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FINAL REPORT
BWR Drywell Debris Transport Phenomena Identification and Ranking Tables (PIRTs)

Gary E. Wilson (INEEL, Project Coordinator)
Brent E. Boyack (LANL)
Mark T. Leonard (ITSC)
Ken A. Williams (FSSI)
Lothar T. Wolf (UMCP)

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Idaho National Engineering and Environmental Laboratory
Nuclear Systems Analysis Technologies Department
Lockheed Martin Idaho Technologies Company
Idaho Falls, Idaho 83415

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Abstract

The Nuclear Regulatory Commission has issued a Regulatory Bulletin and accompanying Regulatory Guide (1.82, Rev. 2) which requires licensees of boiling water reactors to develop a specific plan of action (including hardware backfits, if necessary) to preclude the possibility of early emergency core cooling system strainer blockage following a postulated loss-of-coolant-accident. The postulated mechanism for strainer blockage is destruction of piping insulation in the vicinity of the break and subsequent transport of fragmented insulation to the wetwell. In the absence of more definitive information, the Regulatory Guide recommends that licensees assume a drywell debris transport fraction of 1.0. Accordingly, the Nuclear Regulatory Commission initiated research focused toward developing a technical basis to provide insights useful to regulatory oversight of licensee submittals associated with resolution of the postulated strainer blockage issue. Part of this program was directed towards experimental and analytical research leading to a more realistic specification of the debris transport through the drywell to the wetwell. To help focus this development into a cost effective effort, a panel, with broad based knowledge and experience, was formed to address the relative importance of the various phenomena that can be expected in plant response to postulated accidents that may produce strainer blockage. The resulting phenomena identification and ranking tables reported herein were used to help guide research. The phenomena occurring in boiling water reactors drywells was the specific focus of the panel, although supporting experimental data and calculations of debris transport fractions were considered.

FIN No. W6662 - PIRT Evaluation of LOCA Debris Transport Within a BWR Drywell

Executive Summary

The NRC has issued a Regulatory Bulletin and accompanying Regulatory Guide (1.82, Rev. 2) which requires licensees of BWRs to develop a specific plan of action (including hardware backfits, if necessary) to preclude the possibility of early ECCS strainer blockage following a postulated LOCA. In the absence of more definitive information, the Regulatory Guide recommends that licensees assume a drywell debris transport fraction of 1.0. Accordingly, the NRC initiated research focused toward developing a technical basis to provide insights useful to regulatory oversight of licensee submittals associated with resolution of the postulated strainer blockage issue. Part of this program was directed toward experimental and analytical research to help determine a more realistic specification of the debris transport through the drywell to the wetwell. To help focus this development, a panel, with broad based knowledge and experience, was formed to apply the PIRT process to the transport of break-generated debris through BWR drywells. The first phase of the PIRT project, executed in April-May 1996, was focused toward timely development of initial PIRTs to guide the on-going research. The second and third phases, executed in August 1996 - February 1997, consisted primarily of panel evaluation of the planned experimental effort, and preliminary experimental results. The fourth phase, completed in July 1997, focused on panel review of the final research results in the context of updating the PIRTs based on the new experimental and analytical evidence. Those findings are the primary subject of this <u>final</u> report.

The PIRTs developed by the panel were used to help guide the experimental and analytical research. The early PIRTs have been updated to reflect the new research results. The highly important phenomena from the updated tables are summarized on the next page by drywell location (component), general phenomena type, and time in the transient (blowdown phase and post blowdown phase). Tables 1 and 2 in the body of the report list the full, and final, PIRTs developed by the panel.

Accident scenario and plant design selections are an important part of the PIRT process. Given the combinations of break locations and containment types, a large number of scenarios are possible. Initially the panel focused on a single break type (high elevation main steam line break), a single containment type (Mark I), and no containment spray. However, obvious differences in phenomena importance in a recirculation line break low in the drywell, and in the other two containment designs, were also identified. Thus, the final PIRTs reported herein address both scenarios and all three containment designs, to the extent allowed by the final experimental and analytical evidence.

In the process of reviewing the new experimental and analytical evidence, the panel formulated several observations regarding the total research program. These "insights" are also documented as part of this report, as a secondary objective of the panel efforts. The more important of these follow immediately below in two main topics: 1) Methodology to synthesize research, and 2) Lessons learned regarding the PIRT process.

1) Methodology to synthesize research results into a basis to judge licensee submittals:
   a) The panel believes the structure of the methodology:
      - Will provide a rational technical basis for the desired licensing reviews
      - Is sufficiently flexible that new evidence and assumptions, related to debris size and distribution, can quickly be accommodated to provide a basis for submittal evaluations not covered at the time this report was issued

BWR drywell debris transport highly important phenomena

Component	Phenomenon type	Phenomenon	Highest of the highly ranked phenomena ①
Blowdown phase			
Drywell open areas	Thermal hydraulic related	Pressure driven flows (bulk flows)	✓
		Localized flow field	✓
		Flashing of break liquid effluent ②	✓
	Debris transport & depletion related	Advection/slip	✓
Drywell structures	Thermal hydraulic related	Porosity	✓
		Recirculation (streaming) deluge	✓
	Debris transport & depletion related	Recirculation deluge (streaming) related transport ②	✓
		Impaction	✓
		Adhesion	✓
Drywell floor	Thermal hydraulic related	Pool formation ②	✓
		Pool overflow (timing issue this phase) ②	✓
		Pool flow dynamics ②	
	Debris transport & depletion related	Pool transport (to/through vent) ②	✓
		Settling ②	
Post-blown down phase			
Drywell structures	Thermal hydraulic related	ECCS deluge	
	Debris transport & depletion related	ECCS deluge	
Drywell floor	Thermal hydraulic related	Pool overflow	
		Pool formation	
		Pool flow dynamics ③	✓
	Debris transport & depletion related	Pool transport (to/toward vent) ③	✓
		Settling	

Notes: ① All phenomena listed in the table are of high importance. However, those indicated by a check mark (✓) are the "highest of the high".
② Applies only to the recirculation line break.
③ Applies only in the case of drywell overflow to vent.

b) The panel finds the methodology attractive in that it:
- Clearly delineates important phenomena in the BWR drywell
- Readily incorporates, and links, both experimental and analytical results
- Is comprehensible to engineers having less experience in the subject of interest

c) With respect to the current application of the methodology, the panel perceives the following potential weaknesses [see Section 3.2-3)]:
- The rationale for upper bounds on the transport fraction needs to be strengthened. This perception is related to the the treatment of the upper and lower bounds, and the desirability of additional validation related to the character (size and distribution) of the generated debris.

- The basis for the applied flow velocities in the ARL and CEESI experiments needs strengthened. That is, their applicability to prototypical plant conditions needs to be more strongly demonstrated by a consistent scaling approach [Section .
- The experimental data base for the behavior (including ECCS erosion) of large debris on gratings is considered incomplete. In some part this is related to the above item.
- The data base for the recirculation line LOCA is considered to be too small given the relative importance of that transient and its consequences.

2) Lessons learned regarding the PIRT process:
   a) The generic PIRT process was readily adapted to the needs of the program and proved to be an effective method to organize a highly complex problem into tractable subparts. Consequently, the results were used in planning and conducting the continuing research.
   b) Comparison of the final PIRTs with the initial PIRTs tends to further validate the effectiveness of using independent teams, having collective broad based knowledge, early in research programs addressing new problems, as illustrated by the following:
      - No new phenomena were identified
      - One phenomenon rank moved from moderate to high rank, based on new evidence (i.e., surface wetting during the blowdown phase)
      - In two cases the ranks of related phenomenon effects moved from low to high (i.e., ECCS deluge influence on thermal hydraulics and on debris transport during the post-blowdown phase)
      - Three phenomenon ranks moved from high importance to highest importance (i.e., pool formation, pool overflow and pool transport to/through the vent during the blowdown phase)
      - Although the ranks of several phenomena were increased, the most noticeable trend between the initial and final PIRTs was the decrease in phenomena importance. This validates the built-in rule in the process, that in the absence of evidence, the team is to initially rank phenomena at their highest conceivable rank until further evidence is acquired as to the more realistic rank.

Acknowledgments

Several organizations and individuals were most helpful in the PIRT panel efforts. Although the panel was charted for, and carefully maintained, an independent and separate perspective, the panel acknowledges the aid from:

- Aleck Serkiz (NRC-RES), Michael Marshall, Jr. (NRC-RES) and Robert Elliot (NRC-NRR) for their help in facilitating the panel's increased understanding of the NRC research and licensing needs and objectives.
- DV Rao and Clint Shaffer (SEA) for their help in the panel's understanding of the experimental and analytical research conducted by SEA and ARL. The panel also acknowledges SEA and all of the associated staff for providing the facilities and other aid for the panel meetings.

Mark T. Leonard (ITSC), one of the listed authors of this report, served on the panel from its inception until October 1996. Because of other responsibilities, Mr. Leonard no longer served on the panel after that time. The remaining panel members acknowledge Mr. Leonard's significant contributions to the early work.

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Nomenclature

AHP	Analytical Hierarchy Process
ARL	Alden Research Laboratory, Inc.
BWR	Boiling Water Reactor
BWROG	BWR Owner's Group
CEESI	Colorado Engineering Experimental Station, Inc.
CFD	Computational Fluid Dynamics
DOE	US Department of Energy
ECCS	Emergency Core Cooling Systems
FSSI	Flow Simulation Services, Inc.
INEEL	Idaho National Engineering and Environmental Laboratory
ITSC	Innovative Technology Solutions Corporation
LANL	Los Alamos National Laboratory
LB	Large Break
LOCA	Loss of Coolant Accident
MB	Medium Break
MSLB	Main Steam Line Break
NPP	Nuclear Power Plant
NPSH	Net Pump Suction Head
NRC	US Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
PIRT	Phenomena identification and ranking table
RES	Office of Nuclear Regulatory Research
RHR	Residual Heat Removal
SEA	Science & Engineering Associates, Inc.
UMCP	University of Maryland, College Park

FINAL REPORT
BWR Drywell Debris Transport
Phenomena Identification and Ranking Tables (PIRT)

1. Introduction

1.1 Background

The NRC has issued a Regulatory Bulletin and accompanying Regulatory Guide (1.82, Rev. 2)[1] which requires licensees of BWRs to develop a specific plan of action (including hardware backfits, if necessary) to preclude the possibility of early ECCS strainer blockage following a postulated LOCA. The postulated mechanism for strainer blockage is destruction of piping insulation in the vicinity of the break and subsequent transport of fragmented insulation to the wetwell. In the absence of experimental data and analytical results, demonstrating significant retention of debris in the drywell, the Regulatory Guide recommends that licensees assume 100% of debris, generated as a consequence of the LOCA, is transported from the drywell to the suppression pool. The current recommendation to use a drywell debris transport fraction of 1.0 can pose significant design impacts for some licensees.

A review of incidents that have occurred to date indicate two general categories of ECCS strainer blockage mechanisms. One (an incident in the Barsebäck plant in Sweden involving the spurious opening of a safety valve) involves debris generation in the drywell due to blast effects of high-velocity coolant discharge from the primary coolant system onto piping insulation. Similar effects are expected if a pipe running through the drywell should rupture. Transport of fibrous debris to, and collected on, ECCS strainers reduces NPSH and degrades pump performance. The second category are US incidents in which degraded RHR pump performance was observed as a consequence of pre-existing debris and sludge in the suppression pool collecting on ECCS strainers. This category has already been addressed through a separate NRC bulletin which requested periodic cleaning of BWR suppression pools.

