in the ice condenser melts as heat is transferred to the ice from the break-flow steam passing through the ice condenser.	B-7
P1-71	Liquid draindown	Condition in liquid-vapor counterflow in which the rate of vapor rise is insufficient to prevent liquid downflow.	B-7
P1-72	Condensation	The process by which water vapor becomes a liquid.	B-7
P1-73	Debris advection (into ice condenser)	Transport of airborne debris by the break flow that is directed through the ice condenser into the ice condenser.	B-7
P1-74	Debris suspension	A condition of balance in which the debris carried into the ice condenser remains within the ice condenser, neither passing out the top with the vapor stream nor moving out the bottom with the liquid stream.	None

Table B-1 (cont)
Phenomena Descriptions for PWR Debris Transport during Blowdown Phase PIRT (p. 6 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P1-75	Debris draining (downward)	The downward transport of debris previously carried into the ice condenser by advection by the water from the condensed vapor flow and the ice melted in the ice condenser.	B-7
P1-76	Debris carry through (exit)	Transport of airborne debris by the break flow that is directed through the ice condenser out the exit plane of the ice condenser into the upper-containment compartment open areas.	B-7
P1-77	Debris liftoff (interior)	The removal and return of debris previously captured on ice condenser structures by debris impaction into the water flow moving to the bottom of the ice condenser.	B-7
P1-78	Debris deposition	Capture of debris particles on ice condenser structure surfaces due to inertial impaction.	B-7

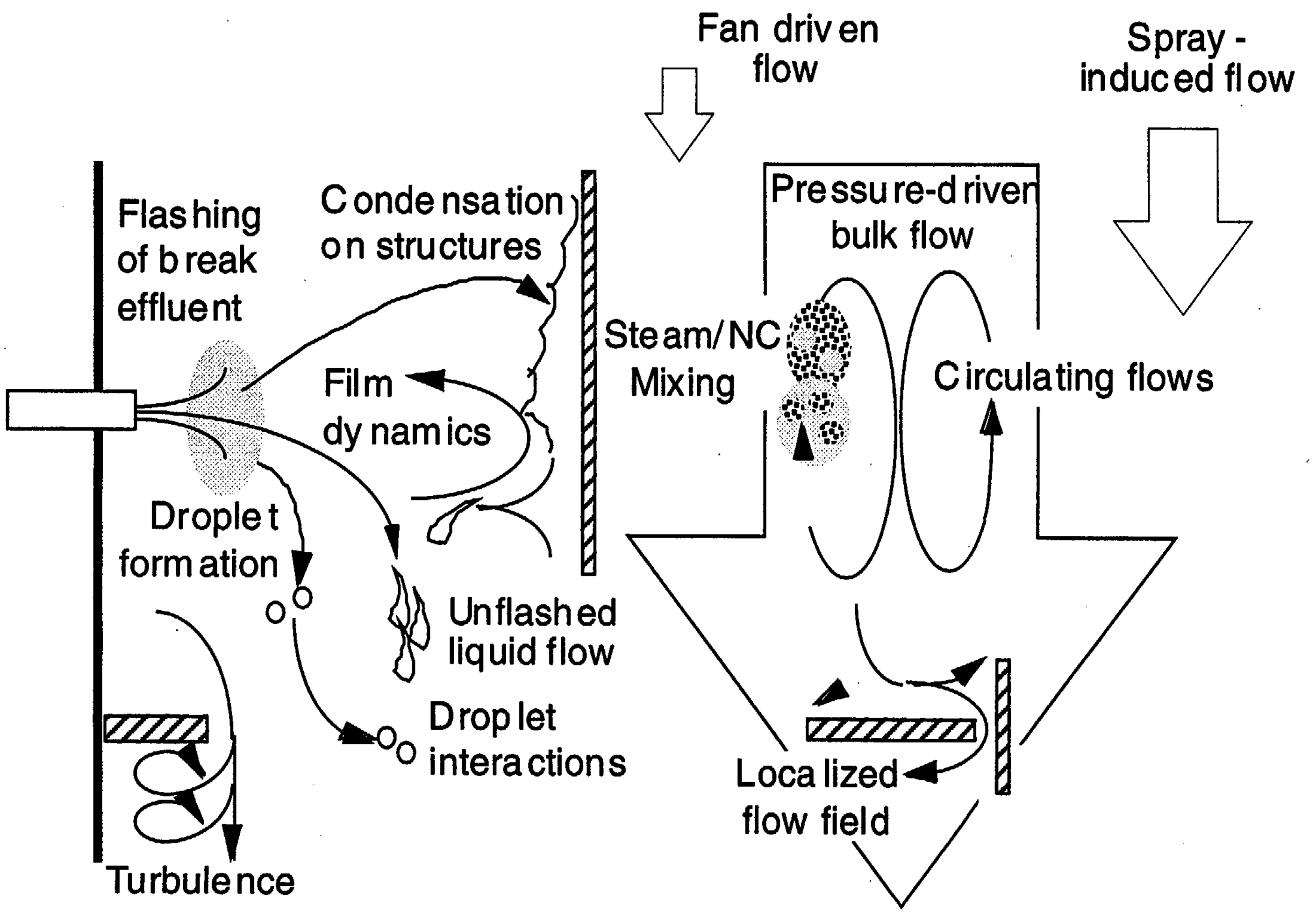

Fig. B-1. Thermal-hydraulic processes in PWR containment upper- and lower-compartment open areas during the blowdown phase of a CL LBLOCA.

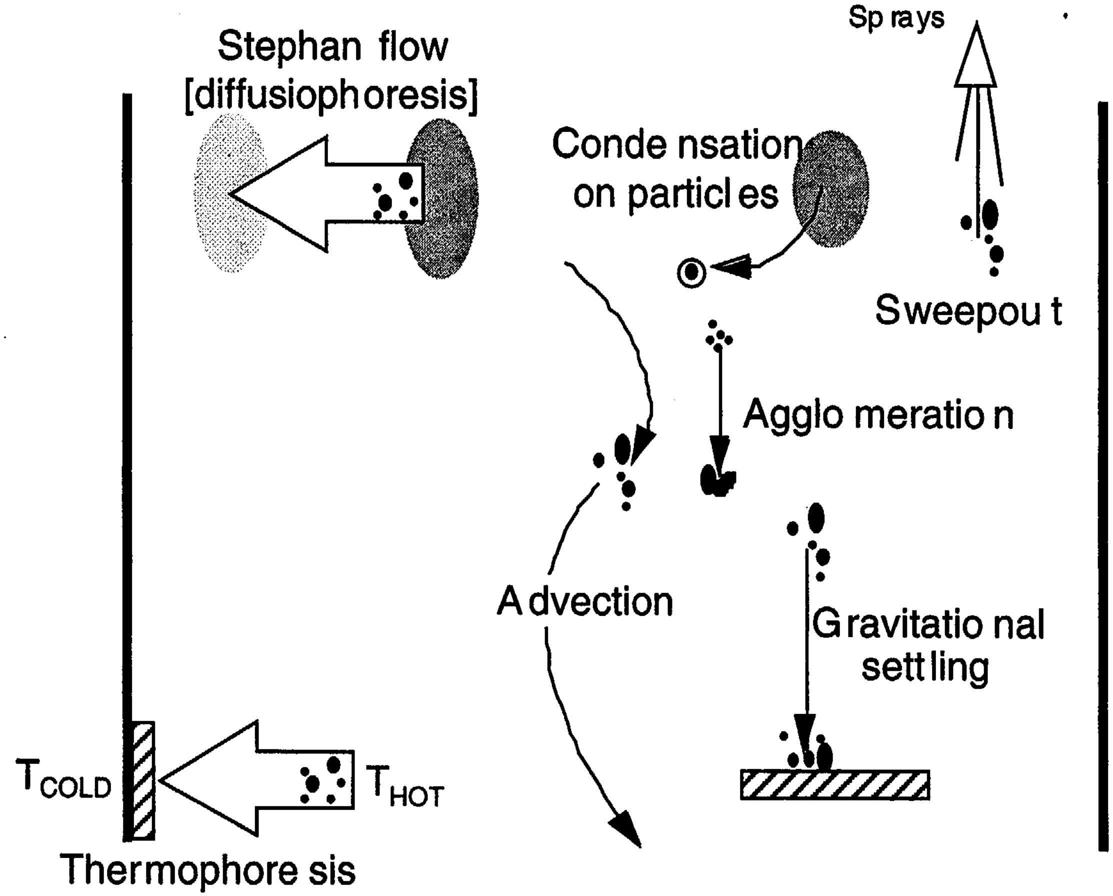

Fig. B-2. Transport/deposition processes for debris in containment upper- and lower-compartment open areas during the blowdown phase of a CL LBLOCA.

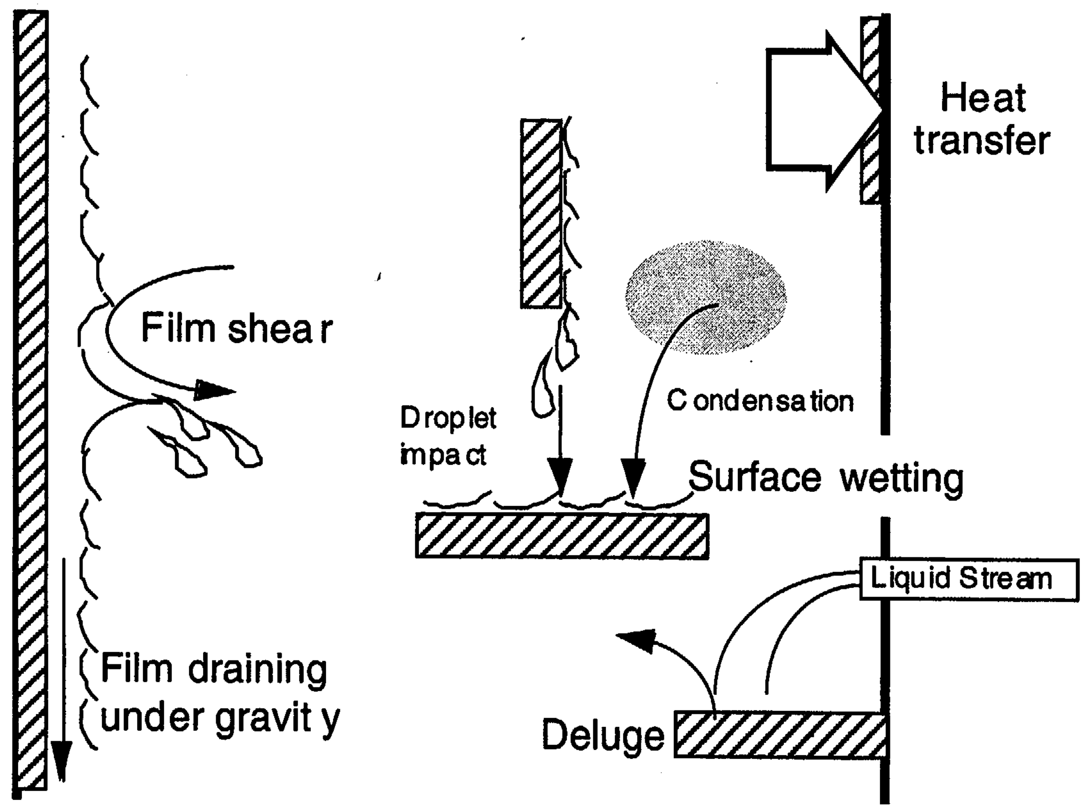

Fig. B-3. Thermal-hydraulic processes on containment lower-compartment structures during the blowdown phase of a CL LBLOCA.

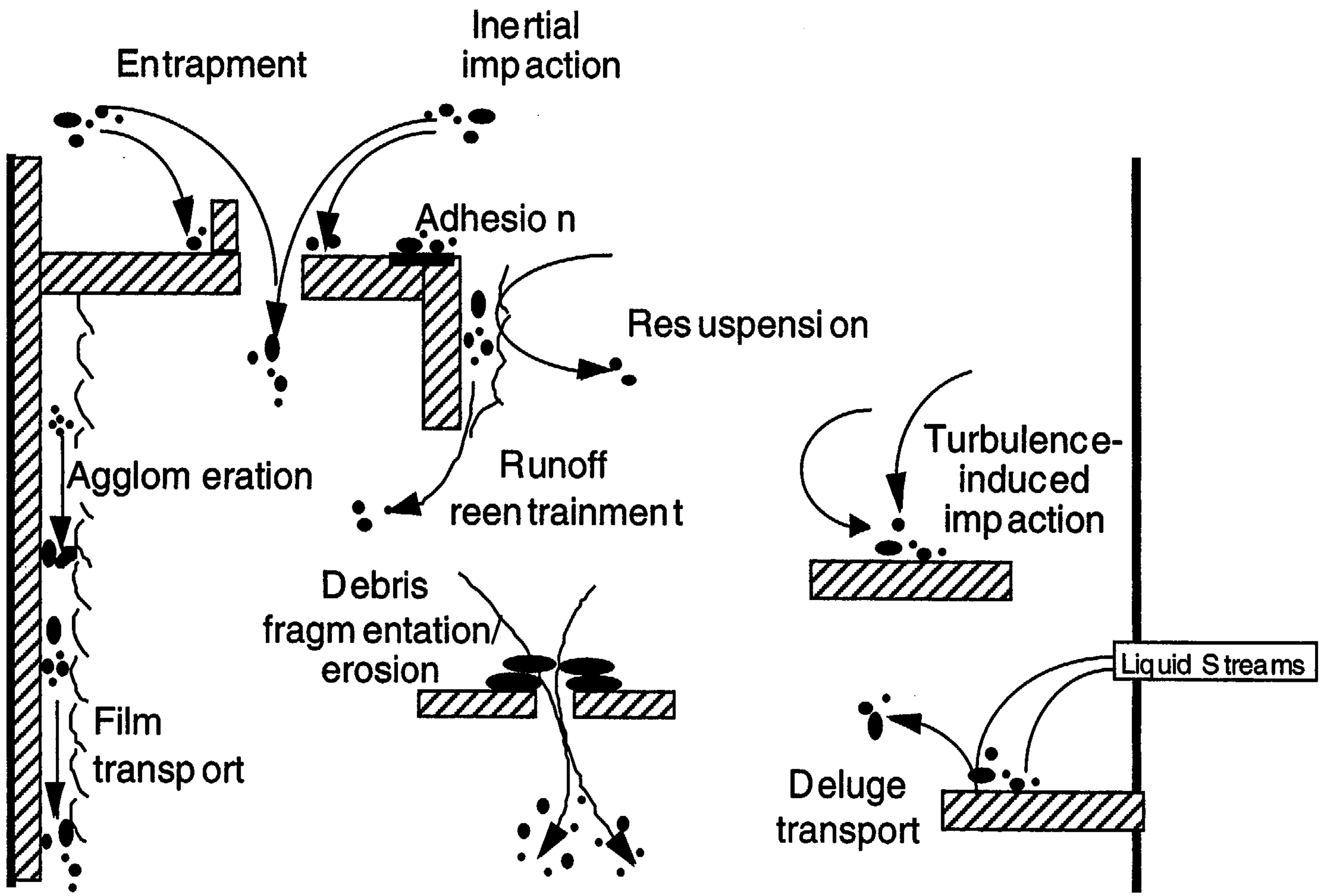

Fig. B-4. Transport/deposition processes for debris on containment lower-compartment structures during the blowdown phase of a CL LBLOCA.

