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GSI-191: DEVELOPMENT OF DEBRIS TRANSPORT FRACTIONS IN SUPPORT OF THE PARAMETRIC EVALUATION

TECHNICAL LETTER REPORT

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EXECUTIVE SUMMARY

The purpose of the Generic Safety Issue (GSI) 191 study is to determine if the transport and accumulation of debris in a containment following a loss-of-coolant accident (LOCA) will impede the operation of the emergency core cooling system (ECCS) in operating pressurized water reactors (PWRs). In the event of a LOCA within the containment of a PWR, thermal insulation and other materials (e.g., coatings and concrete) in the vicinity of the break will be damaged and dislodged. A fraction of this material will be transported to the recirculation (or emergency) sump and accumulate on the screen. The debris that accumulates on the sump screen forms a bed that acts as a filter. Excessive head loss across the debris bed may exceed the net positive suction head (NPSH) margin of the ECCS or containment spray (CS) pumps. For sump screens that are only partially submerged by water on the containment floor, excessive head loss across the debris bed may prevent water from entering the sump. Thus, excessive head loss can prevent or impede the flow of water into the core or containment. Also, excessive head loss across the debris bed may lead to ECCS- or CS-pump damage.

As part of the GSI-191 study, a parametric evaluation was performed to demonstrate whether sump failure is a plausible concern for operating PWRs. The results of the parametric evaluation form a credible technical basis for making a determination of whether sump blockage is a generic concern for the PWR population. This parametric evaluation included performing appropriate technical calculations and supporting experimental work to provide estimates for various parameters that are key to making a vulnerability assessment. These parameters include debris generation quantities, debris transport fractions, debris accumulation quantities (on the sump screen), and the resulting head loss across the sump screen. This effort also includes providing defensible bases for all of the assumptions made in the analyses and explanations of how some of the prominent calculational uncertainties were factored into the decision process. This report documents the determination of the debris transport fractions that were used in the parametric evaluation. Table ES-1 lists these transport fractions. The method used to arrive at these transport fractions and any assumptions necessary for development of these numbers are documented in this report.

The research documented here was used directly in the generic assessment of vulnerability of the PWR population to the sump blockage safety concern as presented in LA-UR-01-4083, “GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance.” Details regarding input data used, methods applied, and assumptions made in the Parametric Evaluation are based on this report.

Table ES-1. Debris Transport Fraction Estimates Used in Parametric Evaluation

Transport Conditions	Favorable Estimate	Unfavorable Estimate
Small LOCA (SLOCA) with Sprays Inactive	0.05	0.10
SLOCA with Sprays Active	0.10	0.25
All Medium LOCAs (MLOCAs) and Large LOCAs (LLOCAs)	0.10	0.25

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LIST OF ACRONYMS AND ABBREVIATIONS

3-D	Three-Dimensional
BWR	Boiling Water Reactor
CFD	Computational Fluid Dynamics
CS	Containment Spray
ECCS	Emergency Core Cooling System
FTDL	Failure-Threshold Debris Loading
GSI	Generic Safety Issue
LANL	Los Alamos National Laboratory
LLOCA	Large LOCA
LOCA	Loss-of-Coolant Accident
MLOCA	Medium LOCA
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RMI	Reflective Metallic Insulation
SLOCA	Small LOCA
TLR	Technical Letter Report
UNM	University of New Mexico
ZOI	Zone of Influence

ACKNOWLEDGEMENTS

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The authors would particularly like to acknowledge the contributions of Dr. A. Maji of the University of New Mexico and his student assistants. These individuals conducted many of the experimental investigations that were used, in part, as the bases for the transport fractions developed in this report. In addition, Dr. B. Letellier and Mr. L. Bartlein of Los Alamos National Laboratory provided critical assistance and insight in the development of the continuing experimental program and application of its preliminary results to the parametric evaluation.

Finally, the authors would like to thank Ms. J. Lujan and Ms. M. Timmers for their assistance with editing and preparation of this document.