Characterization of the debris and amount generated as a consequence of a LOCA in a BWR drywell was addressed through an experimental program supported by the BWROG. Information from the NRC research[2] (including those informally documented efforts given in Appendix C), and to a limited extent from the BWROG work, constitutes the baseline for the PIRT project described herein.

1.2 Objectives

1.2.1 USNRC BWR Debris Transport Research

The primary objective of the NRC research program was to identify analytical methods and experimental evidence, and thereby develop a rational framework for evaluation of licensee submittals related to mitigation of strainer blockages.

1.2.2. PIRT Project

The primary objectives[3] of the project for the PIRT panel were to:

1) Use the PIRT process to identify phenomena and to rank their importance as related to transport of LOCA-generated debris within US BWR drywells,
2) Use the PIRT tables to advise the NRC staff in the analysis of BWR drywell debris transport, from the perspectives of phenomena modeling and identification of present computer codes best suited for such analyses. This initial objective was subsequently expanded to include experimental aspects associated with the overall NRC research objective in Section 1.2.1 above,
3) Advise the NRC staff regarding potential methods to characterize the estimated uncertainties in code predictions and the application of calculations to predict actual plant behavior, and
4) Advise the NRC staff regarding the panel's views about the success expectancy for the experimental and analytical approaches presented to the panel.

These objectives were achieved through a four-phase approach. The first phase was focused toward timely development of initial PIRTs to guide the on-going experimental and analytical methodology development[3, 4]. The second phase consisted of panel review and evaluation of the planned experimental program[5]. The third phase consisted of review of the preliminary experimental program results by one panel member, and reporting of his evaluation to the other panel members and the NRC[6]. The fourth and final phase, reported here, consisted of full panel review and evaluation of the final research results. The primary objective of the final phase was to update the initial PIRTs based on the new experimental and analytical evidence. A secondary objective was to provide the panel's observations and insights for the total research program.

1.3 Report Structure

The primary topic of interest, the PIRTs, are provided in Tables 1 - 2 in Section 2. The highly ranked phenomena, extracted from these tables, are also summarized in the Executive Summary. The base conditions for which the PIRTs were developed are also provided in Section 2, in subsections preceding the tables. Phenomena descriptions and ranking rationales (as referenced in Tables 1 - 2) are provided, respectively in Appendices A and B. Details of the PIRT panel insights regarding the PIRTs, the debris transport related research, and other aspects of the strainer blockage issue are given in Section 3. These results are also summarized in general order of importance in the Executive Summary. Documents more directly related to the PIRT development are referenced throughout the report and identified in Section 4. Other sources of information that completed the general information base available to the panel, or developed in association with panel meetings, are summarized in Appendix C.

2. BWR Drywell Debris Transport PIRTs

2.1 PIRT Process Overview

The information obtained through the application of the PIRT process[7, 8, 9] identifies the requirements which will be imposed on research supporting experiments and/or analytical tools used to simulate accident scenarios. In addition, those requirements are prioritized with respect to their contributions to the reactor phenomenological response to the accident scenario. Because it is not 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 which dominate the transient behavior, although all plausible effects are considered. This screening of plausible phenomena, to determine those which 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. This also adds to the efficiency and generality of the process.

A typical application of the PIRT process is conceptually illustrated in Figure 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 NPP (i.e., those that drive events). Plausible physical phenomena and processes, and their associated system components are identified. From a modeling perspective, phenomena/processes important to a plant response to an accident scenario can be grouped in two separate categories:
1) Higher level system interactions (integral) between components/subsystems , and
2) Those local (within) to 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. Often time can be saved when it can be demonstrated a higher level integral system process is of

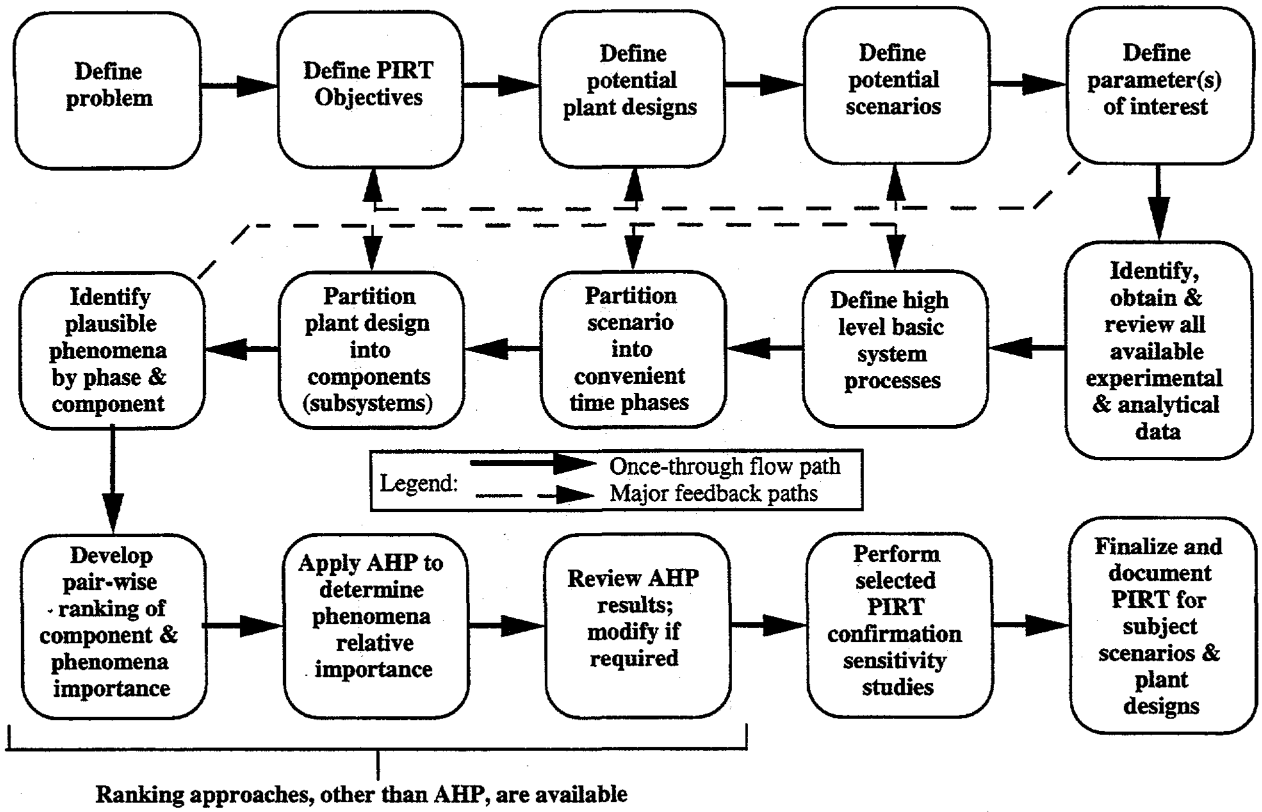

Figure 1. Illustration of typical PIRT process.

low importance during a specific time phase. A subsequent and equally important step is the partitioning of the plant into components/subsystems. This latter step is a significant aid in organizing and ranking phenomena/processes. The phenomena/processes are then ranked with respect to their influence on the primary evaluation criteria, to establish PIRTs. Primary evaluation criteria (or criterion) are normally based on regulatory safety requirements such as those related to restrictions in fuel rods (peak clad temperature, hydrogen generation, etc.) and/or 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 are time dependent as an accident progresses. Thus, it is convenient to partition accident scenarios into time phases in which the dominant phenomena/processes remain essentially constant; each phase is separately investigated. The processes and phenomena associated with each component are examined as are the inter-relations between the components. Cause and effect are differentiated. The processes and phenomena and their respective importance (rank) are judged by examination of experimental data, code simulations related to the plant and scenario, and the collective expertise and experience of the evaluation team. Independent techniques to accomplish the ranking include expert opinion , subjective decision making methods (such as the Analytical Hierarchy Process), and selected calculations. The final product of application of the PIRT process is a set of tables (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 drywell debris transport, the primary elements of interest are described in Sections 2.2 through 2.8. The PIRTs resulting from this specific application are documented in Section 2.9.

2.2 Primary Parameter of Interest

This is the criterion that was defined and used to judge the relative importance of the phenomena/processes important to drywell debris transport. For the present PIRT endeavor, it was obvious that this parameter must be *the fraction of debris mass generated within the "break region"* *that is transported to the wetwell vent entrance*.

2.3 Plant Design(s) Considered

For US BWRs there are three different containment types: Mark I, Mark II and Mark III. There are a total of 37 BWR plants of which 23 have a Mark I design. It was determined that the best approach for the initial PIRT exercise was to focus first on a Mark I design because of its unique features, and then highlight differences expected to impact the other two containment designs. In summary, the approach was to develop a "generic" PIRT that is common to all three designs, but containing "exception" statements that are design specific.

2.4 Accident Scenario(s) Considered

Considerable effort has been given to specifying volumetric debris generation depending on various scenarios (LBLOCA, MBLOCA, steam and recirculation line break, etc.) in NUREG/CR-6224[2]. This study further included the failure probability of numerous weld locations, various elevations, and numerous systems piping. These results concluded that this "spectrum of breaks" can lead to a large variation in volume of debris generated; namely varying from 2 to over 112 ft^3 of debris. Thus, the specific accident scenario considered may have some effect on the relative importance of some phenomena. To accommodate this variable within the time constraints available to complete the PIRT, the panel agreed to consider the following scenario as the primary basis for ranking phenomena:

- Large LOCA: The objective was to base the PIRT on a bounding accident scenario (in terms of debris generation). Primary consideration was given to a steam line break, but major differences in recirculation line breaks were also recognized to account for break effluent fluid conditions.
- Full-power operation at the time of break initiation.

Again the initial approach was to develop a "generic" PIRT with respect to the different scenario conditions, but containing "exception" statements that are scenario dependent.

2.5 Partitioning of Drywell into Components

The panel was fortunate that prior work[2] provided a consistent framework for partitioning the drywell into the four components pictorially illustrated in Figure 2 and described below:

- Open area: The free flow area, excluding the potential pool in the bottom of the drywell and the debris-generating zone-of-influence in the vicinity of the break.
- Structures: All solid boundaries and barriers to the flow stream, including drywell walls, pipes, cabinets, walls, grates, etc.
- Floor: That area where a potential, essentially liquid, pool may form in the lower drywell elevations.
- Vent entrance: The inlet area of the vent where significant interactions with the open area and/or floor components may take place.

Boundary conditions - Based on discussions related to the opinion that break flow was adequately characterized by the proposed methodology, and that the development of debris generation models was already well focused, it was determined these sources were best characterized as boundary conditions to the PIRT work. Therefore, there was no need to define components for these regions. That is, the PIRT process did not give consideration to primary coolant break flow, determination of a representative debris “size distribution”, or other characteristics of the debris source. Debris characterization was an assumed input boundary condition. However, the influence of break flow and debris characterization on the PIRT components (i.e., interactions) was considered[1]. Similarly, existing information related to suppression pool behavior, constituted the vent exit boundary conditions for the PIRT development.