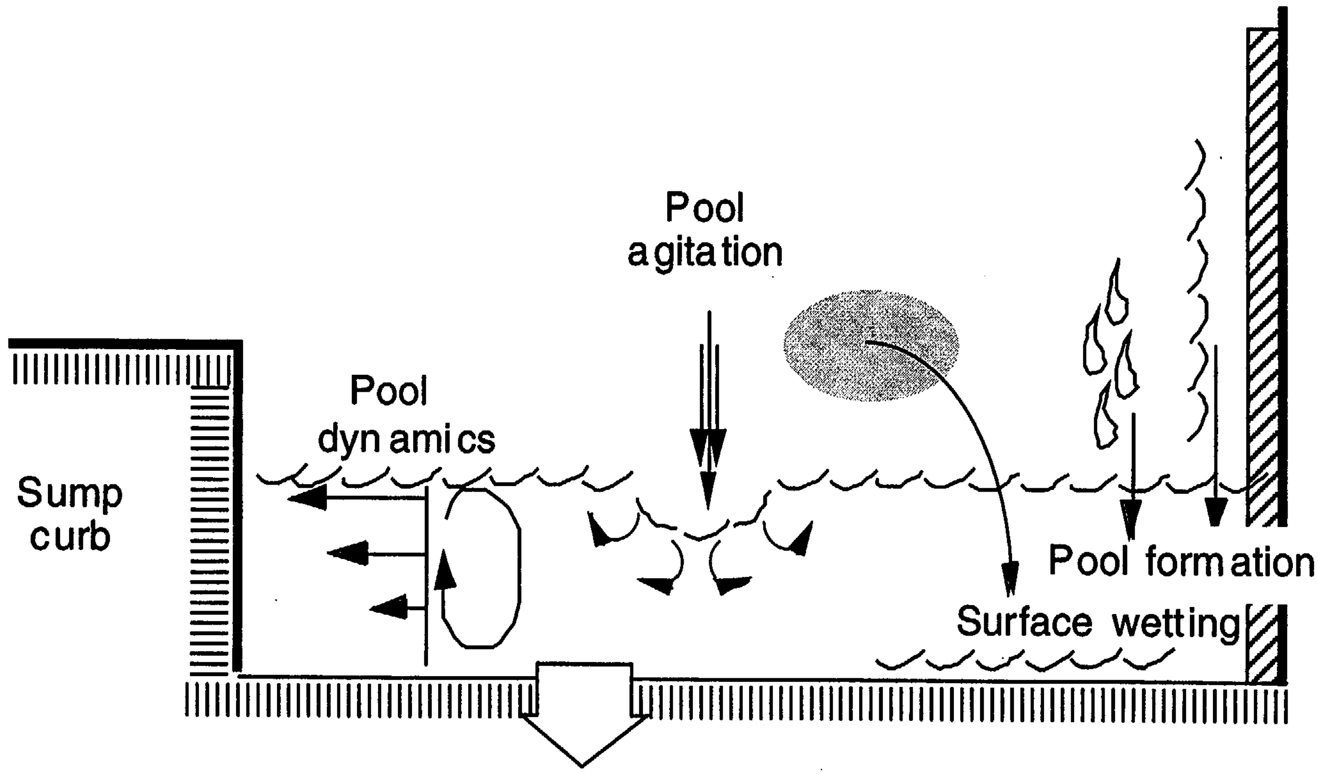

Fig. B-5. Thermal-hydraulic processes on the basemat floor during the blowdown phase of a CL LBLOCA.

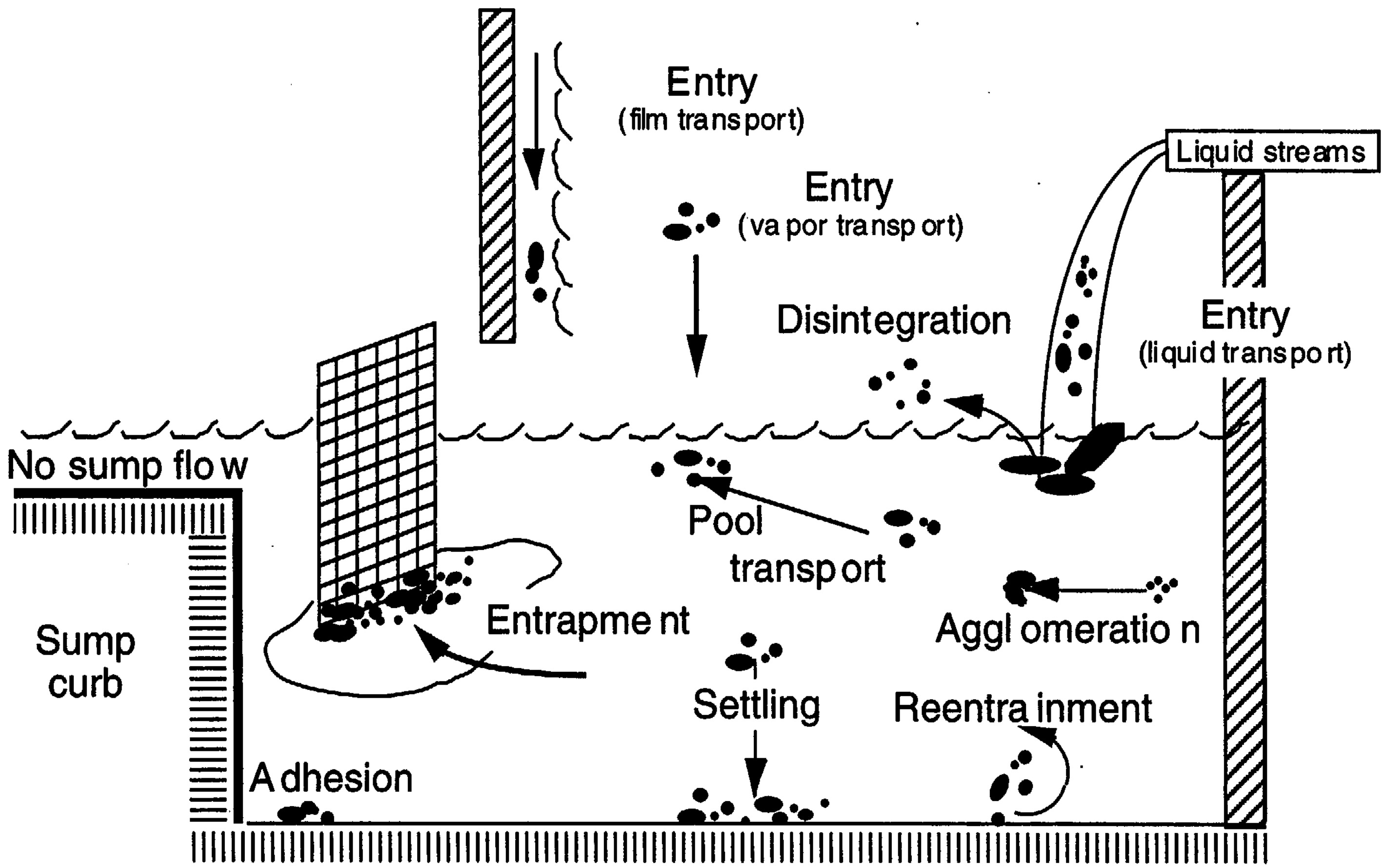

Fig. B-6. Transport/deposition processes for debris on the basemat floor during the blowdown phase of a CL LBLOCA.

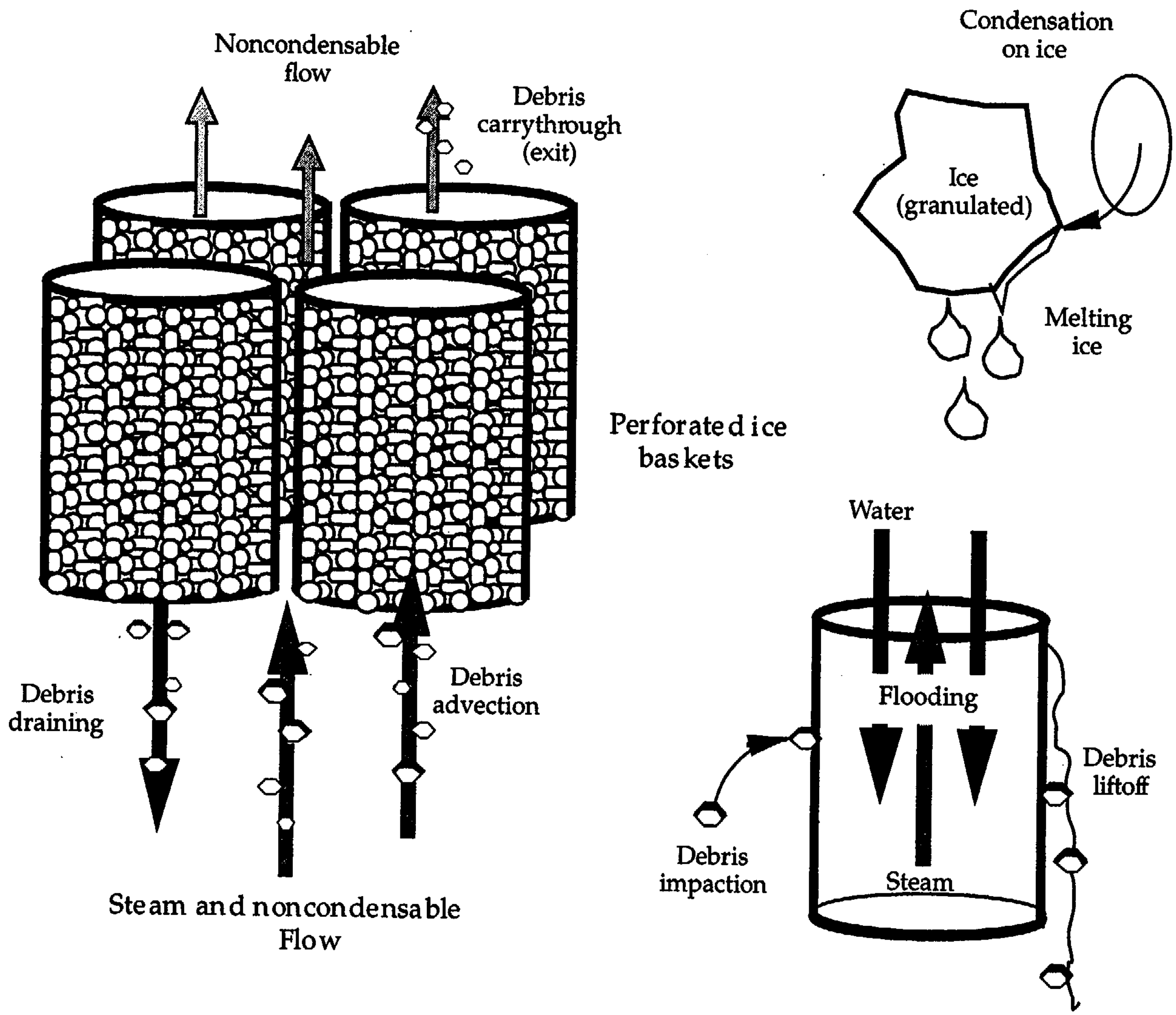

Fig. B-7. Ice condenser processes during the blowdown phase of a CL LBLOCA.

Table B-2
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 1 of 6)
(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-8
P2-2	Fan-driven flow (nonsafety)	Containment flow fields created by operation of the fan-cooling system that begins operation at about 300 s.	B-8
P2-3	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-8
P2-4	Circulating flows	Localized flows driven by buoyancy or other forces.	B-8
P2-5	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-8
P2-6	Turbulence	Turbulent fluid motions within the containment.	B-8
P2-7	Unflashed liquid flow	Liquid entering containment from vessel side of cold-leg break.	B-8
P2-8	Falling condensate	Liquid falling under gravitational force after condensing on fan coolers.	B-8
P2-9	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-8
P2-10	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-8
P2-11	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-9
P2-12	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-9
P2-13	Sweepout	Capture by airborne liquid.	B-9
P2-14	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-9
P2-15	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-9

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 2 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-16	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-9
P2-17	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-9
P2-18	Steam flow	Vapor entering containment from vessel and pump sides of cold-leg break.	B-8
P2-19	Fan-driven flow (nonsafety)	Containment flow fields created by operation of the fan-cooling system that begins operation at about 300 s.	B-8
P2-20	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-8
P2-21	Circulating flows	Localized flows driven by buoyancy or other forces.	B-8
P2-22	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-8
P2-23	Turbulence	Turbulent fluid motions within the containment.	B-8
P2-24	Unflashed liquid flow	Liquid entering containment from vessel side of cold-leg break.	B-8
P2-25	Falling condensate	Liquid falling under gravitational force after condensing, e.g., sheeting action of ice condenser water after hitting flapper valves and falling in sheets to the pool.	B-8
P2-26	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-8
P2-27	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-8
P2-28	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-9
P2-29	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-9

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 3 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-30	Sweepout	Capture by airborne liquid, e.g., the ice condenser water flow entering the lower compartment.	B-9
P2-31	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-9
P2-32	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-9
P2-33	Stephan flow (diffuseophoresis)	Transport of debris particles toward deposition surfaces due to concentration gradients of atmospheric contents (dominated by steam concentration gradients created by condensation on containment structures).	B-9
P2-34	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-9
P2-35	Heat transfer	Transfer of heat from containment atmosphere to walls by convection.	B-10
P2-36	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-10
P2-37	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-10
P2-38	Deluge (streaming)	Large flow rate of liquid effluent from ECCS onto containment structures.	B-10
P2-39	Condensation	Phase transformation (vapor–liquid) as steam cools during its motion through the containment atmosphere, e.g., on structures.	B-10
P2-40	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-11
P2-41	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-11