1.0 INTRODUCTION

The purpose of the Generic Safety Issue (GSI) 191 study is to determine if the transport and accumulation of debris in a containment following a loss-of-coolant accident (LOCA) will impede the operation of the emergency core cooling system (ECCS) in operating pressurized water reactors (PWRs). In the event of a LOCA within the containment of a PWR, thermal insulation and other materials (e.g., coatings and concrete) in the vicinity of the break will be damaged and dislodged. A fraction of this material will be transported to the recirculation (or emergency) sump and accumulate on the screen. The debris that accumulates on the sump screen forms a bed that acts as a filter. Excessive head loss across the debris bed may exceed the net positive suction head (NPSH) margin of the ECCS or containment spray (CS) pumps. For sump screens that are only partially submerged by water on the containment floor, excessive head loss across the debris bed may prevent water from entering the sump. Thus, excessive head loss can prevent or impede the flow of water into the core or containment. Also, excessive head loss across the debris bed may lead to ECCS- or CS-pump damage.

As part of the GSI-191 study, a parametric evaluation was performed to demonstrate whether sump failure is a plausible concern for operating PWRs (Ref. 1). The results of the parametric evaluation form a credible technical basis for determining whether sump blockage is a generic concern for the PWR population. The parametric evaluation included performing appropriate technical calculations and supporting experimental work to provide estimates for various parameters that are key to making a vulnerability assessment. These parameters include debris generation quantities, debris transport fractions, debris accumulation quantities (on the sump screen), and the resulting head loss across the sump screen. This parametric evaluation report also was intended to provide defensible bases for all assumptions made in the analyses and explanations of how some of the prominent calculational uncertainties were factored into the decision process. This technical letter report (TLR) documents the determination of the debris transport fractions that were used in the parametric evaluation and explains the method and assumptions used beyond what was included in the parametric evaluation report.

The scope of the work performed to develop the debris transport fractions used in the parametric evaluation as well as the relationship to the overall objectives of the GSI-191 research program are discussed in Sec. 2 of this TLR. Section 3 lists the assumptions that were made in development of the transport fractions. Section 4 discusses the insights gained from an experimental test program to support GSI-191 and relates those insights to the development of the transport fractions. Section 5 describes the structured methodology used to arrive at the transport fraction estimates used in the parametric evaluation and applies that methodology to develop an estimate of a reasonable debris transport fraction for various LOCA sizes. Finally, Sec. 6 lists the references cited throughout this TLR.

The research documented here was used directly in the generic assessment of the vulnerability of the PWR population to the sump blockage safety concern as presented in LA-UR-01-4083, “GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance.” Details regarding the input data used, the methods applied, and the assumptions made in the parametric evaluation are based on this report.

2.0 SCOPE

One of the specific objectives of the GSI-191 research program was to develop a methodology for estimating debris transport in PWR containments following a LOCA. The overall scope of this effort involved using computational fluid dynamics (CFD) models to predict debris transport and accumulation on the sump screen with the understanding that CFD models would be benchmarked against data obtained from a controlled test program. An experimental program was developed and initiated by Los Alamos National Laboratory (LANL) and the University of New Mexico (UNM) with the specific intention of complementing CFD calculations by providing both (1) basic debris transport characteristics required as an input to the CFD models and (2) integrated three dimensional flume data required to benchmark the CFD model results. The test program to support GSI-191 research has six specific objectives.

1. Characterize the transportability of the debris that might result from a LOCA in a PWR. From these data, derive input parameters appropriate for CFD debris transport calculations.
2. Quantitatively relate debris buildup on sump screens to head loss.
3. Investigate the relative uniformity with which debris may be expected to accumulate on PWR sump screens. This issue was of particular importance for vertical screen arrangements.
4. Identify the features of the containment layout and sump positioning that could affect debris transport and accumulation on the sump screen. Of particular interest are physical features close to the sump screen (e.g., debris curbs).
5. Provide velocity-field and debris-transport data that can be used to benchmark CFD calculations pertaining to three-dimensional (3-D) transport phenomena.
6. Provide insights that can be used to develop guidance for performing plant-specific vulnerability assessments for the debris blockage safety concern. These insights would be included in a so-called “debris source book” that discusses the current state of knowledge of various issues related to the sump blockage safety concern.