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[1] It should be noted that the panel did not necessarily agree that debris generation and characterization is a closed issue from the perspective of the overall research. However, in the absence of a definitive characterization of the debris source for particular accident scenarios, it was agreed that the PIRT development could better proceed by considering these elements as boundary conditions.

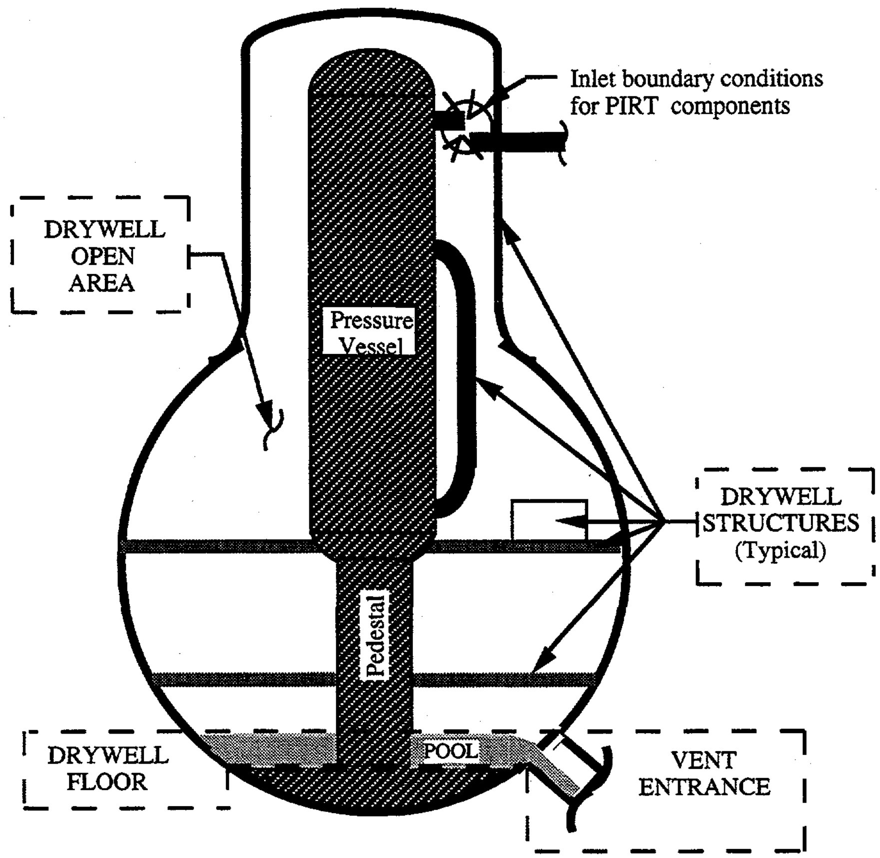

Figure 2. Component partitioning of drywell.

2.6 Partitioning of Scenario into Time Phases

Again prior work[2] provided a clear resolution to this objective:

- Blowdown: From break initiation through that point where the initial, dynamic, high energy nature of the break flow has decayed to essentially constant conditions (≈ 0 to 100 s for LBLOCA). The specific time at which this phase terminates increases with decreasing break size.
- Post-blowdown: End of blowdown to that point in time when debris transport has become essentially insignificant (≈ 30 min for LBLOCA). The boundary between blowdown and this phase included the specification that debris washdown by containment sprays, if present, was contained in the post-blowdown phase.

2.7 System Level Processes

As a first step in the PIRT process, phenomena believed to have some significance to the plant behavior were identified by the previously defined component and time phase partitioning. Early in the process it was determined that major system level interactions were important to identification of the plausible phenomena, and were even more important in the subsequent ranking effort. Therefore, the following five high level system processes were adopted to aid in the effort:

① Gas/vapor transport - Flow of noncondensibles 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 drywell internal structures.

④ Debris transport - Flow of debris through free stream paths and around structures, including transport via gas/vapor, liquid films, 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 Figures A1-A9 in Appendix A.

It may be noted that 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.

2.8 Description of Phenomena Ranking Scale

It was agreed that the use of the labor intensive AHP ranking methodology was not possible within the time constraints of the PIRT effort. Accordingly, it was decided that the low, medium, and high rank scheme should be adopted, where, from prior PIRT applications the following two general interpretations serve as guidelines:

1) Code development and assessment:

- Low = Phenomena has small effect on the primary parameter of interest. Phenomena should be represented in the code, but almost any model will be sufficient,
- Medium = Phenomena has moderate influence on the primary parameter of interest. Phenomena should be well modeled; accuracy maybe somewhat compromised,
- High = Phenomena has dominant impact on the primary parameter of interest. Phenomena should be explicitly and accurately modeled.

2) And for code uncertainty quantification:

- Low = Combined uncertainty of phenomena maybe determined in a bounding fashion, or may be eliminated when justified,

- Medium = Phenomena should be evaluated to determine if uncertainty should be treated individually as are high ranks, or in a combined manner as are low ranks,
- High = Phenomena uncertainty should be individually determined and then combined statistically with other uncertainty sources (root mean square, Monte Carlo sampling, etc.).

During the actual ranking the panel found it helpful to differentiate between the lowest of the low, and highest of the high ranks. Therefore, a numerical ranking scheme of 1 to 5 was adopted with the following meaning:

1 = Lowest importance
2 = Low importance
3 = Moderate importance
4 = High importance
5 = Highest importance

Because these numerical ranks better reflect the panel's ranking conclusions they have been maintained in Tables 1 and 2.

2.9 PIRTs

2.9.1 Blowdown

The PIRT for this time phase is provided in Table 1. The structure of the table is:

- Column 1 - Component in which phenomenon occurs. The components are described in Section 2.5 and Figure 2.
- Column 2 - General phenomenon type.
- Column 3 - Higher level system process with which the phenomenon is associated. These processes are described in Section 2.7.
- Column 4 - Phenomena being ranked.
- Column 5 - Cross reference number for phenomenon description given in Table A1 in Appendix A. Additional pictorial descriptions are provided in Figures A1-A6 as cross referenced in Table A1.
- Column 6 - Phenomenon relative importance rank. The ranking scheme is described at the end of Section 2.8.
- Column 7 - Cross reference number for ranking rationale given in Table B1 in Appendix B.

2.9.2 Post-Blowdown

The PIRT for this time phase is provided in Table 2. The structure of this table is similar to Table 1, except the phenomena descriptions are provided in Table A2 and Figures A7-A9 in Appendix A, and the ranking rationales are given in Table B2 in Appendix B.

2.9.3 Ranking Summary

The high importance phenomena from Tables 1 and 2 have also been summarized in the table in the Executive Summary at the beginning of this report, including indication of the highest of the highly ranked phenomena.

Table 1. BWR debris transport blowdown phase PIRT
(1 of 2)

Component	Phenomenon type	System level process	Phenomenon	Description ①	Rank ②	Ranking rational③
Drywell open areas	Thermal hydraulic related	Gas/vapor transport	Pressure driven flows (bulk flows)	1	5	1
			Mixing (noncondensibles)	2	1	2
			Localized flow field	3	5	3
			Turbulence	4	2	4
		Suspended water transport (incl. gravitational settling)	Flashing of break liquid effluent	5	1 (5)④	5
			Droplet interactions	6	1	6
			Condensation (droplet formation)	7	1	7
		Water surface transport depletion/accumulation/ (implied surface orientation)	Condensation (structural)	8	1	8
			Film Dynamics	9	1	8
	Debris related	Debris transport	Advection/slip	10	5	9
			Agglomeration	11	2	10
			Debris/Flow field coupling	12	1	11
			Debris fragmentation	13	3	12
		Debris depletion	Gravitational settling	14	3	13
			Condensation on particles	15	1	14
			Stephan flow (diffuseophoresis)	16	1	15
			Thermophoresis	17	1	15
Drywell structures	Thermal hydraulic related	Gas/vapor transport	Heat transfer	18	1	16
		Water surface transport depletion/accumulation/ (implied surface orientation)	Porosity	19	5	3
			Film shear	20	1	17
			Surface wetting (condensation, impact)	21	5	18
			Film draining under gravity	22	1	19
			Recirculation (streaming) deluge	23	5	20
	Debris related	Debris transport	Resuspension	24	2	21
			Agglomeration	25	2	22
			Recirculation deluge (streaming) related transport	26	1 (5)④	20
			Film related transport	27	1	19
			Runoff/reentrainment	28	1	23
		Debris depletion	Impaction	29	5	24
			Adhesion	30	5	24

Table 1. BWR debris transport blowdown phase PIRT (2 of 2)

Component	Phenomenon type	System level process	Phenomenon	Description	Rank	Ranking rational
Drywell floor	Thermal hydraulic related	Water surface transport depletion/accumulation/ (implied surface orientation)	Pool formation	31	1 (5)	25
			Pool overflow (timing issue this phase)	32	1 (5)	25
			Heat transfer to structure	33	2	26
			Surface wetting (before pool formation)	34	2	25, 27
			Pool flow dynamics	35	1 (4)	25
	Debris related	Debris transport	Resuspension	36	2	28
			Pool transport (to/through vent)	37	1 (5)	25
		Debris depletion	Agglomeration in pool	38	1 (3)	25
			Adhesion	39	2	25, 27
			Settling	40	1 (4)	25
			Impaction	41	2	25, 27
Vent entrance	Thermal hydraulic related	Gas/vapor transport	Pressure driven flow (bulk) (vapor/gas)	42	1	29
			Localized vapor flow field	43	1	29
		Water surface transport depletion/accumulation/ (implied surface orientation)	Localized liquid flow field	44	1	29
	Debris related	Debris transport	Advected mass	45	1	29
		Debris depletion	Entrainment	46	3	29

Notes

①: See Appendix A for phenomena descriptions.

②: 1 = Lowest importance to debris transport through the drywell to the wetwell; 3 = Moderate importance; 5 = Highest importance; 2 and 4 allow further refinement, where 2 is considered low importance and 4 is considered high importance.

③: See Appendix B for ranking rationales.

④: First entry (without brackets) applies to main steam line break; the value in () applies to the recirculation line break; Typical of all entries so indicated.