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 4 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-42	Deluge transport with ice condenser flow	Relocation of debris from containment structures due to interactions with the deluge of liquid from the ECCS and spray system.	B-11
P2-43	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity. Also called "washdown."	B-11
P2-44	Runoff/reentrainment	Resuspension of debris on structure surfaces into the atmosphere flow stream as liquid films drain off of structures.	B-11
P2-45	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-11
P2-46	Entrapment	Debris is in a space in which fluid velocities are very low, permitting the debris to settle to the floor.	B-11
P2-47	Inertial impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-11
P2-48	Turbulent impaction	Capture of debris particles driven to structure surfaces by turbulence	B-11
P2-49	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-11
P2-50	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
P2-51	Heat transfer to structure	Heat transfer between water on the containment floor and bounding structures.	B-11
P2-52	Pool agitation	Agitation of the pool by liquid streams falling or draining from above.	B-11
P2-53	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 (p. 5 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-54	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-13
P2-55	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-13
P2-56	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-13
P2-57	Reentrainment	Movement of debris off the basemat floor and into higher elevations of the pool.	B-13
P2-58	Disintegration	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-13
P2-59	Pool Transport	Before sump activation at 30 min after accident initiation, nondirected flows exist that create the potential for transport of suspended debris in the pool.	B-13
P2-60	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-13
P2-61	Adhesion	Permanent retention of debris particles on the basemat surface due to mechanical interactions with a rough surface or other forces.	B-13
P2-62	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-13
P2-63	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-13
P2-64	Steam and noncondensable flow	The movement of steam resulting from the pipe break and noncondensable gases existing in containment at the time of the break. Immediately following the break, the flow is directed from the containment lower compartments through the ice condenser and into the containment upper compartment.	B-14

Table B-2 (cont)
Phenomena Descriptions for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 6 of 6)

Reference Number	Phenomena	Phenomena Description	See Figure
P2-65	Ice to liquid (melting)	Ice in the ice condenser changes state from solid to liquid as heat is transferred to the ice from the break-flow steam passing through the ice condenser.	B-14
P2-66	Liquid draindown	Condition in liquid-vapor counterflow in which the rate of vapor rise is insufficient to prevent liquid downflow.	B-14
P2-67	Condensation	The process by which water vapor becomes a liquid.	B-14
P2-68	Debris advection (into ice condenser)	Transport of airborne debris by the break flow that is directed through the ice condenser into the ice condenser.	B-14
P2-69	Debris suspension	A condition of balance in which the debris carried into the ice condenser remains within the ice condenser, neither passing out the top with the vapor stream or moving out the bottom with the liquid stream.	None
P2-70	Debris draining (downward)	The downward transport of debris previously carried into the ice condenser by advection by the water from the condensed vapor flow and the ice melted in the ice condenser.	B-14
P2-71	Debris carry through (exit)	Transport of airborne debris by the break flow that is directed through the ice condenser out the exit plane of the ice condenser into the upper-containment compartment open areas.	B-14
P2-72	Debris liftoff (interior)	The removal and return of debris previously captured on ice condenser structures by debris impaction into the water flow moving to the bottom of the ice condenser.	B-14
P2-73	Debris deposition	Capture of debris particles on ice condenser structure surfaces due to inertial impaction.	B-14

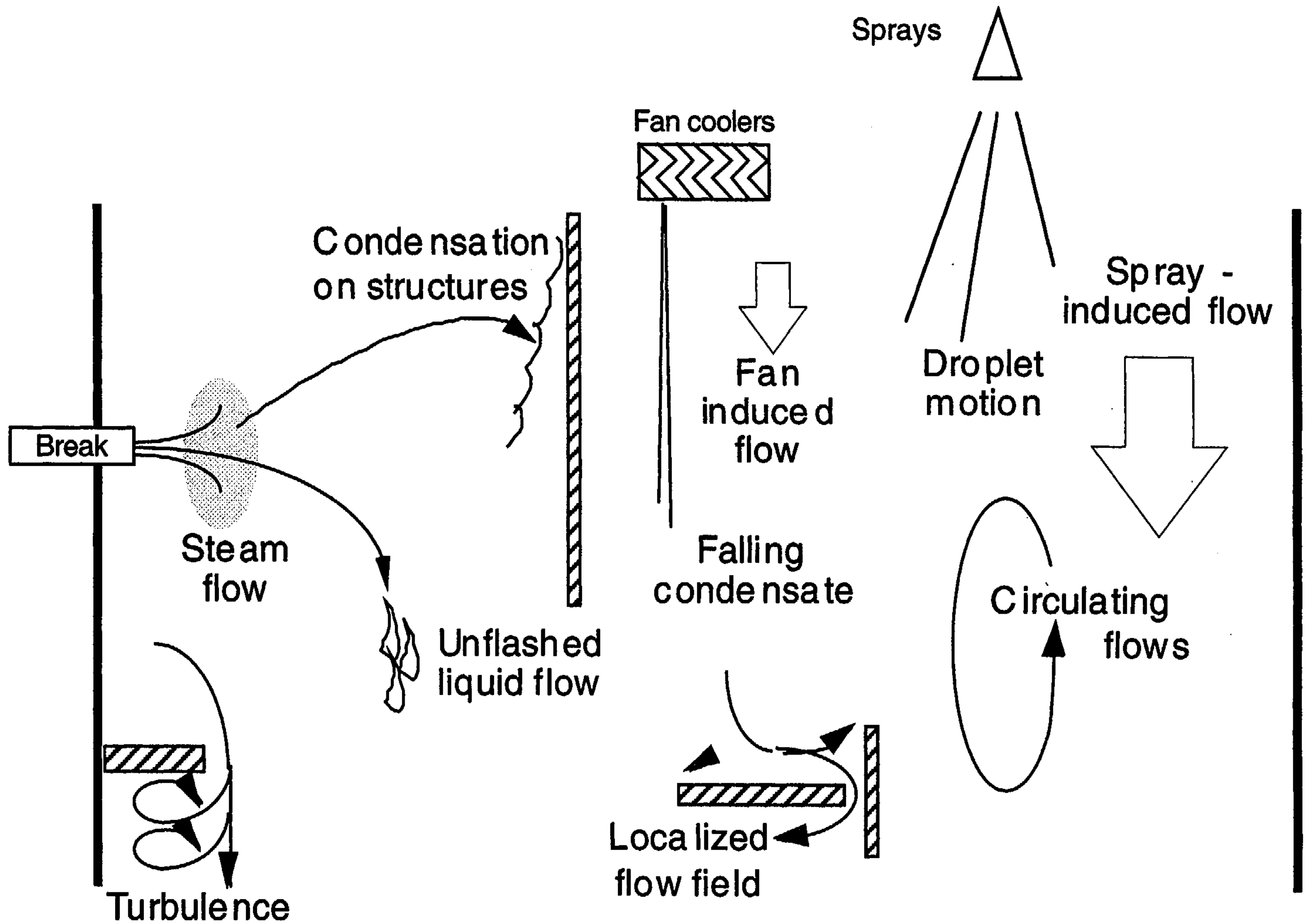

Fig. B-8. Thermal-hydraulic processes in PWR containment upper- and lower-compartment open areas during the post-blowdown phase of a CL LBLOCA.

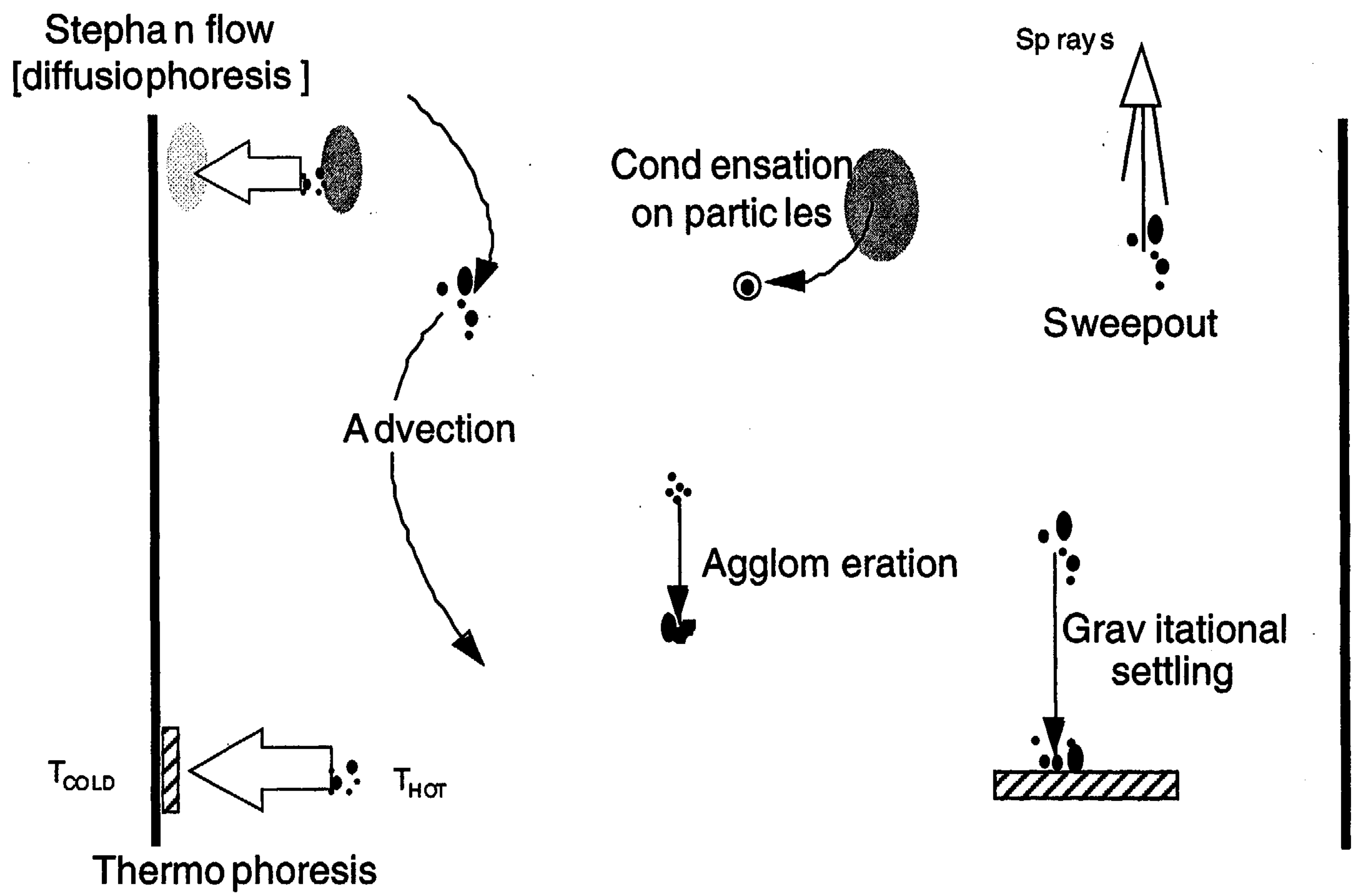

Fig. B-9. Transport/deposition processes for debris in containment upper- and lower-compartment open areas during the post-blowdown phase of a CL LBLOCA.

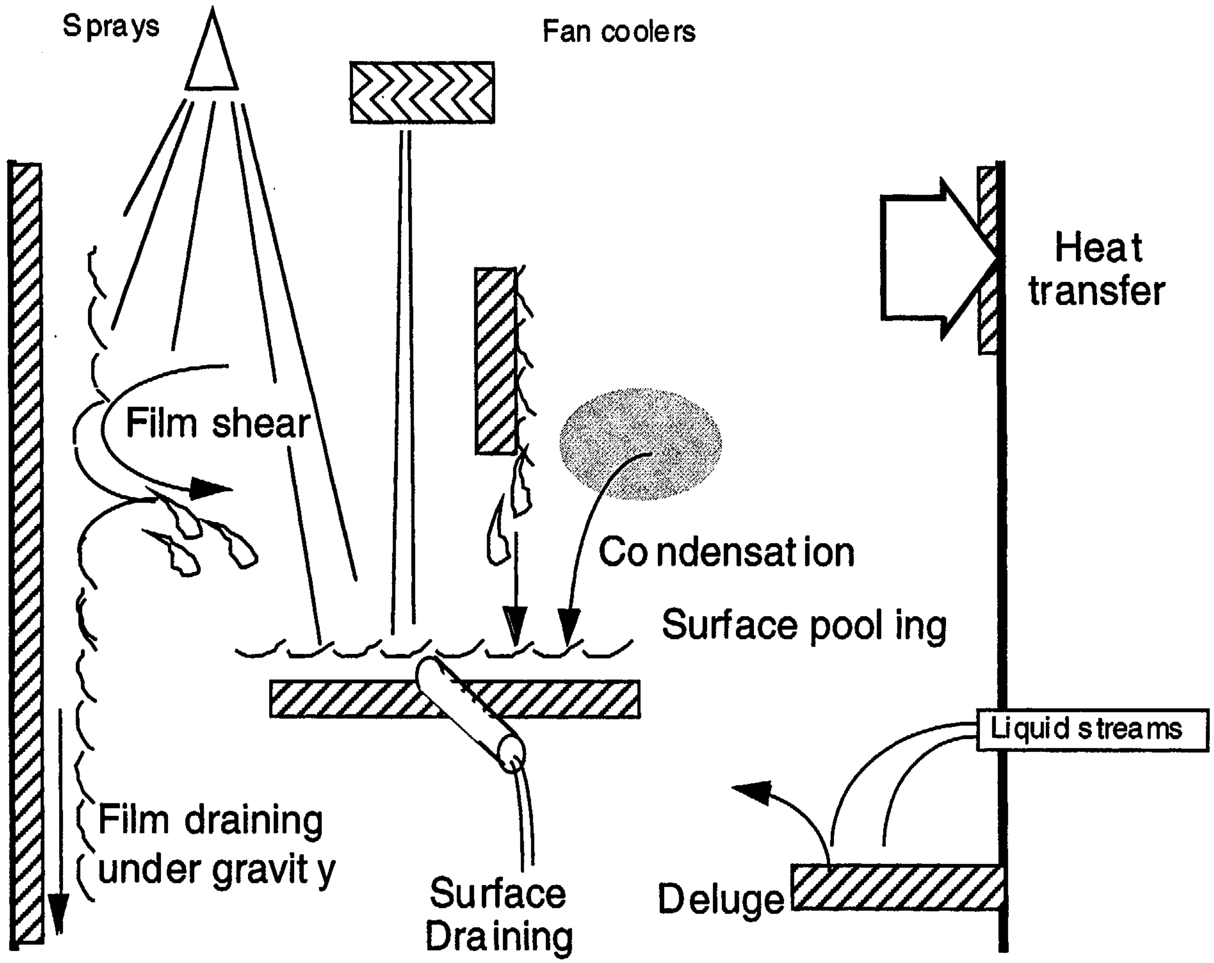

Fig. B-10. Thermal-hydraulic processes on containment lower-compartment structures during the post-blowdown phase of a CL LBLOCA.