The GSI-191 research program, including the experimental initiative, is still underway with the aim of fulfilling these objectives. However, as part of the US Nuclear Regulatory Commission (NRC) and industry efforts to determine the significance of the safety concern, the parametric evaluation for PWR sump performance was performed (as discussed in Sec. 1) before the debris transport test program was completed. This parametric evaluation was aimed at providing a generic assessment of the vulnerability of the PWR population to sump blockage. To support this parametric evaluation, preliminary results and insights from the testing program were applied, as part of a structured methodology, to develop reasonable estimates for debris transport fractions (i.e., the fraction of debris generated that ultimately accumulates on the sump screen) that would be representative for the PWR population following a LOCA. The focus of these estimates was to obtain a “plausible” transport fraction range for fibrous debris, not a best-estimate value. Derivation of best-estimate values would require detailed plant-specific analysis and testing and is not consistent with the spirit of the more generic parametric evaluation. In addition to applying insights from the experimental program, the knowledge gained from the debris transport studies for boiling water reactors (BWRs) was applied while these estimates were developed.

The parametric evaluation was performed to determine whether the debris blockage safety concern could be ruled out for the industry as a whole. The study was intended neither to provide a vulnerability assessment of a specific PWR unit, nor to quantify the likelihood of sump blockage given a LOCA. As such, one rather significant simplification was made while evaluating debris transport fractions for use in the parametric evaluation. This simplification was that only small pieces of fibrous insulation (the individual fibers, or “fines”, in particular) were assumed to contribute to head loss across the sump screen. It was judged that if a potential vulnerability could be shown while making this assumption, including the larger pieces of fibrous material in the analysis would only make the vulnerability assessment worse. The remainder of this report discusses the development of the debris transport fractions used in the parametric evaluation for the fibrous fines and particulate debris.

3.0 ASSUMPTIONS

It was necessary to make several assumptions to estimate the debris transport fractions for use in the parametric evaluation. These assumptions are listed below.

1. A critical part of the parametric evaluation was an assessment of the failure-threshold debris loading (FTDL) for each parametric case that may result in a sump blockage concern. The FTDL metric represents the minimum sump-screen debris loading necessary to induce head loss across the sump in excess of the failure criterion (e.g., $\Delta H_{screen} > NPSH_{Margin}$). As part of this assessment, it was determined that the amount of damaged reflective metallic insulation (RMI) that must be transported to the sump screen to reach the FTDL would be extremely large. Therefore, we did not address RMI transport in the parametric evaluation. Thus, the vulnerability assessment did not, strictly speaking, include the effects of RMI.
2. Large pieces of fibrous debris were assumed not to contribute to screen blockage in the parametric evaluation. As discussed in Sec. 2, this assumption was made primarily to simplify the evaluation. Therefore, large debris is not considered in the debris transport estimates derived here. Ongoing debris accumulation and head loss tests are designed to investigate not only the potential for large pieces of fibrous debris to accumulate on the sump screen but also the potential for large debris to block off pathways that connect various regions of the containment and potentially keep water from entering the sump region. Therefore, consideration of large debris would only increase the likelihood of vulnerability to sump blockage.
3. Erosion and corrosion mechanisms that may degrade fibrous insulation shreds and larger debris were not considered a contributing factor in the debris transport estimates developed for the parametric evaluation. Again, consideration of these phenomena would tend to increase the likelihood of vulnerability to the safety concern.It is assumed that **not** all of the insulation contained in the zone of influence[1] (ZOI) would be generated into “transportable” form. It is assumed that approximately 33% of the insulation would be generated into smaller “transportable” forms.[2] This is generally consistent with findings from BWR debris generation studies, which showed that 23% of destructed insulation would be in the smaller size range (Ref. 4). PWR operating pressures are much higher than BWRs, so a somewhat larger percentage of fine debris generation is not surprising. The other 67% is assumed to be generated in the form of partially torn blankets or large pieces that would sink to the bottom of the pool. However, part of this debris would erode when subjected to falling break water flow, generating smaller transportable pieces. If 10% of the larger debris is assumed to be subject to this type of erosion, approximately 40% of all debris generated can be considered as transportable.
5. The generated insulation fragments would be transported and distributed throughout the containment by an energetic LOCA jet. Only a fraction of this debris would be deposited directly into the pool. The rest of the insulation would not transport to the pool if CS was not activated. This assumption is consistent with analysis of debris transport in BWR drywells (Ref. 5). Vapor flow velocities in containment are much lower for small LOCA (SLOCA) events than for large LOCAs (LLOCAs) (Ref. 6), resulting in less dispersion of debris throughout the containment atmosphere and more deposition of debris in the containment pool.