Table 2. BWR debris transport post-blowdown phase PIRT
(1 of 2)

Component	Phenomenon type	System level process	Phenomenon	Description ①	Rank ②	Ranking rational③
Drywell open areas	Thermal hydraulic related	Gas/vapor transport	Pressure reduction due to condensation	48	≤ 2	30
			Mixed convection flow	49		
			Natural circulation	50		
			Thermal stratification	51		
			Steam-air distribution (species separation)	52		
			Mixing	53		
			Plume	54		
			Diffusion	55		
			Spray-induced turbulence	56		
		Suspended water transport (incl. gravitational settling)	Liquid transport	57		
			Flow regime	58		
			Spray source	59		
	Debris related	Debris transport	Debris advection/slip	60		
			Stephan flow (diffuseophoresis)	61		
			Thermophoresis	62		
			Debris T-H interactions (both directions)	63		
		Debris depletion	Gravitational settling	64		
			Removal by airborne liquid	65		
			Condensation on particles (growth, change in characteristic)	66		
			Agglomeration (growth, change in characteristics)	67		
Drywell structures	Thermal hydraulic related	Gas/vapor transport	Condensation	68	2	31
		Water surface transport/depletion/accumulation/ (implied surface orientation)	Film draining under gravity	69	2 (3)④	31
			Film shear	70	2	32
			ECCS deluge	71	4	33
	Debris related	Debris transport	Entrapment/Impaction	72	I⑤	N/A
			Resuspension into flow stream	73	2	34
			Film related transport	74	2 (3)④	31
			ECCS deluge related transport	75	4	33
		Debris depletion	Agglomeration	76	2	22
			Mechanical entrapment	77	2	35
			Runoff/reentrainment	78	2	31

Table 2. BWR debris transport post-blowdown phase PIRT (2 of 2)

Component	Phenomenon type	System level process	Phenomenon		Rank	Ranking rational
Drywell floor	Thermal hydraulic related	Gas/vapor transport	Heat transfer to structure	79	2	36
		Water depletion/accumulation/surface/transport (implied surface orientation)	Pool overflow	80	4⑥	37
			Asymmetric effects	81	1	38
			Pool formation	82	4⑥	39
			Pool flow dynamics	83	3 (5)④	40
	Debris related	Debris transport	Pool transport (to/toward vent)	84	3 (5)④	40
		Debris depletion	Settling	85	4⑥	41
			Impaction	86	I	N/A
			Resuspension into drywell open area	87	I	N/A
			Agglomeration	88	1 (3)④	22
			Debris fragmentation	89	1 (2)④	42
Vent entrance	Thermal hydraulic related	Gas/vapor transport	Press-driven flow (bulk)	90	1	43
			Localized vapor flow field	91	1	43
		Suspended water transport (incl. gravitational settling)	Advected liquid mass	92	1	44
		Water depletion/accumulation/surface transport (implied surface orientation)	Localized liquid flow field	93	1 (3)④	39
	Debris related	Debris transport	Advected mass	94	1 (3)④	45
		Debris depletion	De-entrainment and/or re- entrainment	95	2	43

Notes

①: See Appendix A for phenomena descriptions.

②: 1 = Lowest importance to debris transport through the drywell to the wetwell; 3 = Moderate importance; 5 = Highest importance; 2 and 4 allow further refinement, where 2 is considered low importance and 4 is considered high importance.

③: See Appendix B for ranking rationales.

④: First entry (without brackets) applies to main steam line break in which it is most unlikely there will be overflow of the drywell pool. Ranking in () applies to the recirculation line break, particularly when the drywell overflows.

⑤: Indicated phenomena has insignificant effect on debris transport through the drywell to the wetwell (typical of all entries so indicated and listed solely to show phenomena was considered, but rejected as having any significance).

⑥: Applies only to non-throttled ECCS conditions; otherwise the rank is low (<3).

3. Panel Insights Regarding BWR Debris Transport

The information provided in Table 3 was developed by the NRC to help guide the panel deliberations. The PIRT results provided in Section 2 and the experimental and analytical research related insights given below were strongly influenced by the needs and objectives stated in Table 3.

Table 3. Goals and associated success criteria for NRC-NRR's development and application of an analysis framework for evaluating debris transport.

Goal	Approach	Product	Success Criteria
Identify & rank important phenomena	PIRT	PIRT report	a) Consensus ranking of most important phenomena b) Whether identified phenomena can be incorporated into calculational tools identified
Develop calculational methodology	Evaluate applicable calculational tools & transport models (i.e., MELCOR/CFD), test against available information or related use. Use PIRT panel experts & other analysts if needed	Calculational methods & models to estimate fraction of debris transported to wetwell	Calculational methodology which accounts for important phenomena & judged by experts to have a basis for acceptance & application
Apply calculational methodology	Perform MARK I, II & III reference plant calculations	Containment specific calculations which estimate fraction of debris which might be transported to the wetwell	Provide insights into important plant modeling requirements & calculational method(s) influences
Estimate calculational sensitivities & uncertainties①	Perform sensitivity & uncertainty analyses for reference plant conditions	Parametric trends & uncertainty estimates for debris transport fractions	a) Confirm ranking of controlling phenomena & use of selected codes/models b) Ability to perform evaluations without need to commit extensive resources
Respond to NRR USER needs to understand key phenomena & their significance in review of licensee submittals	Use insights gained from above to judge licensee estimates of debris transport in the drywell	Technical findings report with condensed guidelines	Clarity & ease of applying insights from methodology & sample plant calculations

① Uncertainty in this context relates to statements of realistic bounds on the parameters of interest, rather than to statistically based quantification and characterization of uncertainty often associated with the term "uncertainty analysis".

3.1 PIRT Related Insights

The insights given below are primarily in the context of lessons learned at the conclusion of the PIRT effort.

1) The generic PIRT process was readily adapted to the needs of the program and proved to be an effective method to organize a highly complex problem into tractable subparts.

Consequently, the results were used in planning and conducting the continuing research. Two panel recommendations and one warning developed from the PIRT efforts were found to be of particular utility:

- Recommendation to perform end-to-end calculations,
- Recommendation to develop a methodology that an engineer not familiar with the issue could understand, and
- Warning that the resources needed to successfully validate the computer codes, initially considered for a methodology strongly based on analytical modeling, was considered beyond those available to the program.

2) Comparison of the final PIRTs with the initial PIRTs[3, 4] tends to further validate the effectiveness of using independent teams, having collective broad based knowledge, early in research programs addressing new problems, as illustrated by the following:

- No new phenomena were identified
- One phenomenon rank moved from moderate to high rank, based on new evidence (i.e., surface wetting during the blowdown phase)
- In two cases the ranks of related phenomenon effects moved from low to high (i.e., ECCS deluge influence on thermal hydraulics and on debris transport during the post-blowdown phase)
- Three phenomenon ranks moved from high importance to highest importance (i.e., pool formation, pool overflow and pool transport to/through the vent during the blowdown phase)
- Although the ranks of several phenomena were increased, the most noticeable trend between the initial and final PIRTs was the decrease in phenomena importance. This validates the built-in rule in the process, that in the absence of evidence, the team is to initially rank phenomena at their highest conceivable rank until further evidence is acquired as to the more realistic rank.

3.2 Methodology to Synthesize Research Results Into a Basis to Judge Licensee Submittals

1) The panel believes the structure of the methodology:

- Will provide a rational technical basis for the desired licensing review

- Is sufficiently flexible that new evidence and assumptions, related to debris size and distribution, can quickly be accommodated to provide basis for submittal evaluations not covered at the time this report was issued

2) The panel finds the methodology attractive in that it:

   - Clearly delineates important phenomena in the BWR drywell
   - Readily incorporates, and links, both experimental and analytical results
   - Is comprehensible to engineers having less experience in the subject of interest

3) With respect to the current application of the methodology, the panel perceives the following potential weaknesses[2]:

   - The rationale for upper bounds on the transport fraction needs to be strengthened. The consistently small differences between the central and upper bound values in the current application of the methodology need to be better demonstrated as realistic, or as unimportant. In addition, the use of 0.00 and 1.00 lower and upper bound values is considered unrealistic, particularly on the basis of engineering judgment. Given the inherent complexity of the phenomenological problem, and the diversity in BWR containment designs, it is surprising that the methodology produces such a small range of variation in transport factor for the sample case documented thus far. The panel believes this could be the result of the applied sample data, and suggests application of the methodology with a different data set to demonstrate this is not a generic, inherent characteristic of the methodology.
   - The ultimate quantitative insights provided by the methodology are influenced by the assumed character of the generated debris. Useful insights as to that character have been gained through the BWROG, CEESI and ARL experiments. However, the panel believes additional independent validation of the potential character of the generated debris is desirable. Without more complete knowledge of debris size distribution the upper bound uncertainties may be too low and, thus possible non-conservative.

   The panel believes it is important that the above two comments be put into perspective by recognizing both items can be accommodated to a large extent by using higher upper bound values for the parameters of interest. However, doing so leads to increased

[2] It should be noted the PIRT panel reviewed the subject methodology prior to completion of formal documentation in D. V. Rao et al., *Drywell Debris Study: Final Report*, NUREG/CR-6369, SEA, Inc. (September 1997). Details of the methodology can be found in the indicated NUREG. To the extent the panel's comments are addressed in the NUREG, those comments herein may no longer apply.

uncertainty in the ultimate quantitative insights provided by the methodology (and imposes the burden that a valid rationale for the assumed upper bounds be provided).

- The basis for the applied flow velocities in the ARL and CEESI experiments needs to be strengthened. That is, their applicability to prototypical plant conditions needs to be more strongly demonstrated.
- The experimental data base for the behavior (including ECCS erosion) of large debris on gratings is considered incomplete. In some part this is related to the above item. The data base was constructed based on limited BWROG and ARL experimental results that indicate medium and large pieces of insulation, retained by the grating, are not significantly fragmented as blowdown of the drywell progresses. The panel suggests that further separate effect tests, at prototypical conditions, could significantly increase the confidence that the medium and large debris are mostly retained by the gratings.
- The data base for the recirculation line LOCA is considered too small relative to the importance of that transient and its consequences. That is, the largest part of the research was focused on the MSLB, while the highest estimated transport fractions were associated with the recirculation line break.

4) The PIRT panel believes that the overall BWR LOCA-debris drywell transport problem is inherently very complex. The panel is not aware of any existing analytical tool (computer code) available to handle these phenomena in a fully integrated manner. Even state-of-the-art separate effects CFD codes are lacking in some key aspects, e.g., inertial impaction of debris. Therefore, the panel considers it unlikely that a purely predictive approach to issue resolution can be successfully defended with current state-of-the-art analytical tools. From this perspective the panel concludes:

   - The NRC objectives (see Table 3) for the research were well founded and appropriate
   - The mid-course change in the research, to obtain more experimental data and move away from a heavy dependency on an analytical tool(s), was appropriate
   - The methodology developed to synthesize the experimental data and analysis results was a suitable and scrutable approach to provide the desired insights for auditing licensee submittals

4. References

[1] USNRC, *Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident*, Regulatory Guide 1.82, Revision 2 (May 1996).

[2] G. Zigler et al., *Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris*, NUREG/CR-6224, Science And Engineering Associates, Inc. (October 1995).

[3] Letter Report: Summary Minutes: First BWR Debris Transport PIRT Meeting, Transmitted by letter GEW-12-96 (May 20, 1996).

[4] Letter Report: Transmittal Of Initial BWR Debris Transport PIRT, Gary E. Wilson to Aleck Serkiz, transmitted by GEW-14-96 (6/27/96).

[5] Letter Report: Transmittal Of BWR Debris Transport PIRT Panel Review Of SEA Experimental Plan, Gary E. Wilson to Aleck Serkiz, transmitted by GEW-47-96 (11/15/96).

[6] Letter Report: January 28-29, 1997, Drywell Task Program Review and Planning Meeting, Brent E. Boyack to Gary E. Wilson, transmitted by TSA-10-97-158 (2/10/98).