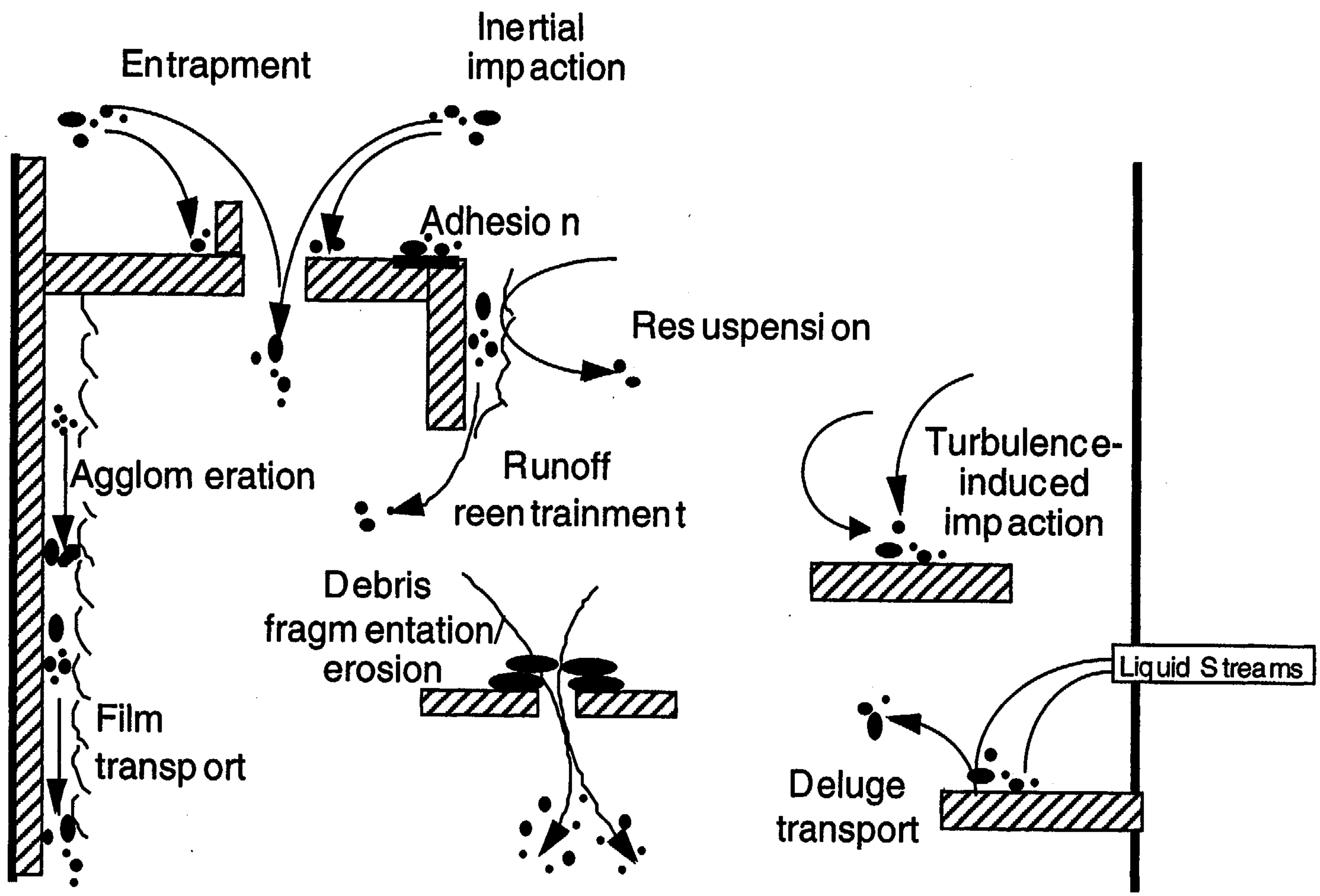

Fig. B-11. Transport/deposition processes for debris on containment lower-compartment structures during the post-blowdown phase of a CL LBLOCA.

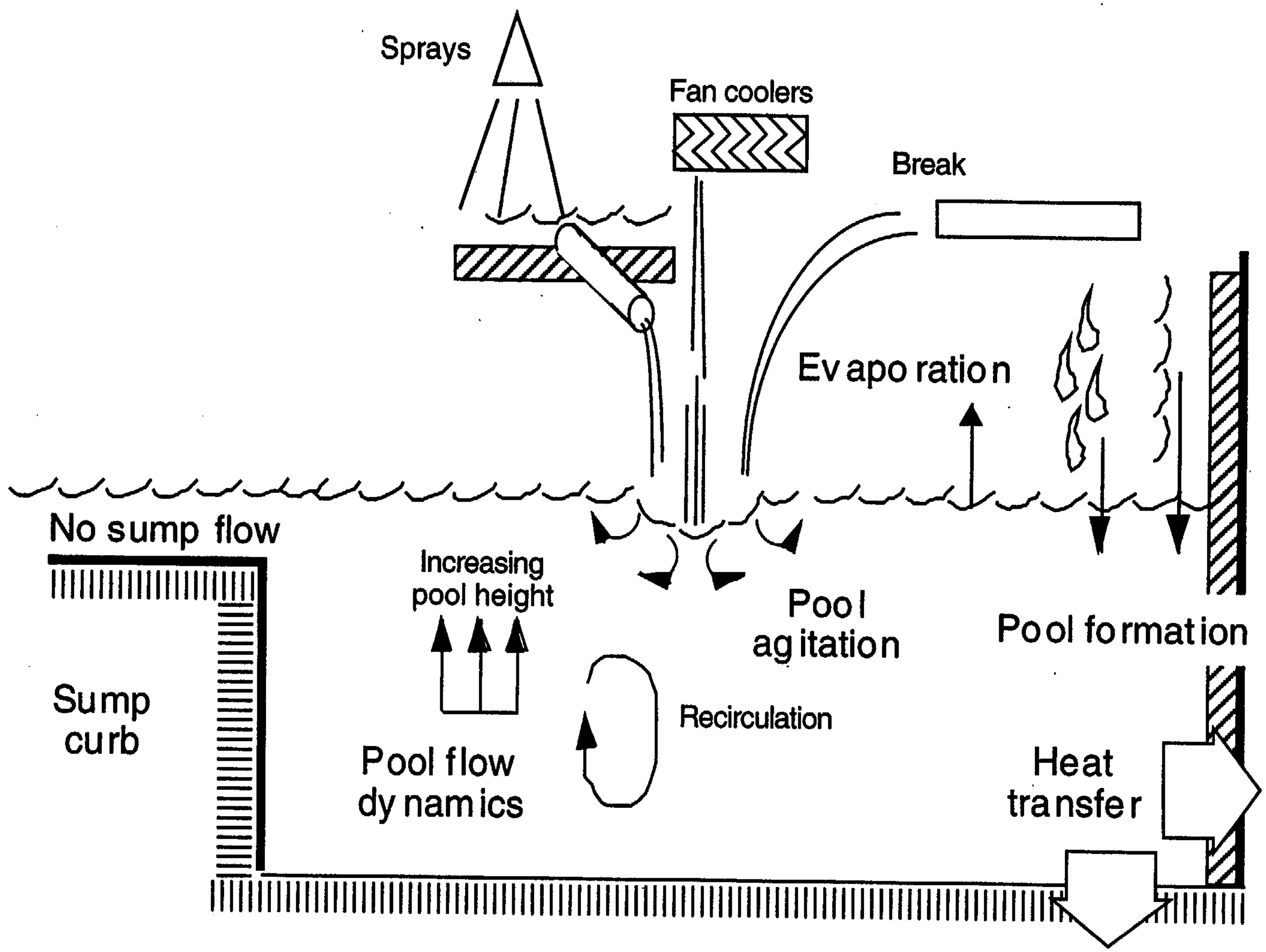

Fig. B-12. Thermal-hydraulic processes on the basemat floor during the post-blowdown phase of a CL LBLOCA.

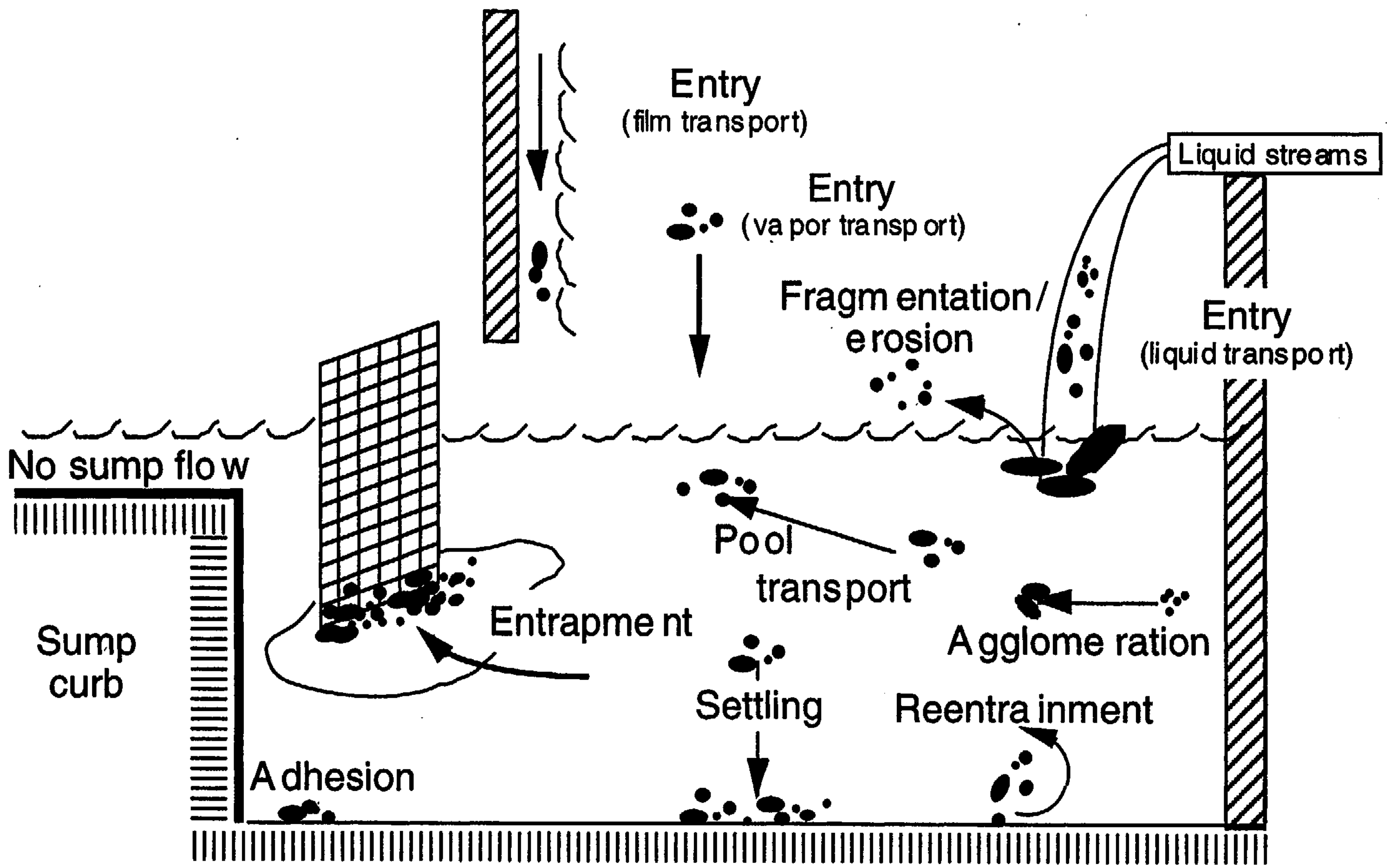

Fig. B-13. Transport/deposition processes for debris on the basemat floor during the post-blowdown phase of a CL LBLOCA.

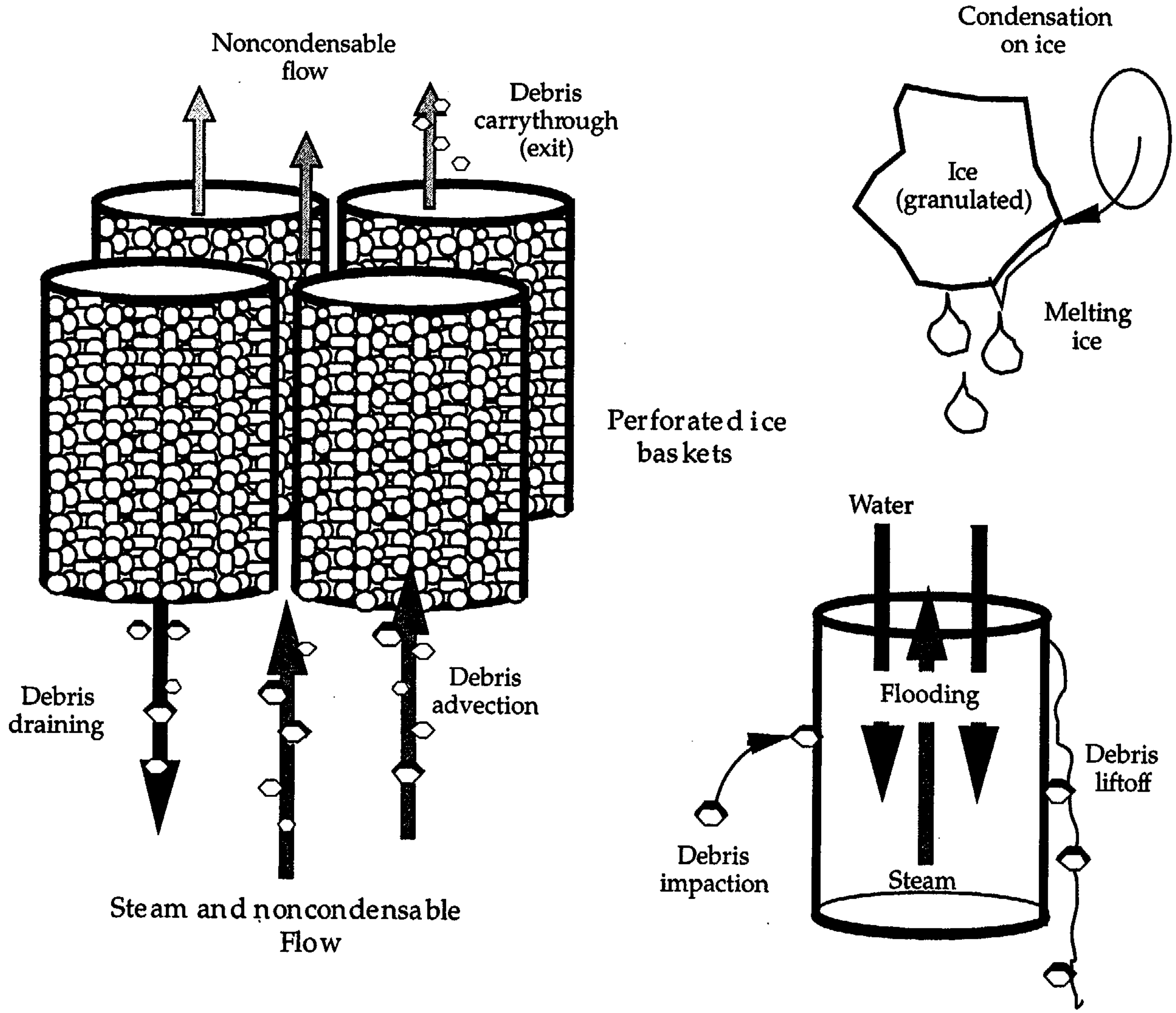

Fig. B-14. Ice condenser processes during the post-blowdown phase of a CL LBLOCA.