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[1] The ZOI is usually defined as the zone within which the break jet would have sufficient energy to generate debris of transportable size and form.

[2] Debris generation experiments suggest that up to 50% of the debris may be in transportable form (Refs. 2 and 3). This finding applies to both calcium-silicate and fiberglass insulation. Thus, 33% presents a reasonable estimate considering that not all insulation is arranged as in the configurations tested.

4.0 INSIGHTS FROM EXPERIMENTAL WORK

Three sets of debris transport and accumulation experiments were performed that contributed to development of the debris transport fractions used in the parametric evaluations. These three sets of tests are described below, and details of the experiments and the results are provided in Secs. 4.1 through 4.3. It should be noted that these tests were planned and performed as part of the overall GSI-191 research programs with objectives that extend outside the scope of the parametric evaluation. Detailed test reports for this experimental work are planned for future release. However, the test specifics that provide insights related to development of transport fractions for use in the parametric evaluation are described here.

1. A set of separate-effects tests in a “linear flume” was designed to investigate the transport characteristics of various types of debris in water pools. These tests provide insight into how specific types of debris may behave under known hydraulic conditions.
2. A set of tests was performed in a 3-D tank configured to represent the layout of a representative PWR containment floor. These “integrated” tests provide an estimate of the fraction of debris entering the pool that would accumulate on the sump screen.
3. A set of debris accumulation tests was performed in the linear flume to investigate how fine fibrous and calcium-silicate debris would be expected to accumulate on a PWR sump screen under various flow conditions.

4.1 Debris Separate-Effects Tests

Experiments were conducted at the UNM hydrology laboratory to investigate the pool transport behavior of various types of insulation debris under simulated LOCA conditions. These tests were performed in two open-channel linear flumes, such as the one shown in Fig. 1. A complete description of the flume tests, including discussions of objectives, test methods, detailed apparatus descriptions, test results and test insights, is documented separately (Ref. 7). The remainder of this section provides a brief overview of the test objectives and test results that were relevant to the development of the debris transport fractions used in the parametric evaluation.

The experimental program was designed to collect data on debris transportability as functions of debris type/size, flow patterns, floor type, and fluid velocity. The tests were performed using a variety of debris types, including the fiberglass and calcium-silicate debris types being considered in the parametric evaluation. For each debris type, the test program was designed to study the various mechanisms (e.g., tumbling) available for its transport as a function of fluid conditions. The following properties were selected for measurement based on analytical formulations and literature reviews.

1. **Physical and Settling Characteristics of the Debris**. Debris characterization provides a measure of the debris being tested and thus a practical measure for comparing results from different tests. The debris characteristics measured are (a) the physical size of the debris fragments (recorded photographically), (b) the weight of the debris fragments, and (c) the terminal velocity of a presoaked debris fragment in the water column.
2. **Debris-Settling Velocity in the Flume**. Settling velocity is the velocity at which debris settles in the flume while the fragments are subjected to horizontal flow velocity and residual turbulence simultaneously. By comparing the measured settling velocity of debris fragments in a flume with the terminal velocity measured from settling column tests, insights can be drawn regarding (a) the effect of turbulence on settling and (b) the effect of turbulence and shape factor on horizontal travel distance.
3. **Transport Distance in the Flume**. Transport distance refers to the horizontal distance traveled by a piece of debris dropped at the top surface of the fluid before it touches the floor. These measurements can be used to draw insights into the flow patterns that exist in the flume and their effect on suspended debris transport.