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

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

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

Appendix A:

Phenomena Descriptions for BWR Debris Transport PIRTs

Table A1. Phenomena descriptions for BWR debris transport blowdown phase PIRT (1 of 4)
(Reference number relates to entry in Table 1 in the report main body)

Reference Number	Phenomena	Phenomena Description	See Figure
1	Pressure driven flows (bulk flows)	Net (macro-scopic) flow characteristics of the drywell atmosphere.	A1
2	Mixing (noncondensibles)	Mixing (or stratification) of noncondensible gases in the drywell atmosphere (N2 or air) with the two-phase break effluent.	A1
3	Localized flow field	Flow direction and/or velocities that differ from the bulk (net) atmosphere flow characteristics due to localized geometries.	A1
4	Turbulence	Local fluid vortexes or flow eddies created by flow around obstacles.	A1
5	Flashing of break liquid effluent	Phase transformation (liquid ⇨ vapor) due to expansion across choked break plane.	A1
6	Droplet interactions	Mechanical interactions between suspended water droplets due to diffusion, settling, or any other process causing relative motion.	A1
7	Condensation (droplet formation)	Phase transformation (vapor ⇨ liquid) as steam cools during its motion through the drywell atmosphere creating nucleation-size water droplets.	A1
8	Condensation (structural)	Heat and mass transfer from steam in the drywell atmosphere to surfaces of drywell structures associated with steam condensing on cooler structures.	A1
9	Film dynamics	The interaction between gas flow in the drywell atmosphere and liquid (condensate) films on structure surfaces; including interfacial shear, surface instability and droplet re-entrainment.	A1
10	Advection/slip	Transport of airborne debris within the carrier gas medium.	A2
11	Agglomeration	Mechanical interaction among suspended debris particles by which two or more small particles combine to form a larger conglomerate particle.	A2
12	Debris/Flow field coupling	The influence of local variations in fluid flow field on debris transport and deposition.	A1/A2
13	Debris fragmentation	Break up of relatively large pieces of debris into smaller particles that can be re-entrained into the flow stream due to fluid shear created (for example) by locally-high flow velocities at constricted flow areas.	A2

Table A1. Phenomena descriptions for BWR debris transport blowdown phase PIRT (2 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
14	Gravitational settling	Downward relocation (sedimentation) of debris in the drywell atmosphere onto structure surfaces under the force of gravity.	A2
15	Condensation on particles	Heat and mass transfer from steam in the drywell atmosphere to surfaces of suspended debris particles with steam condensing onto particle surface.	A2
16	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 drywell structures).	A2
17	Thermophoresis	Transport of debris particles toward deposition surfaces due to temperature gradients within the atmosphere and between the atmosphere and bounding structures.	A2
18	Heat transfer	Cooling of drywell atmosphere due to heat transfer to structures.	A3
19	Porosity	Variations in fluid flow area and flow as related to the density of the structures in the drywell, and due to the "tortureosity" of the flow path around those structures.	A3
20	Film shear	The interfacial interaction between gas flow in the drywell atmosphere and liquid (condensate) films on structure surfaces.	A3
21	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.	A3
22	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	A3
23	Recirculation (streaming) deluge	Large flow rate of liquid effluent from a low-elevation (e.g., recirculation line) break in the reactor coolant system onto drywell structures, or from sprays when activated.	A3
24	Resuspension	Re-entrainment of debris previously deposited on structure surfaces into the atmosphere flow stream due to local fluid/structure shear forces.	A4
25	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.	A4

Table A1. Phenomena descriptions for BWR debris transport blowdown phase PIRT (3 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
26	Recirculation deluge (streaming) related transport	Relocation of debris from drywell structures due to interactions with the deluge of liquid from recirculation pipe breaks, or sprays.	A4
27	Film related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity.	A4
28	Runoff/re-entrainment	Re-suspension of debris on structure surfaces into the flow stream as liquid films drain off of structures.	A4
29	Impaction	Capture of debris particles on structure surfaces due to inertial impaction.	A4
30	Adhesion	Permanent retention of debris particles on a structure surface due to mechanical interactions with a rough surface or other forces.	A4
31	Pool formation	Creation of a pool of water on the drywell floor sufficiently deep to allow overflow into wetwell transfer piping due to the accumulation of water from all sources higher in the drywell (e.g., film drainage, droplet settling).	A5
32	Pool overflow (timing issue this phase)	Transport of water from pool on drywell floor into wetwell vent pipes.	A5
33	Heat transfer to structure	Heat transfer between water on drywell floor and bounding structures	A5
34	Surface wetting (before pool formation)	Wetting of drywell floor due to steam condensation or settling of suspended water droplets.	A5
35	Pool flow dynamics	Multi-dimensional flow patterns and velocities within the pool of water on the drywell floor; includes free-surface (vertical) velocity profile and turbulent mixing (circulation) flows.	A5
36	Resuspension	Re-entrainment of debris into the atmospheric flow stream from the drywell floor due to high shear forces at the surface of the floor.	A6
37	Pool transport (to/through vent)	Relocation of debris in the pool of water on the drywell floor toward wetwell vent pipe entrances.	A6
38	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.	A6
39	Adhesion	Permanent retention of debris particles on the drywell floor due to mechanical interactions with a rough surface or other forces.	A6
40	Settling	Downward relocation (sedimentation) of debris within the pool of water on the drywell floor under the force of gravity.	A6

Table A1. Phenomena descriptions for BWR debris transport blowdown phase PIRT (4 of 4)

Reference Number	Phenomena	Phenomena Description	See Figure
41	Impaction	Capture of debris on the surface of the drywell floor (or water pool) due to inertial deposition.	A6
42	Pressure driven flow (bulk) (vapor/gas)	Vent entrance component phenomenon similar to Ref. No. 1, this table.	
43	Localized vapor flow field	Vent entrance component phenomenon similar to Ref. No. 3, this table.	
44	Localized liquid flow field	Vent entrance component phenomenon similar to Ref. No. 3, this table.	
45	Advected mass	Vent entrance component phenomenon similar to Ref. No. 10, this table.	
46	Entrainment	Capture of debris from the bulk flow stream.	A5, A6
47	**Deleted in final PIRT**		

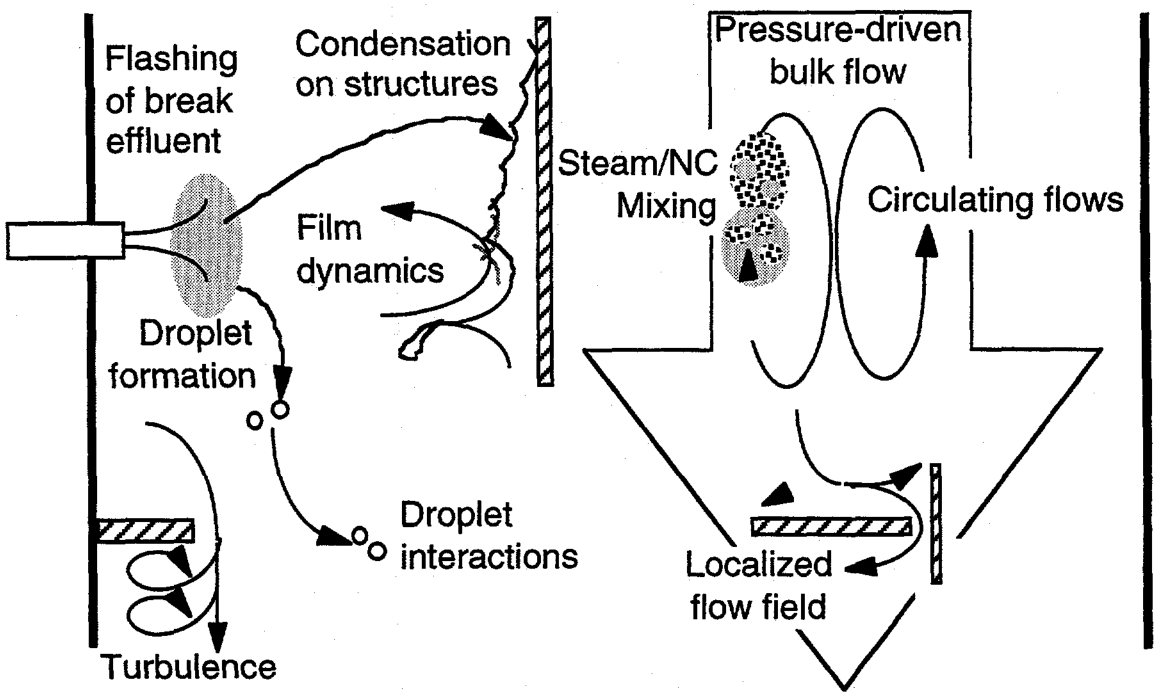

Figure A1. Thermal-hydraulic Pocesses in Drywell Open Areas
-- Blowdown Phase --

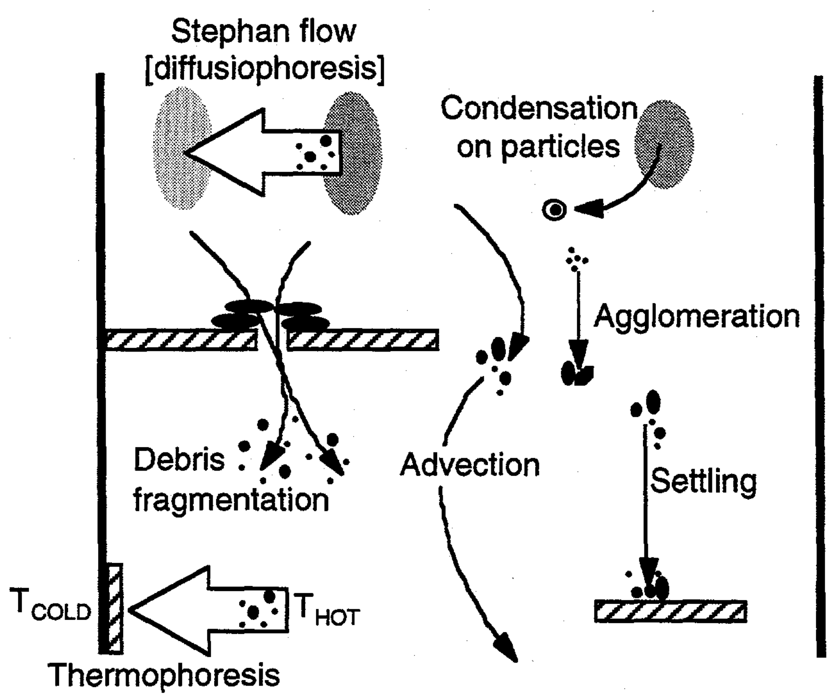

Figure A2. Transport / Deposition Processes for Debris in Drywell Open Areas
-- Blowdown Phase --