Table B-3
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 1 of 7)
(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 cold-leg break.	B-15
P3-2	Fan-driven flow (nonsafety)	Containment flow fields created by operation of the fan-cooling system that begins operation at about 300 s.	B-15
P3-3	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-15
P3-4	Circulating flows	Localized flows driven by buoyancy or other forces.	B-15
P3-5	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-15
P3-6	Turbulence	Turbulent fluid motions within the containment.	B-15
P3-7	Unflashed liquid flow	Liquid entering containment from vessel side of cold-leg break.	B-15
P3-8	Falling condensate	Liquid falling under gravitational force after condensing on fan coolers.	B-15
P3-9	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-15
P3-10	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-15
P3-11	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-16
P3-12	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	B-16
P3-13	Sweepout	Capture by airborne liquid.	B-16
P3-14	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-16
P3-15	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-16

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 2 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-16	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-16
P3-17	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-16
P3-18	Steam flow	Vapor entering containment from vessel and pump sides of cold-leg break.	B-15
P3-19	Fan-driven flow (nonsafety)	Containment flow fields created by operation of the fan-cooling system that begins operation at about 300 s.	B-15
P3-20	Spray-induced flow	Local fluid vortices, eddies, or fields created by spray-containment atmosphere interactions.	B-15
P3-21	Circulating flows	Localized flows driven by buoyancy or other forces.	B-15
P3-22	Localized flow field	Flow field in a small area, e.g., induced by objects.	B-15
P3-23	Turbulence	Turbulent fluid motions within the containment.	B-15
P3-24	Unflashed liquid flow	Liquid entering containment from vessel side of cold-leg break.	B-15
P3-25	Falling condensate	Liquid falling under gravitational force after condensing, e.g., sheeting action of ice condenser water after hitting flapper valves and falling in sheets to the pool.	B-15
P3-26	Droplet motion	Movement of droplets introduced into containment by the spray system.	B-15
P3-27	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-15
P3-28	Advection	Transport of airborne debris within the carrier gas medium by flows at a spectrum of scales from bulk to turbulent eddies.	B-16
P3-29	Agglomeration	Mechanical interaction among suspended debris particles 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 (p. 3 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-30	Sweepout	Capture by airborne liquid, e.g., the ice condenser water flow entering the lower compartment.	B-16
P3-31	Gravitational settling	Downward relocation (sedimentation) of debris in the containment atmosphere onto structure surfaces under the force of gravity.	B-16
P3-32	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-16
P3-33	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-16
P3-34	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	B-16
P3-35	Heat transfer	Transfer of heat from containment atmosphere to walls by convection.	B-17
P3-36	Film shear	The interfacial interaction between gas flow in the containment atmosphere and liquid (condensate) films on structure surfaces.	B-17
P3-37	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	B-17
P3-38	Deluge (streaming)	Large flow rate of liquid effluent from ice condenser, ECCS, and spray onto containment structures.	B-17
P3-39	Condensation	Phase transformation (vapor–liquid) as steam cools during its motion through the containment atmosphere, e.g., on structures.	B-17
P3-40	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-18
P3-41	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-18

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 4 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-42	Deluge transport	Relocation of debris from containment structures due to interactions with the deluge of liquid from the ice condenser, ECCS, and spray system.	B-18
P3-43	Film-related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity. Also called "washdown."	B-18
P3-44	Runoff/reentrainment	Resuspension of debris on structure surfaces into the atmosphere flow stream as liquid films drain off of structures.	B-18
P3-45	Disintigration	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-18
P3-46	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 such as the rooms below the ice condenser	B-18
P3-47	Inertial impaction	Capture of debris particles on structure surfaces due to inertial impaction.	B-18
P3-48	Turbulent impaction	Capture of debris particles driven to structure surfaces by turbulence.	B-18
P3-49	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	B-18
P3-50	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-19
P3-51	Heat transfer to structure	Heat transfer between water on the containment floor and bounding structures.	B-19
P3-52	Pool agitation	Agitation of the pool by liquid streams falling or draining from above; water sources are ice condenser water flow, ECCS, and sprays.	B-19

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 5 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-53	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-19
P3-54	Sump induced flow	Following sump activation, a directed flow is established toward the sump.	B-20
P3-55	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-20
P3-56	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-20
P3-57	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-20
P3-58	Reentrainment	Movement of debris off the basemat floor and into higher elevations of the pool.	B-20
P3-59	Disintegration	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-20
P3-60	Pool Transport	After sump activation at 30 min, directed flows are initiated and debris suspended in the pool can be transported toward the sump.	B-20
P3-61	Sump induced overflow	Transport of suspended debris over the sump curb and to the trash rack/debris screens. 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-20
P3-62	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-20
P3-63	Adhesion	Permanent retention of debris particles on the basemat surface due to mechanical interactions with a rough surface or other forces.	B-20

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 6 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-64	Settling	Downward relocation (sedimentation) of debris within the pool of water on the containment floor under the force of gravity.	B-20
P3-65	Precipitate formation	A substance separating, in solid particles, from a liquid; specifically, the reaction of chemicals in the ECC water with debris such as paint coating to produce a solid.	B-21
P3-66	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-21
P3-67	Steam and noncondensable flow	The movement of steam resulting from the pipe break and noncondensable gases existing in containment at the time of the break. Immediately following the break, the flow is directed from the containment lower compartments through the ice condenser and into the containment upper compartment.	B-21
P3-68	Ice to liquid (melting)	Ice in the ice condenser changes state from solid to liquid as heat is transferred to the ice from the break-flow steam passing through the ice condenser.	B-21
P3-69	Liquid draindown	Condition in liquid-vapor counterflow in which the rate of vapor rise is insufficient to prevent liquid downflow.	B-21
P3-70	Condensation	The process by which water vapor becomes a liquid.	B-21
P3-71	Debris advection (into ice condenser)	Transport of airborne debris by the break flow that is directed through the ice condenser into the ice condenser.	B-21
P3-72	Debris suspension	A condition of balance in which the debris carried into the ice condenser remains within the ice condenser, neither passing out the top with the vapor stream nor moving out the bottom with the liquid stream.	None
P3-73	Debris draining (downward)	The downward transport of debris previously carried into the ice condenser by advection by the water from the condensed vapor flow and the ice melted in the ice condenser.	B-21

Table B-3 (cont)
Phenomena Descriptions for PWR Debris Transport during Sump Operation Phase PIRT (p. 7 of 7)

Reference Number	Phenomena	Phenomena Description	See Figure
P3-74	Debris carry through (exit)	Transport of airborne debris by the break flow that is directed through the ice condenser out the exit plane of the ice condenser into the upper-containment compartment open areas.	B-21
P3-75	Debris liftoff (interior)	The removal and return of debris previously captured on ice condenser structures by debris impaction into the water flow moving to the bottom of the ice condenser.	B-21
P3-76	Debris deposition	Capture of debris particles on ice condenser structure surfaces due to inertial impaction.	B-21

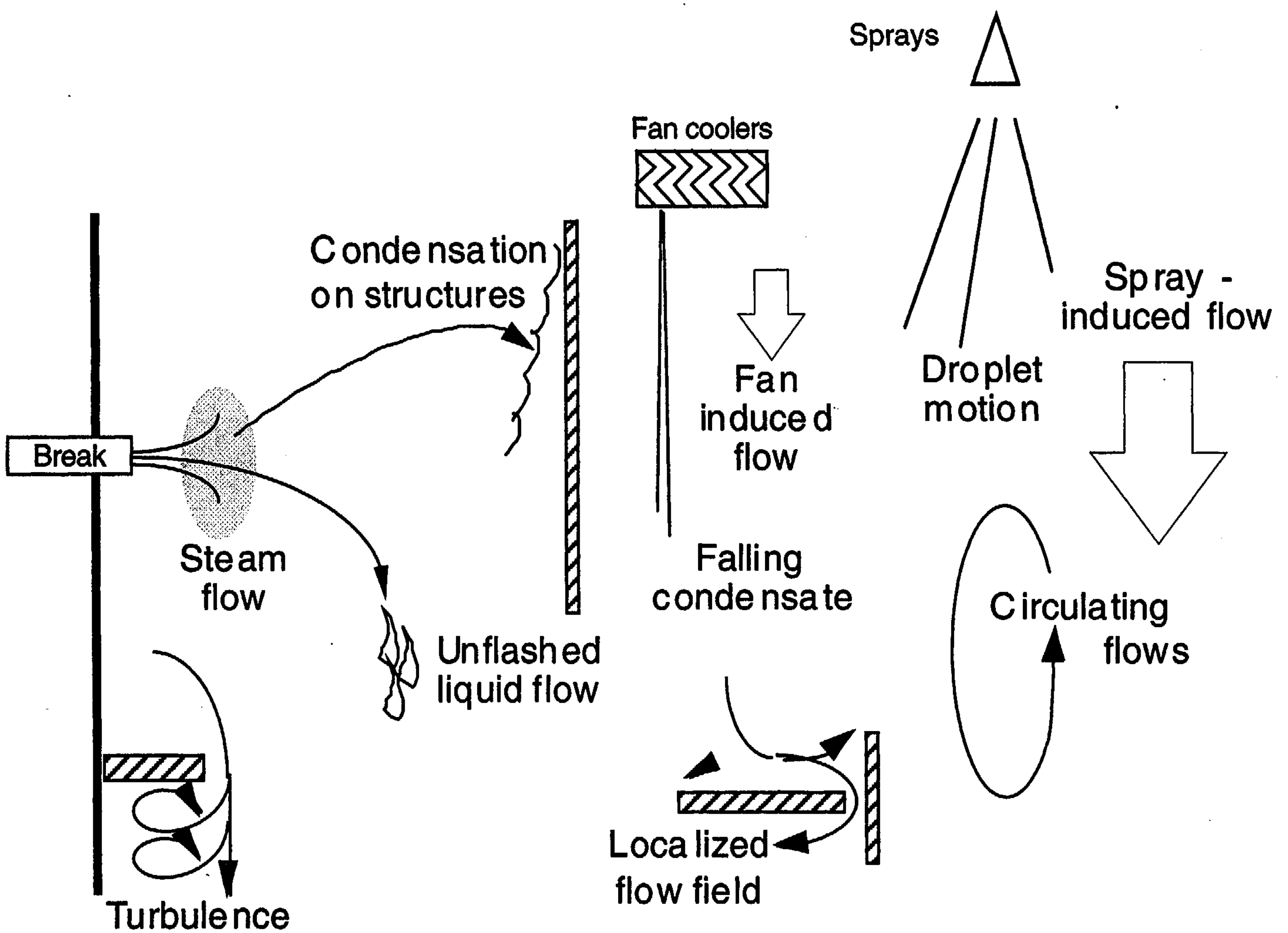

Fig. B-15. Thermal-hydraulic processes in PWR containment upper- and lower-compartment open areas during the sump-operation phase of a CL LBLOCA.

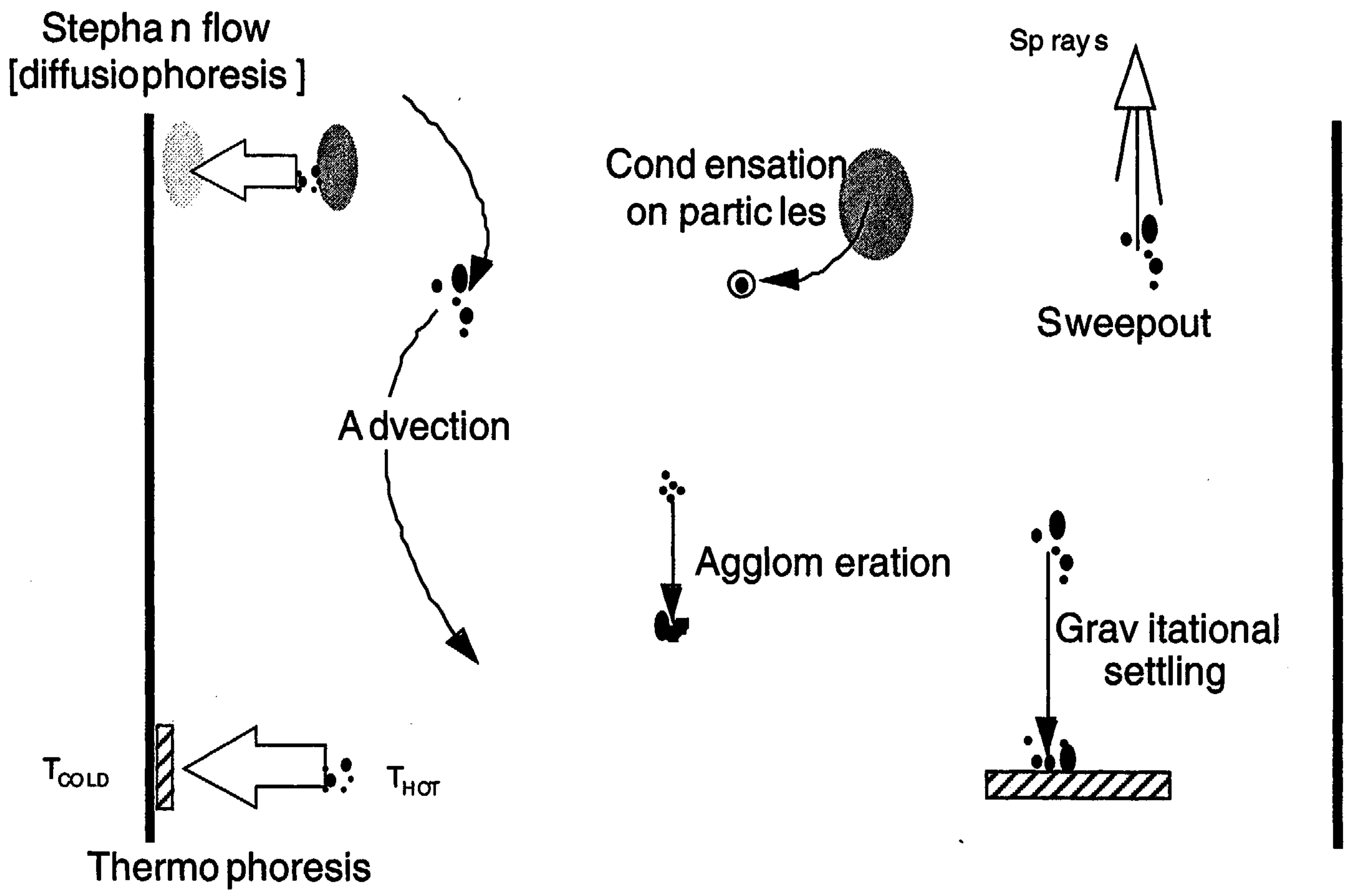

Fig. B-16. Transport/deposition processes for debris in containment upper- and lower-compartment open areas during the sump-operation phase of a CL LBLOCA.