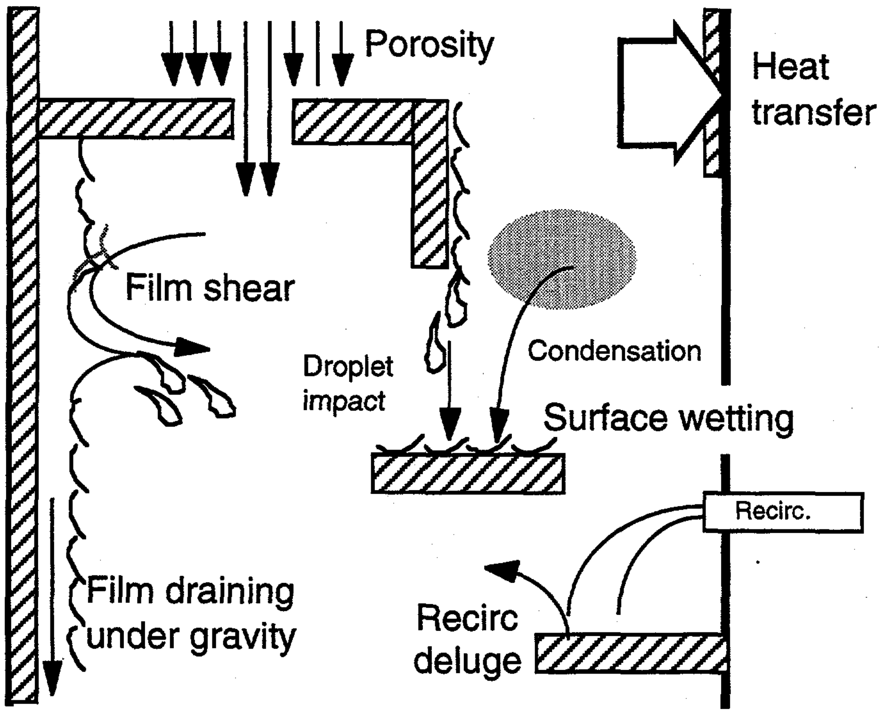

Figure A3. Thermal-hydraulic Processes on Drywell Structures
-- Blowdown Phase --

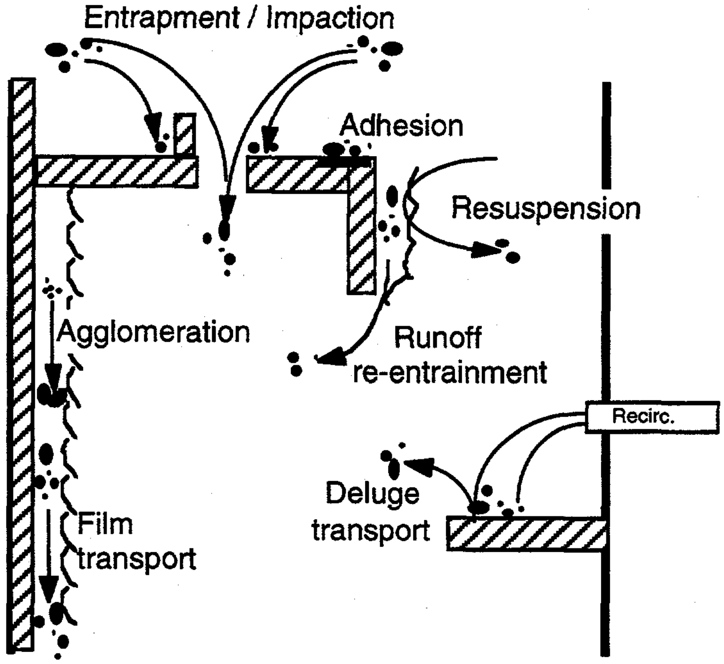

Figure A4. Transport / Deposition Processes for Debris on Drywell Structures
-- Blowdown Phase --

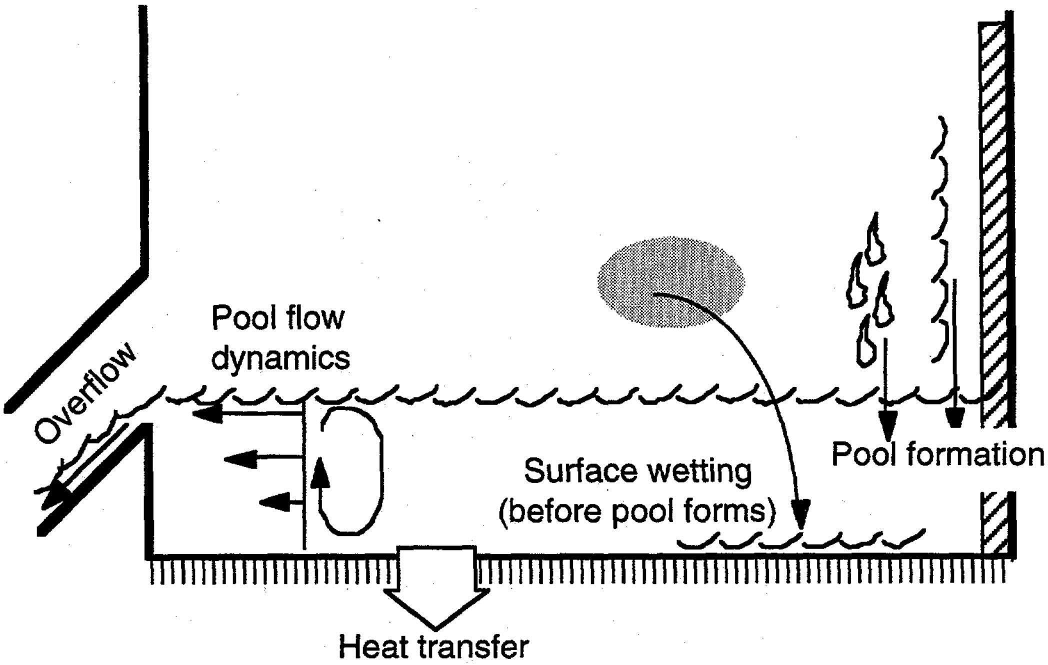

Figure A5. Thermal-hydraulic Processes on the Drywell floor
-- Blowdown Phase --

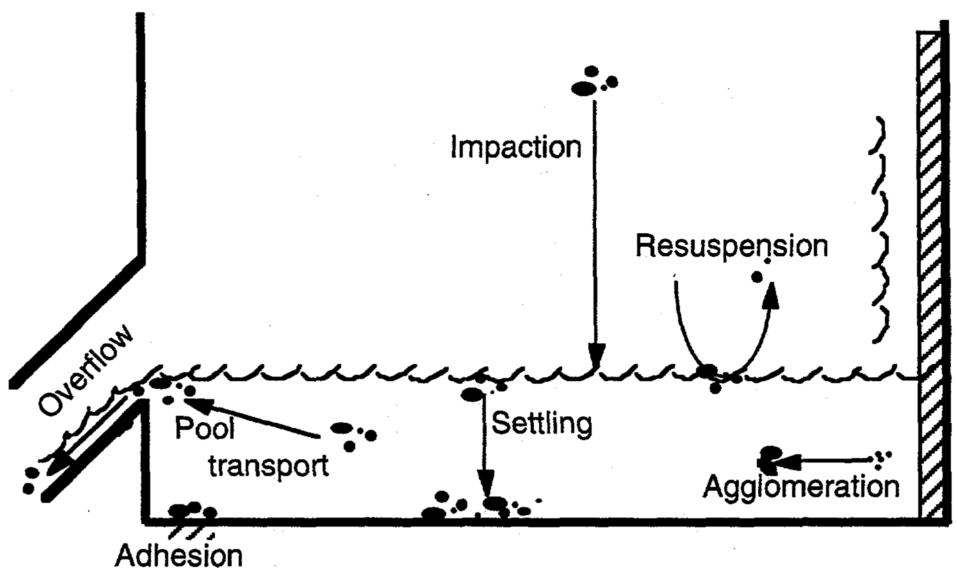

Figure A6. Transport / Deposition Processes for Debris on the Drywell floor
-- Blowdown Phase --

Table A2. Phenomena descriptions for BWR debris transport post-blowdown phase PIRT (1 of 3)
(Reference number relates to entry in Table 2 in the report main body)

Reference Number	Phenomena	Phenomena Description	See Figure
48	Pressure reduction due to condensation	Drywell pressure reduction due to reduction in vapor volume fraction.	A7
49	Mixed convection flow	Mixed forced and gravity induced flow.	A1
50	Natural circulation	Localized flow driven by buoyancy forces.	A1
51	Thermal stratification	Formation of vertical temperature gradient.	
52	Steam-air distribution (species separation)	Flow patterns promoting species separation.	
53	Mixing	Similar to Ref. No. 2, Table A1.	
54	Plume	Centralized local flow pattern.	
55	Diffusion	Migration due to localized phenomena.	
56	Spray-induced turbulence	Local fluid vortexes or flow eddies created by spray interactions.	A1
57	Liquid transport	Movement of liquid by forced and gravity induced forces.	
58	Flow regime	Flow field with standardized attributes.	
59	Spray source	Effects of spray source configuration and attributes.	
60	Debris advection/slip	Similar to Ref. No. 10, Table A1.	
61	Stephan flow (diffuseophoresis)	Similar to Ref. No. 16, Table A1.	
62	Thermophoresis	Similar to Ref. No. 17, Table A1.	
63	Debris T-H interactions (both directions)	Similar to Ref. No. 12, Table A1.	
64	Gravitational settling	Similar to Ref. No. 14, Table A1.	
65	Removal by airborne liquid	Capture by airborne liquid.	
66	Condensation on particles (growth, change in characteristic)	Similar to Ref. No. 15, Table A1.	
67	Agglomeration (growth, change in characteristics)	Similar to Ref. No. 11, Table A1.	
68	Condensation	Phase transformation (vapor ⇨ liquid) as steam cools during its motion through the drywell atmosphere (on structures and suspended particles).	A7
69	Film draining under gravity	Downward, free-surface flow of liquid (water) films on structure surfaces by gravity.	A7
70	Film shear	The interfacial interaction between gas flow in the drywell atmosphere and liquid (condensate) films on structure surfaces.	A7
71	ECCS deluge	Large flow rate of liquid effluent from ECCS onto drywell structures.	A7

Table A2. Phenomena descriptions for BWR debris transport post-blowdown phase PIRT (2 of 3)

Reference Number	Phenomena	Phenomena Description	See Figure
72	Entrapment/Impaction	Capture of debris particles on structure surfaces due to either transport into confined spaces due to localized flow fields or inertial impaction.	N/A
73	Resuspension into flow stream	Re-entrainment of debris previously deposited on structure surfaces into the atmosphere flow stream due to local fluid/structure shear forces.	A7
74	Film related transport	Relocation of debris along structure surfaces due to flow of liquid films under the force of gravity.	A7
75	ECCS deluge	Relocation of debris from drywell structures due to interactions with the deluge of liquid from ECCS.	A7
76	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.	A7
77	Mechanical 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.	A7
78	Runoff/reentrainment	Re-suspension of debris on structure surfaces into the atmosphere flow stream as liquid films drain off of structures.	A7
79	Heat transfer to structure	Heat transfer between water on the drywell floor and bounding structures.	A8
80	Pool overflow	Transport of water from pool on drywell floor into wetwell vent pipes.	A8
81	Asymmetric effects	Preferential transport of water towards a sub-set of the total number of wetwell vent pipes due (for example) to azimuthal asymmetries in water source locations (e.g., recirculation line break location).	A8
82	Pool formation	Creation of a pool of water on the drywell floor sufficiently deep to allow overflow into wetwell transfer piping due to accumulation of water from all sources higher in the drywell (e.g., film drainage, droplet settling).	A8
83	Pool flow dynamics	Multi-dimensional flow patterns and velocities within the pool of water on the drywell floor; includes free-surface (vertical) velocity profile and turbulent mixing (circulation) flows.	A8
84	Pool transport (to/toward vent)	Relocation of debris in the pool of water on the drywell floor toward wetwell vent pipe entrances.	A9

Table A2. Phenomena descriptions for BWR debris transport post-blowdown phase PIRT (3 of 3)

Reference Number	Phenomena	Phenomena Description	See Figure
85	Settling	Downward relocation (sedimentation) of debris within the pool of water on the drywell floor under the force of gravity.	
86	Impaction	Capture of debris on the surface of the drywell floor pool due to inertial impaction.	N/A
87	Resuspension into drywell open area	Re-entrainment of debris into the atmospheric flow stream from the drywell floor due to high shear forces at the surface of the floor.	N/A
88	Agglomeration	Mechanical interaction among debris particles on the drywell floor by which two or more small particles combine to form a larger conglomerate particle.	A9
89	Debris fragmentation	Break up of relatively large pieces of debris on the drywell floor (pool surface) into smaller particles due to inertial impact of liquid break effluent from a recirculation line break.	A9
90	Pressure-driven flow (bulk)	Similar to Ref. No's. 1 & 42, Table A1.	
91	Localized vapor flow field	Similar to Ref. No's. 3 & 43, Table A1.	
92	Advected liquid mass	Similar to Ref. No's. 10 & 45, Table A1.	
93	Localized liquid flow field	Similar to Ref. No's. 3 & 44, Table A1.	
94	Advected mass	Similar to Ref. No's. 10 & 45, Table A1.	
95	Entrainment	Similar to Ref. No. 46, Table A1.	
96	**Deleted from final PIRT**		

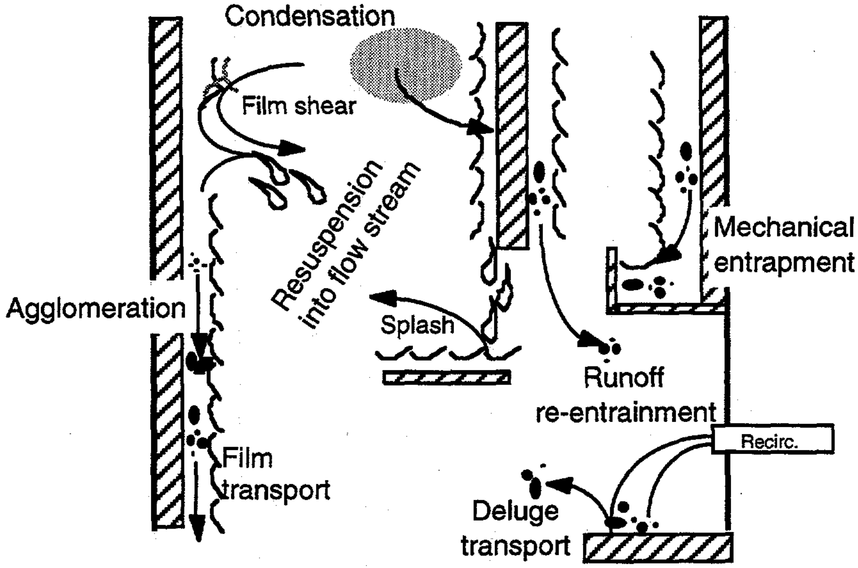

Figure A7. Thermal-hydraulic & Debris Transport / Deposition Processes on Drywell Structures
-- Post-blowdown Phase --

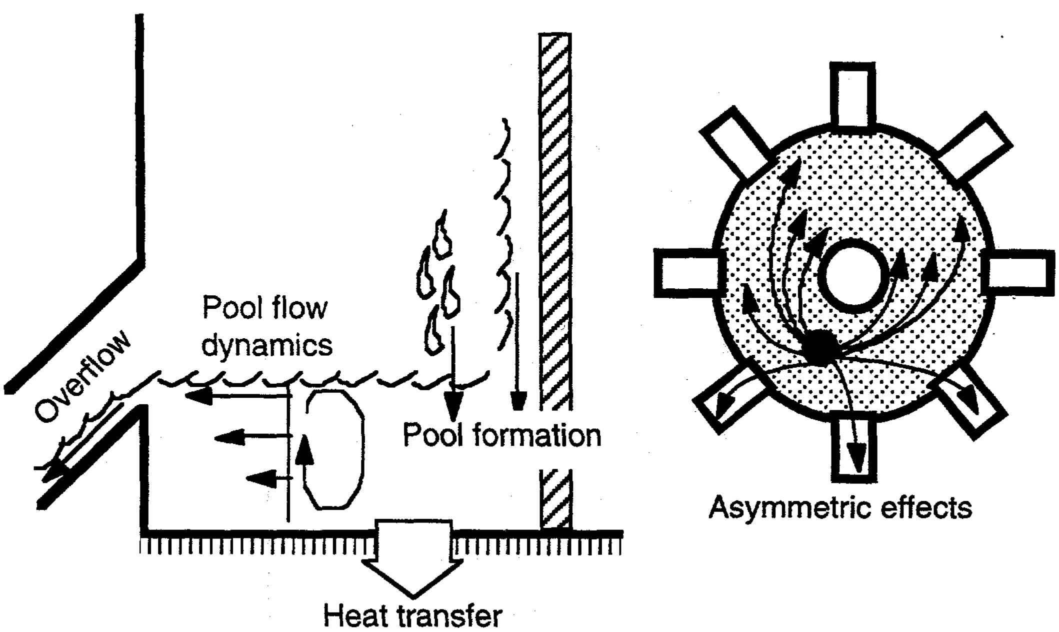

Figure A8. Thermal-hydraulic Processes on the Drywell floor
-- Post-blowdown Phase --

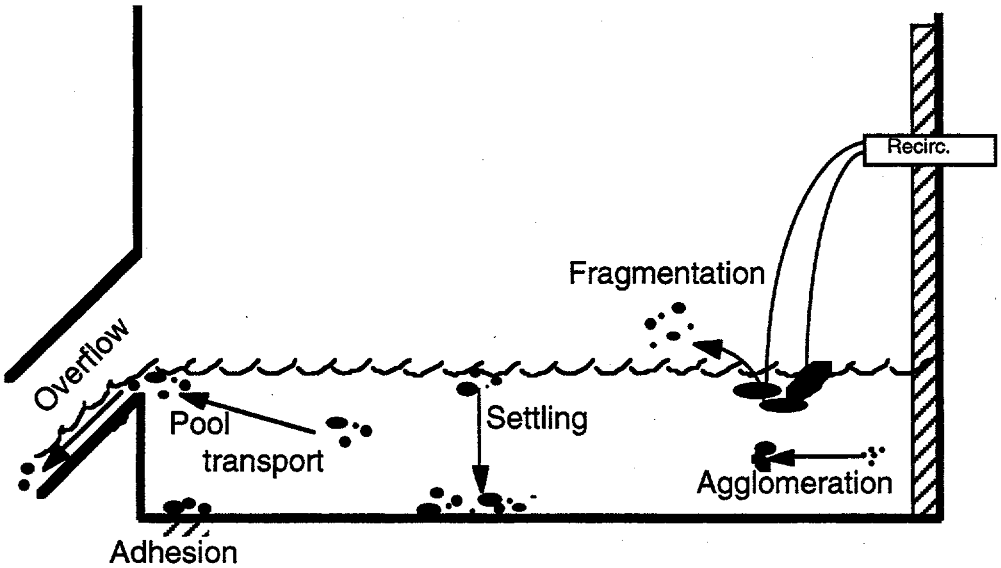

Figure A9. Transport / Deposition Processes for Debris on the Drywell floor
-- Post-blowdown Phase --

Appendix B:

Ranking Rationales for BWR Debris Transport PIRTs

Table B1. Ranking rationales for BWR debris transport blowdown phase PIRT (1 of 2)
(Reference number relates to entry in Table 1 in the report main body)

Reference Number	Phenomena	Ranking Rationale
1	Pressure driven flows (bulk flows)	The dominant transport medium for all debris that reaches the wet well. CFD calculations (Williams for 0.6 s of MSLB, Ref. C29) show large fraction of drywell free volume is in unidirectional flow.
2	Mixing (noncondensibles)	Only significant influence is effect on steam condensation, which during 60 s blowdown is relatively small. Jet thermal mixing is not controlling bulk flow.
3	Localized flow field	Most significant debris depletion mechanism (impaction). The new experimental evidence strengthened the high rank because of the exhibited localized flow field mechanism for "smalls" debris avoidance of impaction and, thus, total transport to wetwell. Break orientation has significant potential influence on impaction.
4	Turbulence	An effect of channeling, thus of lower order importance.
5	Flashing of break liquid effluent	Relates to amount of liquid exiting break. Low for MSLB; (high for recirculation line break).
6	Droplet interactions	Assumes w/o spray. Does not significantly affect debris transport because does not influence the bulk flow field.
7	Condensation (droplet formation)	No significant condensation in open area (excluding break boundary region). This is free stream condensation associated with the rapid depressurization. For the MSLB, it was assumed that the droplet formation occurred within the source cell of approximately 10 m^3.
8	Condensation (structural)	Of low importance to T/H behavior in open area because the volume of steam condensing is small compared to an open area volume.
9	Advection/slip	Dominant debris transport mechanism (correlates with pressure driven and localized flow fields).
10	Agglomeration	Low rank is based on overall new evidence, including the experiments.
11	Debris/Flow field coupling	Debris density is too low to result in significant feedback effect.
12	Debris fragmentation	(a) Outside of break localized region, significant further breakup not experimentally observed. (b) Dynamic mechanical processes (i.e., weedeater, cutting tools) required to produce debris for experiments is unlikely to be duplicated in NPP.
13	Gravitational settling	New experimental evidence indicates gravitational induced path vector is secondary to flow induce path vector.
14	Condensation on particles	Low rank is based on overall new evidence, including the experiments.

Table B1. Ranking rationales for BWR debris transport blowdown phase PIRT (2 of 2)

Reference Number	Phenomena	Ranking Rationale
15	Stephan flow (diffuseophoresis) & Thermophoresis	Insignificant to debris transport in this phase.
16	Heat transfer	Moderate-order effect on debris transport because of influence on containment depressurization. Diminishes the peak pressure (driving potential) for the flow to the wetwell but the effect is moderate.
17	Film shear	Velocity not high enough to produce significant shear.
18	Surface wetting (condensation, impact)	High rank is based on overall new evidence, including the experiments.
19	Film draining under gravity	Low rank is based on overall new evidence, including the experiments.
20	Recirculation (streaming) deluge	Deluge of liquid considered to be insignificant during MSLB. (One of the dominant mechanisms (with vapor/gas transport) of debris during the recirculation line break.)
21	Resuspension	Low rank is based on overall new evidence, including the experiments.
22	Agglomeration	Lower order effect (i.e., debris growth vs. direct removal).
23	Runoff/reentrainment	New experimental evidence indicates this is not a significant contributor to airborne debris mass during this time phase.
24	Entrapment/impaction & Adhesion	Dominant mechanism for removing high-speed airborne debris.
25	Pool formation, Pool overflow (timing issue this phase), Pool flow dynamics, Pool transport (to/through vent), Agglomeration in pool & Settling	Pool formation and its effects considered to be insignificant during the MSLB. (In the recirculation line break, drywell floor is of equal importance to drywell open area and structures; however, only if pool forms and then overflows to vent. Pool dynamics affecting debris settling or suspension is important to debris transport to the vent.)
26	Heat transfer to structure	Importance to surface wetting.
27	Surface wetting (before pool formation), Adhesion & Impaction	For the MSLB, experimental evidence indicates drywell floor is not a significant contributor to debris transport behavior during blowdown. The "smalls" were transported regardless. The medium, large and "canvassed" debris amounts below the bottom grate are not significant to total amount of debris.
28	Resuspension	Importance related to likelihood in context of low free stream velocity.
29	Pressure driven flow (bulk) (vapor/gas), Localized vapor & liquid flow fields, Advected mass, De-entrainment & Re-entrainment	a) Mark I & II: Component is of overall less importance to debris transport than other components because essentially all debris arriving at component is transported to the drywell. This conclusion applies only to the Mark I and II containments. b) This conclusion may not apply to the Mark III, therefore, in the final PIRT the rank was increased to moderate importance.