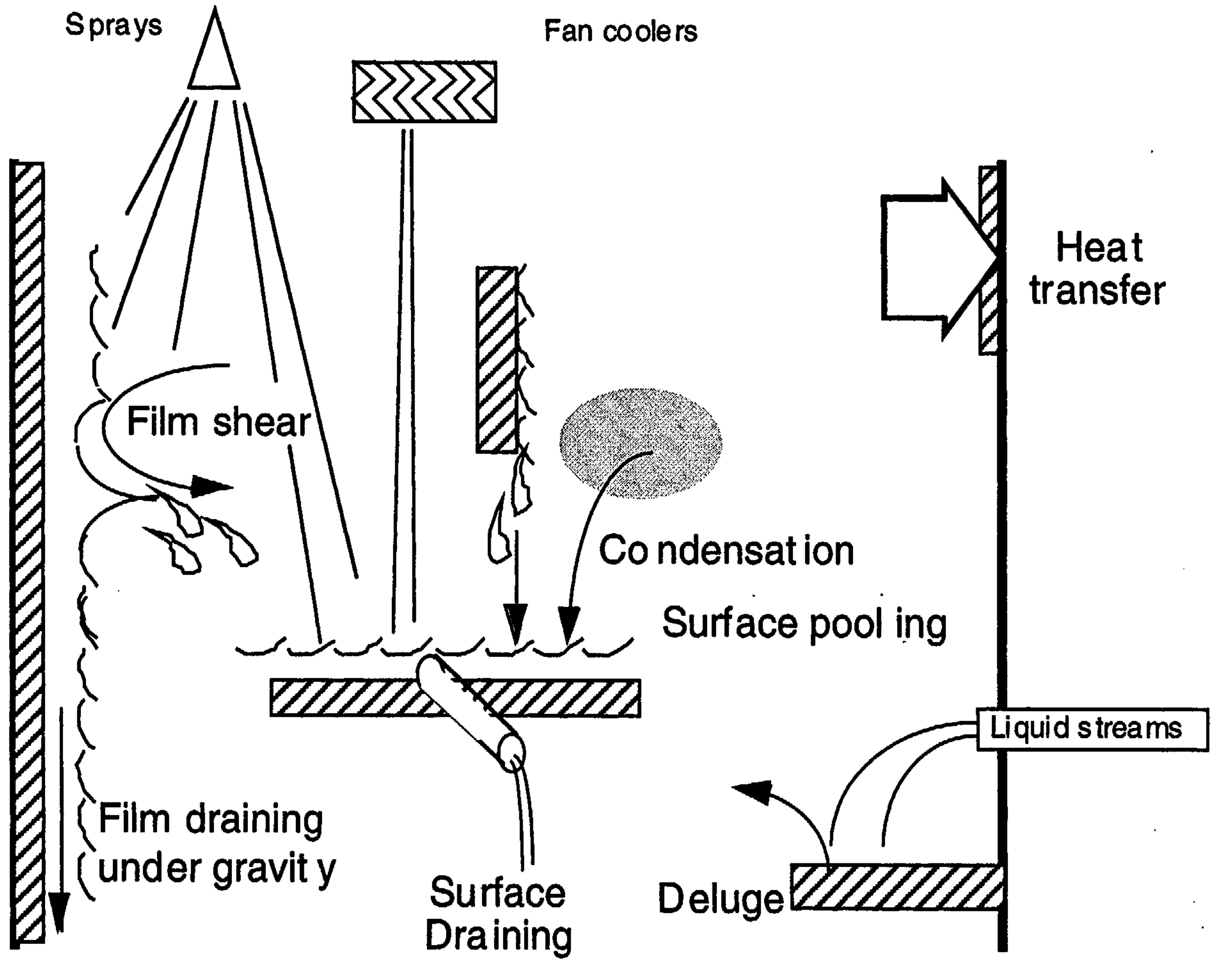

Fig. B-17. Thermal-hydraulic processes on containment lower-compartment structures during the sump-operation phase of a CL LBLOCA.

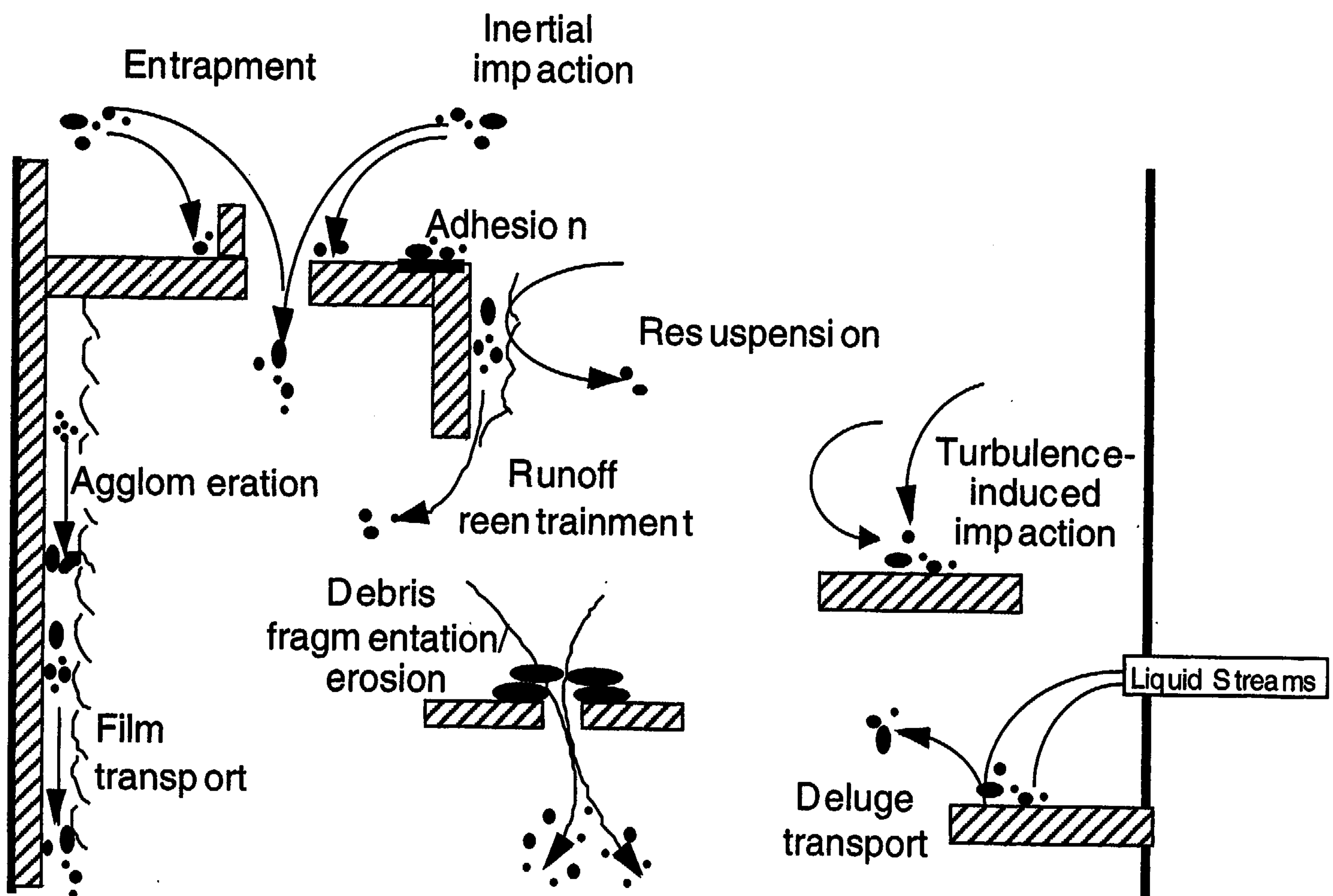

Fig. B-18. Transport/deposition processes for debris on containment lower-compartment structures during the sump-operation phase of a CL LBLOCA.

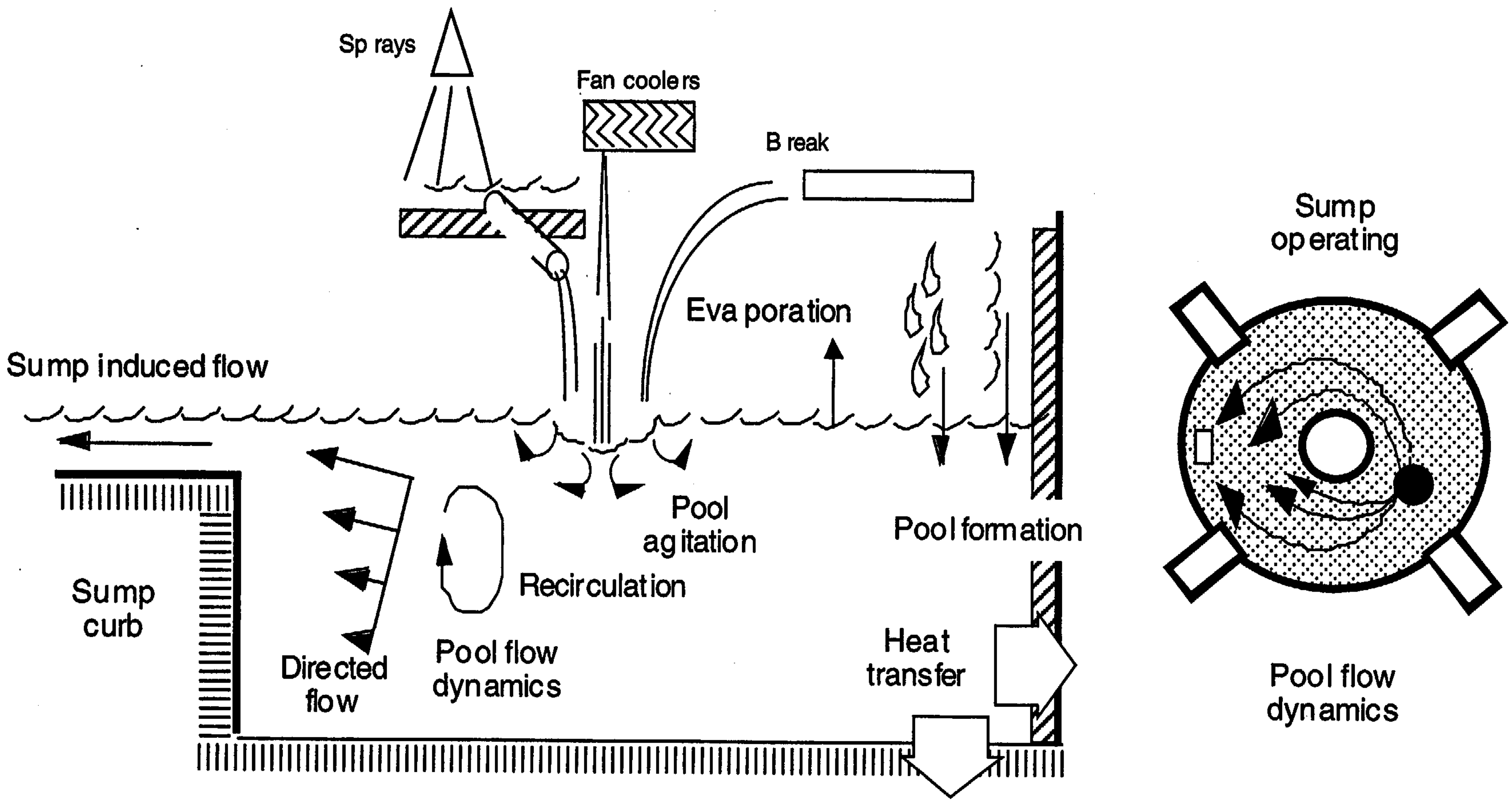

Fig. B-19. Thermal-hydraulic processes on the basemat floor during the sump-operation phase of a CL LBLOCA.

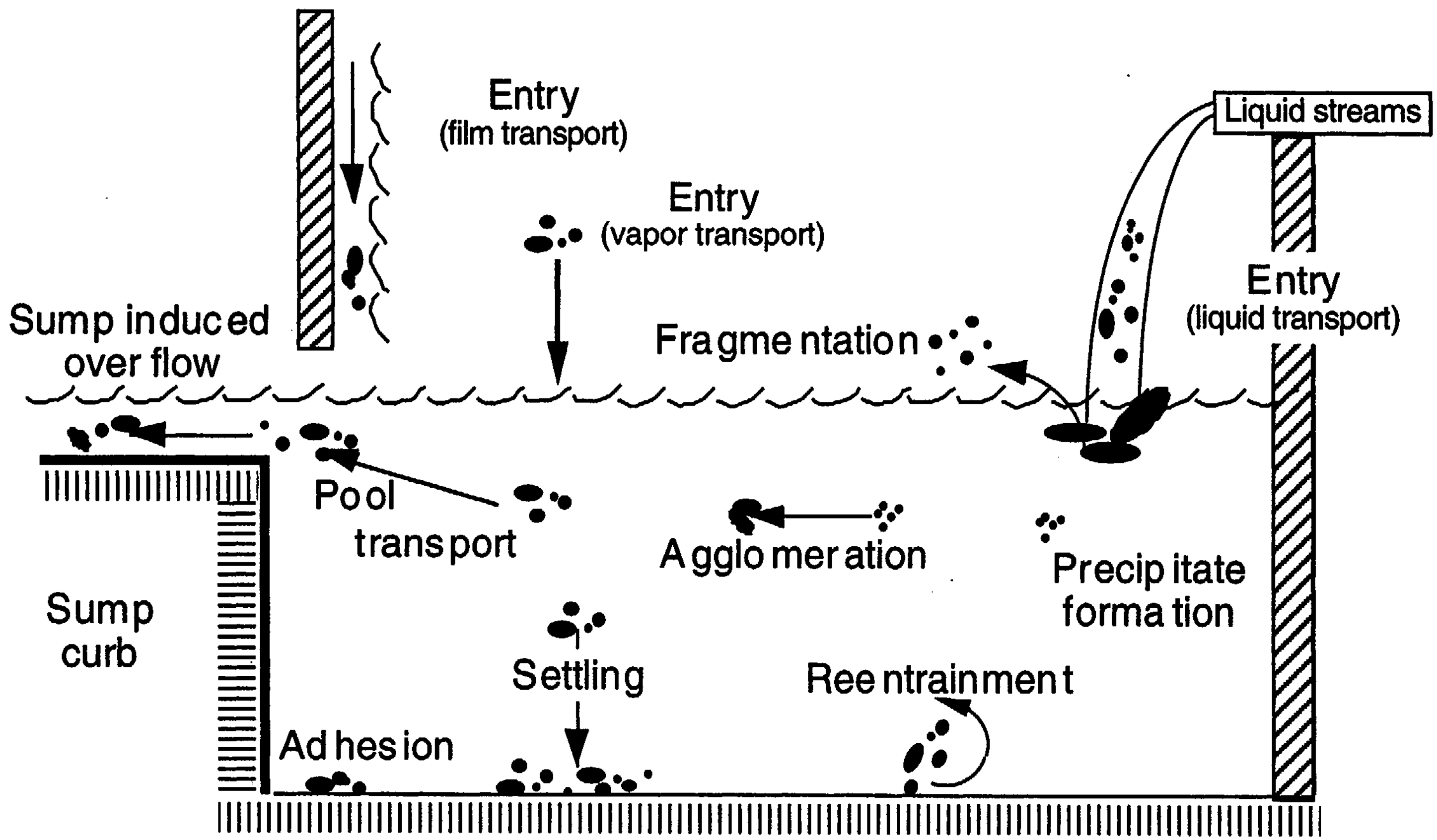

Fig. B-20. Transport/deposition processes for debris on the basemat floor during the sump-operation phase of a CL LBLOCA.

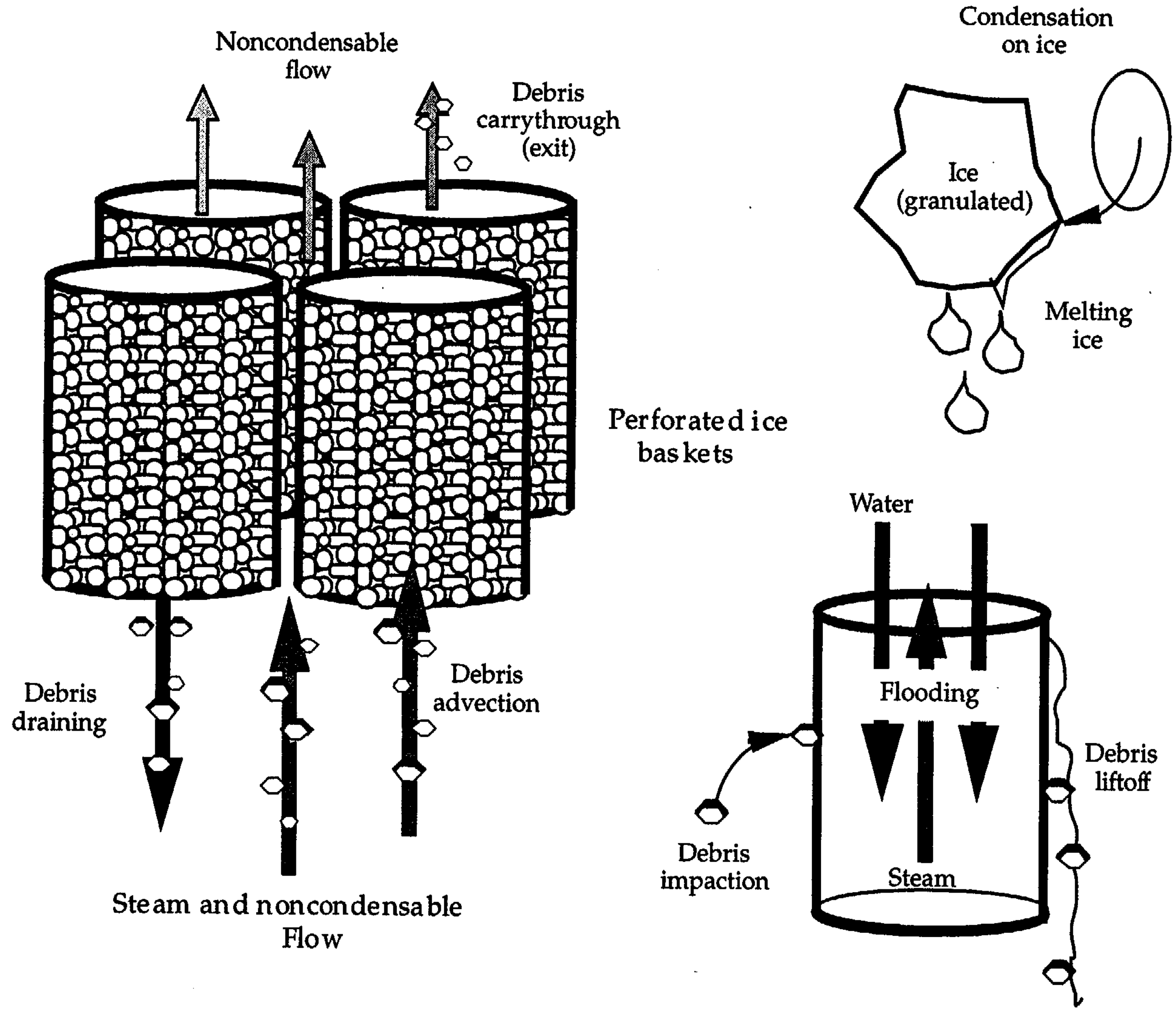

Fig. B-21. Ice-condenser processes during the sump-operation phase of a CL LBLOCA.

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 (p. 1 of 6)
(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)	All phenomena occurring in the containment upper compartment are judged to have little influence on debris transport during the blowdown phase of the accident. All or nearly all of the steam break flow is condensed in the ice condenser. Little or no transport of debris into the containment upper compartment is anticipated. Thus, there is little or no impact on debris movement or depletion during this phase.	B-1
P1-2	Fan-driven flows	See P1-1.	B-1
P1-3	Spray-induced flows	Sprays not activated during this phase.	B-1
P1-4	Circulating flows	See P1-1.	B-1
P1-5	Steam/noncondensable mixing	See P1-1.	B-1
P1-6	Localized flow field	See P1-1.	B-1
P1-7	Turbulence	See P1-1.	B-1
P1-8	Unflashed liquid flows	Break in lower compartment.	B-1
P1-9	Flashing of break liquid effluent	Break in lower compartment.	B-1
P1-10	Droplet interactions	See P1-1.	B-1
P1-11	Droplet formation via condensation	See P1-1.	B-1
P1-12	Condensation on structures	See P1-1.	B-1
P1-13	Film dynamics	See P1-1.	B-1
P1-14	Advection	See P1-1.	B-2
P1-15	Agglomeration	See P1-1.	B-2
P1-16	Sweepout	See P1-1.	B-2
P1-17	Gravitational settling	See P1-1.	B-2
P1-18	Condensation on particles	See P1-1.	B-2
P1-19	Stephan flow (diffusiophoresis)	See P1-1.	B-2

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

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-20	Thermophoresis	See P1-1.	B-2
P1-21	Pressure-driven flows (bulk flows)	Bulk flows have a dominant impact on movement of debris through containment lower compartment to ice condenser.	B-1
P1-22	Fan-driven flows	Created flow field is remote from the ZOI.	B-1
P1-23	Circulating flows	Secondary flows have only a minor effect on debris movement and depletion.	B-1
P1-24	Steam/noncondensable mixing	Little or no impact on debris movement or depletion during this phase.	B-1
P1-25	Localized flow field	Secondary flows through and around structures have only a minor effect on debris movement and depletion.	B-1
P1-26	Turbulence	Turbulent flows through and around structures have only a minor effect on debris movement and depletion.	B-1
P1-27	Unflashed liquid flows	Amount of liquid available to affect debris movement and depletion during this phase is small.	B-1
P1-28	Flashing of break liquid effluent	Little or no impact on debris movement or depletion during this phase.	B-1
P1-29	Droplet interactions	Little or no impact on debris movement or depletion during this phase.	B-1
P1-30	Droplet formation via condensation	Little or no impact on debris movement or depletion during this phase.	B-1
P1-31	Condensation on structures	Little or no impact on debris movement or depletion during this phase.	B-1
P1-32	Film dynamics	Little or no impact on debris movement or depletion during this phase.	B-1
P1-33	Advection	Can have a moderate influence on debris movement and/or depletion as debris is transported and distributed.	B-2

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

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-34	Agglomeration	Little agglomeration during period of high velocities and agitation.	B-2
P1-35	Entrapment	Moderate depletion mechanism during this phase for large and heavy debris. Debris is entrapped in the dead-ended annular space below the ice condenser.	B-2
P1-36	Gravitational settling	Moderate depletion mechanism during this phase for large and heavy debris given the strong steam flows in the confined open areas of the containment lower compartment.	B-2
P1-37	Condensation on particles	Little or no impact on debris movement or depletion during this phase.	B-2
P1-38	Stephan flow (diffusiophoresis)	Little or no impact on debris movement or depletion during this phase.	B-2
P1-39	Thermophoresis	Little or no impact on debris movement or depletion during this phase.	B-2
P1-40	Heat transfer	Little or no impact on debris movement or depletion during this phase.	B-3
P1-41	Film shear	Little or no impact on debris movement or depletion during this phase.	B-3
P1-42	Surface wetting (condensation, impact)	Debris impacting surfaces will not adhere unless the surface is wet.	B-3
P1-43	Film draining under gravity	Little or no impact on debris movement or depletion during this phase.	B-3
P1-44	Deluge (streaming)	Moderate impact on debris movement or depletion during this phase caused by ice melting and downward flow into the pool.	B-3
P1-45	Resuspension	Little or no impact on debris movement or depletion during this phase.	B-4
P1-46	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-4
P1-47	Deluge (streaming) transport	Moderate deluge flow during blowdown phase with both break flow and flow due to melting ice.	B-4
P1-48	Film transport	Little or no impact on debris movement or depletion during this phase.	B-4
P1-49	Runoff/reentrainment	Little or no impact on debris movement or depletion during this phase.	B-4
P1-50	Disintegration	Small amount of additional fragmentation outside the ZOI during this phase as debris is rapidly swept into ice condenser compartment.	B-2

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

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-51	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
P1-52	Turbulence-related impaction	Turbulent microscale effect is small for all debris types.	B-4
P1-53	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
P1-54	Pool formation	Little or no impact on debris movement or depletion during this phase.	B-5
P1-55	Heat transfer to structure	Little or no impact on debris movement or depletion during this phase.	B-5
P1-56	Pool agitation	This is the major phenomenon for determining whether the debris is suspended or settling, as well as contributing to fragmentation and erosion to varying degrees with the different debris types, Cal-Sil being the most sensitive to pool agitation.	B-5
P1-57	Pool dynamics	The importance of pool dynamics is the greatest when the pool depths are small and decreases as the pool depth increases. Dynamics such as recirculation contribute to keeping debris suspended longer.	B-5
P1-58	Entry via film transport	Primary process is transport via streams, not film drainage.	B-6
P1-59	Entry via vapor transport	Primary process is transport via streams, not film drainage.	B-6
P1-60	Entry via liquid transport	Dominant mechanism, with large liquid flows due to ice melt.	B-6
P1-61	Reentrainment	Moderate level of reentrainment by liquid flows from melting ice.	B-6
P1-62	Disintegration	Moderate amount of fibrous disintegration due to agitation but large amount of Cal-Sil disintegration due to material fragility.	B-6
P1-63	Pool transport	Short time frame with bulk movement to cavity, the cavity being a region of low velocity in the late stages of the phase.	B-6
P1-64	Agglomeration in pool	Little or no impact on debris movement or depletion during this phase.	B-6

Table C-1 (cont)
Ranking Rationales for PWR Debris Transport during Blowdown Phase PIRT (p. 5 of 6)
(Reference number relates to entry in Table 4-2 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-65	Adhesion	Little or no impact on debris movement or depletion during this phase.	B-6
P1-66	Settling	Little or no impact on debris movement or depletion during this phase.	B-6
P1-67	Impaction	Little or no impact on debris movement or depletion during this phase.	B-6
P1-68	Entrapment	Moderate amount of entrapment in low velocity regions or against obstacles is expected.	B-6
P1-69	Steam and noncondensable flow	Dominant directed flow, which moves large amount of debris from ZOI into space below ice condenser.	B-7
P1-70	Ice to liquid (melting)	Downward draining of water from the melted ice is the dominant mechanism for moving debris back into the water pool feeding the sump.	B-7
P1-71	Liquid draining (downward)	Will occur but is of moderate importance because water from condensed steam and ice melt will fall downward in any case; the details are not significant.	B-7
P1-72	Condensation	A dominant process for affecting debris distribution. Absent condensation, debris transport would continue in a steam environment and be more likely to be carried into the upper compartment from which it would be less likely to return to the sump. During this phase, essentially all steam is condensed, adding to the water source for downward transport in two ways: melting ice and the condensed liquid itself.	B-7
P1-73	Debris advection (into ice condenser)	Location of fiber, Cal-Sil, and RMI and the manner of transport is the dominant influence on its potential for ultimate transport to the sump.	B-7
P1-74	Debris suspension	Suspension is a transitory phenomenon but of moderate importance on fiber and Cal-Sil because suspended debris is more likely to drain downward than debris that is deposited on structures within the ice condenser. There is no influence on RMI.	None

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

Reference Number	Phenomena	Ranking Rationale	See Figure
P1-75	Debris draining (downward)	Dominant mechanism for returning fiber, Cal-Sil, and RMI to the lower containment areas where it can subsequently be transported to the sump.	B-7
P1-76	Debris carry through (exit)	Little debris of any type will be carried upward into the upper compartment; it will either be deposited in the ice condenser on the baskets or transported downward through the ice condenser into the water pool feeding the sump.	B-7
P1-77	Debris liftoff (interior)	Believed to be a minor contributor to debris transport of any type because little debris is expected to adhere to surfaces within the ice condenser.	B-7
P1-78	Debris deposition	Little debris of any type will be deposited on the ice condenser support structures (bottom of ice condenser and other structures) and will adhere.	B-7

Table C-2
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 1 of 7)
(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	All phenomena occurring in the containment upper compartment are judged to have little influence on debris transport during the post-blowdown phase of the accident. Little transport of debris into the containment upper compartment is anticipated. Thus, there is little or no impact on debris movement or depletion during this phase.	B-8
P2-2	Fan-driven flow	See P2-1.	B-8
P2-3	Spray-induced flow	See P2-1.	B-8
P2-4	Circulating flows	See P2-1.	B-8
P2-5	Localized flow field	See P2-1.	B-8
P2-6	Turbulence	See P2-1.	B-8
P2-7	Unflashed liquid flow	See P2-1.	B-8
P2-8	Falling condensate	See P2-1.	B-8
P2-9	Droplet motion	See P2-1.	B-8
P2-10	Condensation on structures	See P2-1.	B-8
P2-11	Advection	See P2-1.	B-9
P2-12	Agglomeration	See P2-1.	B-9
P2-13	Sweepout	See P2-1.	B-9
P2-14	Gravitational settling	See P2-1.	B-9
P2-15	Condensation on particles	See P2-1.	B-9
P2-16	Stephan flow (diffuseophoresis)	See P2-1.	B-9
P2-17	Thermophoresis	See P2-1.	B-9

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 2 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-18	Steam flow	Velocity decreasing; most of the debris subject to steam transport moved during the blowdown phase.	B-8
P2-19	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-8
P2-20	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-8
P2-21	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-8
P2-22	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-8
P2-23	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-8
P2-24	Unflashed liquid flow	Insignificant source of liquid for debris sweepout.	B-8
P2-25	Falling condensate	Insignificant source of liquid for debris sweepout.	B-8
P2-26	Droplet motion	Insignificant source of liquid for debris sweepout.	B-8
P2-27	Condensation on structures	Structures wetted during blowdown phase; little or no additional impact on debris movement or depletion during this phase.	B-8
P2-28	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-9