Table B2. Ranking rationales for BWR debris transport post-blowdown phase PIRT (1 of 1)
(Reference number relates to entry in Table 2 in the report main body)

Reference Number	Phenomena	Ranking Rationale
30	All referenced phenomena listed under the drywell open area component in Table 2 in the report main body	Assigned rank for this component is 2 because airborne debris during this phase is negligible. See drywell turnover figure showing about 7 turnovers during the blowdown phase. An important related factor of this component assignment is that no process/phenomena will have a rank higher than the component rank.
31	Condensation, Film draining under gravity, Film related transport, and Runoff/re-entrainment	Low rank is based on overall new evidence, including the experiments.
32	Film shear	Moderate contributor to resuspension.
33	ECCS deluge	New experimental evidence, related to washdown/erosion, indicates phenomenon is significant to debris transport.
34	Re-suspension into flow stream	Only important in fast draining films which already transport debris.
35	Mechanical entrapment	Low rank is based on overall new evidence, including the experiments.
36	Heat transfer to structure	Low rank is based on overall new evidence, including the experiments.
37	Pool overflow	Dominant mechanism for debris transport to wetwell.
38	Asymmetric effects	Low potential to significantly affect amount of debris transported to wetwell.
39	Pool formation & Localized liquid flow field	Considered improbable for MSLB, but (moderate to high contributor to debris transport to wetwell in the recirculation line break).
40	Pool flow dynamics & Pool transport (to/toward vent)	Relates to fraction of debris available for overflow transport. Significant pool formation and overflow effects considered improbable for MSLB, but (can be significant for recirculation line break).
41	Settling	Major contributor to pool entrapment of debris.
42	Debris fragmentation	New experimental evidence indicates continued fragmentation is insignificant in both transients.
43	Pressure-driven flow (bulk)	Very little suspended debris in gas/vapor field; low vapor velocity.
44	Advected liquid mass	Only contribution is by runoff from structures.
45	Advected mass	Relates to potential of flow conditions to carry over debris to wetwell. Considered improbable for the MSLB, and (moderate for the recirculation line break).

Appendix C:

Information Base Used in the Application of the PIRT Process to Debris Transport in a BWR Drywell

Documents associated with the first PIRT meeting

C1 W. W. Durgin and J. Noreika, *The Susceptibility of Fibrous Insulation Pillows to Debris Formation Under Exposure to Energetic Jet Flows*, NUREG/CR-3170, Alden Research Laboratory (March 1983).

C2 Kevin W. Brinckman, *Results of Hydraulic Tests on ECCS Strainer Blockage and Material Transport in a BWR Suppression Pool*, EC-059-1006, Revision 0 (May 1994).

C3 SEA, *A Methodology for Estimating BWR Drywell Transport Fractions During Blowdown and Washdown*, SEA N0. 93-554-06-A:12, Science And Engineering Associates, Inc. (July 1995).

C5 Aleck W. Serkiz et al., *An Overview of the BWR ECCS Strainer Blockage Issues*, NUREG/CR-0149, Volume 3, Brookhaven National Laboratory (March 1996) pp175-199.

C6 George E. Hecker et al., *Experiments of ECCS Strainer Blockage and Debris Settling in Suppression Pools*, NUREG/CR-0149, Volume 3, Brookhaven National Laboratory (March 1996) pp201-225.

C7 Gilbert L. Zigler and D. V. Rao, *The Strainer Blockage Assessment Methodology Used in the BLOCKAGE Code*, NUREG/CR-0149, Volume 3, Brookhaven National Laboratory (March 1996) pp227-235.

C8 D. V. Rao et al., *Proposed Methodology for Modeling LOCA Debris Transport in BWR Drywells*, Science And Engineering Associates, Inc. (February 5, 1996).

C9 G. E. Wilson, *Statistically Based Uncertainty Analysis for Ranking of Component Importance in the Thermal Hydraulic Safety Analysis of the Advanced Neutron Source Reactor*, EGG-NE-10078, EG&G Idaho, Inc. (1992).

C10 T. Saaty, *Decision-Making For Leaders*, Belmont, CA, Lifetime Learning Publications, Wadsworth Inc. (1982).

C11 Gilbert L. Zigler, *NUREG/CR-6224 Overview*, Science and Engineering Associates (April 1996).

C12 Clint Shaffer, *Overview of Proposed Analytical Methods for Addressing Debris Transport Problem*, Science and Engineering Associates (April 16, 1996).

C13 George Hecker, *Why Use CFD For Drywell Transport?*, Alden Research Laboratory (April 1996).

C14 D. V. Rao, *Phenomenological Considerations in Drywell Debris Transport*, Science and Engineering Associates (April 16-18, 1996).

C15 Gary E. Wilson, *PIRT Process Considerations*, Idaho National Engineering Laboratory (April 1996).

C16 Letter Report: First Meeting Approved Minutes For BWR Debris Transport PIRT, Gary E. Wilson to Aleck Serkiz, transmitted by GEW-12-96 (5/20/96).

Documents associated with the second PIRT meeting

C17 D. V. Rao et al., *Drywell Debris Transport Methodology: Responses to PIRT Panel Request for Information*, SEA No. 96-3104-06-A:1, Science And Engineering Associates, Inc. (May 1996).

C18 D. V. Rao, *Accident Progression Scenarios for BWR*, Science And Engineering Associates, Inc. (May 1996).

C19 D. V. Rao et al., *SEA/ARL Proposed Methodology for Important Phenomena Identified by PIRT Panel*, Science And Engineering Associates, Inc. (May 1996).

C20 Mark Leonard, *Basic Information on Non-Spherical Particle Transport Properties*, Innovative Technology Solutions Corp. (May 1996).

C21 John E. Brockmann, *Aerosol Physics*, Sandia National Laboratories (May 1996).

C22 Lothar Wolf and Mark Leonard, *Collection of Schematics Describing Important Physical Phenomena for Debris Transport in BWR Containment During and After LOCA*, University of Maryland and Innovative Technology Solutions Corp. (May 1996).

C23 Lothar Wolf, *Description of Coupled Thermohydraulics and Aerosol Phenomena in LWR Containment*, University of Maryland (May 1996).
C24 Lothar Wolf, *Suggestions for Dimensionless Presentations of Major Aerosol Transport Processes in LWR Containments*, University of Maryland (May 1996).
C25 Lothar Wolf, *Overview of Experimental and Analytical Results of Containment LOCA and Aerosol Behaviors*, University of Maryland (May 1996).
C26 Lothar Wolf, *Summary of Unpublished German Experiments on Insulation Damages and Floating Behavior*, University of Maryland (May 1996).
C27 K. Mun and L. Wolf, *GOTHIC Computation and Comparisons with Data of Marviken (BWR) Test 17*, University of Maryland (May 1996).
C28 K Mun and L. Wolf, *GOTHIC Computation of BWR Mark I LOCA with Spray Operation*, University of Maryland (May 1996).
C29 Ken A. Williams, *CFD Simulation of BWR Drywell Response to MSLB Event*, Flow Simulation Services, Inc. (May 15, 1996).
C30 Mark Leonard, *Insights from Some Quick MELCOR Calculations*, Innovative Technology Solutions Corp. (May 1996).
C31 Eric Haskin and Francisco Souto, *Sensitivity Analysis Approach Proposed for Debris Drywell Transport Study*, University of New Mexico and Science And Engineering Associates, Inc. (May 1996).
C32 Letter Report: Transmittal Of Initial BWR Debris Transport PIRT, Gary E. Wilson to Aleck Serkiz, transmitted by GEW-14-96 (6/27/96).

<u>Documents associated with the PIRT panel review/evaluation of experimental program</u>

C33 D. V. Rao et al., *Drywell Debris Transport Study, Draft Phase 1 Letter Report*, SEA 96-3105-010-A:2 (September 27, 1996).
C34 Letter Report: Transmittal Of BWR Debris Transport PIRT Panel Review Of SEA Experimental Plan, Gary E. Wilson to Aleck Serkiz, transmitted by GEW-47-96 (11/15/96).
C35 D. V. Rao, D. Cremer, B. Carpenter, and K. Weingardt, "Drywell Debris Transport Testing Program Review/Planning," Science & Engineering Associates, Inc. presentation (January 28, 1997).
C36 C. Shaffer, "Reconciliation and Integration of Experimental Data and Analyses," Science & Engineering Associates, Inc. presentation (January 28, 1997).
C37 Letter Report: January 28-29, 1997, Drywell Task Program Review and Planning Meeting, Brent E. Boyack to Gary E. Wilson, transmitted by TSA-10-97-158 (2/10/98).
C38 Phillip S. Stacy et al., *Experimental Evaluation of Inertial Debris Capture on BWR Drywell Structures Following a LOCA (Draft)*, ARL (April 1997).
C39 D. V. Rao et al., *Experimental Study of Erosion of Insulation Debris by Recirculating ECCS Flow Following a LOCA*, Letter Report SEA 97-3105-A:7, SEA (May 20, 1997).
C40 D. V. Rao et al., Drywell Debris Transport Testing CEESI Test Program: Description and Results, Presentation Handout SEA 97-3105-A:8, SEA (May 21, 1997).
C41 Clint Shaffer, Drywell Floor Pool CFD Calculations, Presentation Handout SEA 97-3105-A:9, SEA (May 21, 1997).
C42 Clint Shaffer et al., Debris Transport Study: Deductions and Quantification, Presentation Handout SEA 97-3105-A:10 Revision 1, SEA (June 5, 1997).
C43 Clint Shaffer, Debris Transport Study: Quantification Results and Logic Charts, Presentation Handout SEA 97-3105-A:11, SEA (June 5, 1997).
C44 D. V. Rao, *LOCA Debris Transportability in the Drywell Floor Pool: Interpretation of ARL/PPL Flume Transport Data*, Letter Report SEA 97-3105-A:12, SEA (May 20, 1997).
C43 D. V. Rao, Drywell Debris Transport Study: Program Outline and Milestones, Presentation Handout SEA 97-3105-A:13, SEA (May 21, 1997).