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 3 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-29	Agglomeration	Little or no impact on debris movement or depletion during this phase. Steam and noncondensable flows are the dominant mechanisms for removal of suspended debris from the containment atmosphere.	B-9
P2-30	Sweepout	Little debris sweepout expected in containment lower compartment because most debris was transported into the ice condenser and the sweepout flows, e.g., sprays in the upper compartment are local.	B-9
P2-31	Gravitational settling	Little debris settling expected in containment lower compartment because most debris was transported into the ice condenser and the sweepout flows, e.g., sprays in the upper compartment are local.	B-9
P2-32	Condensation on particles	Little impact on movement or depletion of fine debris during this phase. Steam and noncondensable flows are the dominant mechanisms for removal of suspended debris from the containment atmosphere.	B-9
P2-33	Stephan flow (diffuseophoresis)	Little or no impact on debris movement or depletion during this phase.	B-9
P2-34	Thermophoresis	Little or no impact on debris movement or depletion during this phase.	B-9
P2-35	Heat transfer	Little or no impact on debris movement or depletion during this phase.	B-10
P2-36	Film shear	Little or no impact on debris movement or depletion during this phase.	B-10
P2-37	Film draining under gravity	Little or no impact on debris movement or depletion during phase.	B-10
P2-38	Deluge (streaming)	Little or no impact on debris movement or depletion during this phase of any debris sources except Cal-Sil, which is subject to breakup as it enters areas of streaming and is impacted by the falling water.	B-10
P2-39	Condensation	Amount of liquid accumulating on surface through condensation is small relative to the amount of liquid deposited by the containment sprays.	B-10
P2-40	Resuspension into flow stream	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 (p. 4 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-41	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-11
P2-42	Deluge transport	Little or no impact on debris movement or depletion during this phase of any debris sources except Cal-Sil, which is subject to breakup as it enters areas of streaming and is impacted by the falling water.	B-11
P2-43	Film-related transport	A small amount of debris may be on vertical surfaces and subject to transport.	B-11
P2-44	Runoff/reentrainment	Little or no impact on debris movement or depletion during this phase.	B-11
P2-45	Disintegration	Little or no impact on debris movement or depletion during this phase of any debris sources except Cal-Sil, which is subject to both erosion and fragmentation by any stressing action.	B-11
P2-46	Entrapment	Little debris depletion by settling on horizontal surfaces in areas where either stagnant or low velocity liquid resides.	B-11
P2-47	Inertial impaction	Little or no impact on debris movement or depletion during this phase.	B-11
P2-48	Turbulence impaction	Little or no impact on debris movement or depletion during this phase.	B-11
P2-49	Adhesion	Adhesion to structures in the containment during the process of liquid transport to lower levels is a depletion mechanism of little importance.	B-11
P2-50	Pool formation	Liquid approaching the containment floor in discrete streams creates the pool and has a moderate influence on the distribution of debris in the pool.	B-12
P2-51	Heat transfer to structure	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 (p. 5 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-52	Pool agitation	This is the major phenomenon for determining whether the debris is suspended or settling, as well as contributing to fragmentation and erosion to varying degrees with the different debris types, Cal-Sil being the most sensitive to pool agitation.	B-12
P2-53	Pool flow dynamics	The importance of pool dynamics is the greatest when the pool depths are small and decreases as the pool depth increases. Dynamics such as recirculation contribute to keeping debris suspended longer. The impact is moderate on all debris except for Cal-Sil, which disintegrates when moved.	B-12
P2-54	Entry via film transport	Minor 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.	B-13
P2-55	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-13
P2-56	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-13
P2-57	Reentrainment	May be some reentrainment when pool depth is small, but little is expected when pool height is greater.	B-13
P2-58	Disintegration	Fibrous: Little or no impact on debris movement or depletion during this phase. Cal-Sil: Pieces will disintegrate in water pools, stay in suspension longer, and become more transportable. Other: Little or no impact on debris movement or depletion during this phase.	B-13

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 6 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-59	Pool transport	Dominant mechanism for debris transport within the pool. During this phase the sump is not operating so the dominant importance relates to the movement of debris within the sump ZOI. The movement can be toward or away from the sump.	B-13
P2-60	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-13
P2-61	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-13
P2-62	Settling	Dominant mechanism for debris depletion during this phase. Smaller sizes of fibrous debris may remain suspended as will Cal-Sil. RMI will settle out, as will other debris.	B-13
P2-63	Entrapment	Moderate debris depletion by settling on horizontal surfaces in areas where either stagnant or low velocity liquid resides.	B-13
P2-64	Steam and noncondensable flow	During post-blowdown phase, the quantity of steam released from the break is much reduced compared with the blowdown phase. This steam moves to the ice condenser where it is condensed but has little potential to move debris.	B-14
P2-65	Ice to liquid (melting)	During post-blowdown phase, the quantity of steam released from the break is much reduced compared with the blowdown phase. All of the steam is condensed to water and continues to melt ice with the downward flow of water, which can potentially wash any debris remaining in the ice condenser into the pool in the containment lower compartment. The water thus generated does contribute to pool agitation as it drains into the pool and is, therefore, of moderate importance.	B-14
P2-66	Liquid draining (downward)	Will occur but is of little importance because water from condensed steam and ice melt (reduced in amount by the post-blowdown phase) will fall downward in any case; the details are not significant.	B-14

Table C-2 (cont)
Ranking Rationales for PWR Debris Transport during Post-Blowdown Phase PIRT (p. 7 of 7)
(Reference number relates to entry in Table 4-3 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P2-67	Condensation	See P2-65.	B-14
P2-68	Debris advection (into ice condenser)	Transport of debris into the ice condenser during this phase is not anticipated.	B-14
P2-69	Debris suspension	Suspension of debris within the ice condenser by upward flowing steam and noncondensables during this phase is not anticipated for any debris type.	B-14
P2-70	Debris draining (downward)	The potential for downward transport of any remaining debris of any insulation type (fibrous, Cal-Sil, reflective metallic, or other) is low because the majority of the debris was returned to the pool during the blowdown phase.	B-14
P2-71	Debris carry through (exit)	The transport of debris into the ice condenser is not anticipated; therefore, the carry through of debris to the ice condenser is likewise not anticipated.	B-14
P2-72	Debris liftoff (interior)	The potential for liftoff of any remaining debris of any insulation type (fibrous, Cal-Sil, reflective metallic, or other) is low because the majority of the debris was returned to the pool during the blowdown phase and the water flows were greater during the blowdown phase.	B-14
P2-73	Debris deposition (interior)	Transport of debris into the ice condenser during this phase is not anticipated; therefore, deposition of debris within the ice condenser is likewise not anticipated.	B-14

Table C-3
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 1 of 7)
(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	All phenomena occurring in the containment upper compartment are judged to have little influence on debris transport during the sump operation phase of the accident. The sprays are operating and water is draining through drain holes to the lower compartment. There is little or no impact on debris movement or depletion during this phase.	B-15
P3-2	Fan-driven flow	See P3-1.	B-15
P3-3	Spray-induced flow	See P3-1.	B-15
P3-4	Circulating flows	See P3-1.	B-15
P3-5	Localized flow field	See P3-1.	B-15
P3-6	Turbulence	See P3-1.	B-15
P3-7	Unflashed liquid flow	See P3-1.	B-15
P3-8	Falling condensate	See P3-1.	B-15
P3-9	Droplet motion	See P3-1.	B-15
P3-10	Condensation on structures	See P3-1.	B-15
P3-11	Advection	See P3-1.	B-16
P3-12	Agglomeration	See P3-1.	B-16
P3-13	Sweepout	See P3-1.	B-16
P3-14	Gravitational settling	See P3-1.	B-16
P3-15	Condensation on particles	See P3-1.	B-16
P3-16	Stephan flow (diffuseophoresis)	See P3-1.	B-16
P3-17	Thermophoresis	See P3-1.	B-16

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 2 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-18	Steam flow	Velocity decreasing; most of the debris subject to steam transport moved during the blowdown phase.	B-15
P3-19	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-15
P3-20	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-15
P3-21	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-15
P3-22	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-15
P3-23	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-15
P3-24	Unflashed liquid flow	Insignificant source of liquid for debris sweepout.	B-15
P3-25	Falling condensate	Insignificant source of liquid for debris sweepout.	B-15
P3-26	Droplet motion	Insignificant source of liquid for debris sweepout.	B-15
P3-27	Condensation on structures	Structures wetted during blowdown phase; little or no additional impact on debris movement or depletion during this phase.	B-15
P3-28	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-16

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 3 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-29	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-16
P3-30	Sweepout	Little or no impact on debris movement or depletion during this phase.	B-16
P3-31	Gravitational settling	Little debris settling expected in containment lower compartment because most debris was transported into the ice condenser and the sweepout flows, e.g., sprays in the upper compartment are local.	B-16
P3-32	Condensation on particles	Little or no impact on debris movement or depletion during this phase.	B-16
P3-33	Stephan flow (diffuseophoresis)	Little or no impact on debris movement or depletion during this phase.	B-16
P3-34	Thermophoresis	Little or no impact on debris movement or depletion during this phase.	B-16
P3-35	Heat transfer	Little or no impact on debris movement or depletion during this phase.	B-17
P3-36	Film shear	Little or no impact on debris movement or depletion during this phase.	B-17
P3-37	Film draining under gravity	Little or no impact on debris movement or depletion during phase.	B-17
P3-38	Deluge (streaming)	Little or no impact on debris movement or depletion during this phase on any debris sources	B-17
P3-39	Condensation	Amount of liquid accumulating on surface through condensation is small relative to the amount of liquid deposited by the containment sprays.	B-17
P3-40	Resuspension into flow stream	Little or no impact on debris movement or depletion during this phase.	B-18

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 4 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-41	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-18
P3-42	Deluge transport	Little or no impact on debris movement or depletion during this phase for any of the debris types.	B-18
P3-43	Film-related transport	Little or no impact on debris movement or depletion during this phase.	B-18
P3-44	Runoff/reentrainment	Little or no impact on debris movement or depletion during this phase.	B-18
P3-45	Disintegration	Little or no impact on debris movement or depletion during this phase of any debris sources except Cal-Sil, which is subject to both erosion and fragmentation by any stressing action.	B-18
P3-46	Entrapment	Little or no impact on debris movement or depletion during this phase.	B-18
P3-47	Inertial impaction	Little or no impact on debris movement or depletion during this phase.	B-18
P3-48	Turbulence impaction	Little or no impact on debris movement or depletion during this phase.	B-18
P3-49	Adhesion	Little or no impact on debris movement or depletion during this phase.	B-18
P3-50	Pool formation	Liquid approaching the containment floor in discrete streams creates the pool but has less influence on the distribution of debris in the pool than during previous phases.	B-19
P3-51	Heat transfer to structure	Little or no impact on debris movement or depletion during this phase.	B-19

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 5 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-52	Pool agitation	This is the major phenomenon for determining whether the debris is suspended or settling, as well as contributing to fragmentation and erosion to varying degrees with the different debris types, Cal-Sil being the most sensitive to pool agitation.	B-19
P3-53	Pool flow dynamics	The importance of pool dynamics is the greatest when the pool depths are small and decreases as the pool depth increases. Dynamics such as recirculation contribute to keeping debris suspended longer.	B-19
P3-54	Sump-induced flow	Dominant process for transport of debris to the sump from remote regions.	B-19
P3-55	Entry via film transport	Little or no impact on debris movement or depletion during this phase.	B-20
P3-56	Entry via vapor transport	Little or no impact on debris movement or depletion during this phase.	B-20
P3-57	Entry via liquid transport	Little or no impact on debris movement or depletion during this phase.	B-20
P3-58	Reentrainment	Once the sump pumps begin to operate, debris residing within some region of influence near the sump 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-20
P3-59	Disintegration	Fibrous: Little or no impact on debris movement or depletion during this phase. Cal-Sil: Moderate impact as this debris will disintegrate in water pools, stay in suspension longer and become more transportable. Much of this behavior is expected to have occurred earlier. Other: Little or no impact on debris movement or depletion during this phase.	B-20

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 6 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-60	Pool transport	Dominant mechanism for transport of any debris type within the pool caused by operation of the sump pumps.	B-20
P3-61	Sump-induced overflow	Dominant mechanism for debris transport into the sump.	B-20
P3-62	Agglomeration	Little or no impact on debris movement or depletion during this phase.	B-20
P3-63	Adhesion	Moderately important where the horizontal flow velocity in the pool at the containment floor is small and adhesion is sufficiently strong as to retain debris in place on the floor.	B-20
P3-64	Settling	Moderate mechanism for debris depletion during this phase. Smaller sizes of fibrous debris may remain suspended, as will Cal-Sil. RMI will settle out, as will other debris.	B-20
P3-65	Precipitate formation	Precipitate has potential for remaining suspended for extended periods of time. If transported to the sump, it has the potential for filling the voids in fibrous but partial blockages.	None
P3-66	Entrapment	The amount of precipitate formed during the interval defined by the 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.	None
P3-67	Steam and noncondensable flow	During the sump operation phase, the quantity of steam released from the break continues to decrease with the decay heat. This steam moves to the ice condenser until the ice is melted at about 2 h. The steam is condensed but has little potential to move debris.	B-21
P3-68	Ice to liquid (melting)	The remainder of the ice in the ice condenser is melted by approximately 2 h. Little or no impact on debris movement or depletion during this phase.	B-21

Table C-3 (cont)
Ranking Rationales for PWR Debris Transport during Sump-Operation Phase PIRT (p. 7 of 7)
(Reference number relates to entry in Table 4-4 in the report main body)

Reference Number	Phenomena	Ranking Rationale	See Figure
P3-69	Liquid draining (downward)	Little or no impact on debris movement or depletion during this phase.	B-21
P3-70	Condensation	Little or no impact on debris movement or depletion during this phase.	B-21
P3-71	Debris advection (into ice condenser)	Transport of debris into the ice condenser during this phase is not anticipated.	B-21
P3-72	Debris suspension	Suspension of debris within the ice condenser by upward flowing steam and noncondensables during this phase is not anticipated for any debris type.	None
P3-73	Debris draining (downward)	The potential for downward transport of any remaining debris of any insulation type (fibrous, Cal-Sil, reflective metallic, or other) is low because the majority of the debris was returned to the pool during the blowdown phase.	B-21
P3-74	Debris carry through (exit)	The transport of debris into the ice condenser is not anticipated; therefore, the carry through of debris to the ice condenser is likewise not anticipated.	B-21
P3-75	Debris liftoff (interior)	The potential for liftoff of any remaining debris of any insulation type (fibrous, Cal-Sil, reflective metallic, or other) is low because the majority of the debris was returned to the pool during the blowdown phase, and the water flows were greater during the blowdown phase.	B-21
P3-76	Debris deposition (interior)	Transport of debris into the ice condenser during this phase is not anticipated; therefore, deposition of debris within the ice condenser is likewise not anticipated.	B-21