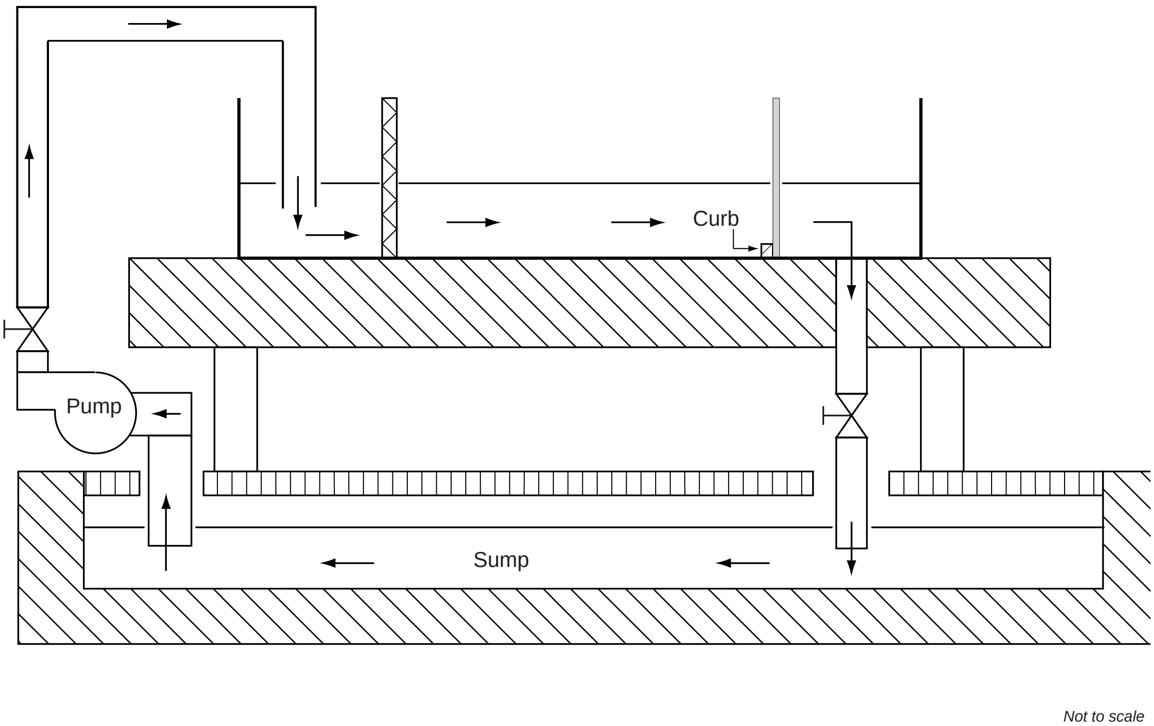

Fig. 1. Schematic of Large Flume Assembly.

4. **Tumbling Velocity**. Tumbling velocity refers to the minimum fluid velocity (averaged over the flume cross section) required to induce tumbling (or sliding) of the debris fragments on the flume bottom. Two metrics were used to provide the range for tumbling velocity: (a) incipient tumbling velocity and (b) bulk tumbling velocity. The incipient tumbling velocity refers to the fluid velocity required to initiate tumbling of the smaller pieces (within a given size class) or to initiate tumbling of pieces with special shapes that provide higher drag coefficient. The bulk tumbling velocity refers to the fluid velocity required to induce 'bulk-scale' movement of a given class of debris.
5. **Vertical Mixing Velocity**.[3] Flow past a stationary fragment of debris induces an upward force commonly referred to as the lift. When the lift provided by the flow is large enough to overcome the gravitational force, debris becomes waterborne (or re-entrained). It is known that at very high fluid velocities, lift would be sufficient to vertically mix the debris to near uniformity. The intent was to measure the fluid velocity that induces vertical mixing.
6. **Lift at the Curb Velocity**. This defines the minimum fluid velocity (averaged over the flume cross section) required to lift a fragment of debris that reaches the curb via tumbling (or sliding) on the floor and transport it upward to be deposited on the screen.
7. **Screen Retention Velocity**. This defines the minimum fluid velocity (averaged over the flume cross section) required to retain the debris fragments on the screen surface.
8. **Dissolution and Erosion of Debris**. Dissolution and erosion of debris when it is subjected to high temperatures and high fluid turbulence were studied. A particular emphasis was on dissolution of calcium-silicate debris in hot water.

Two linear flumes were used to perform the separate-effects tests: a small flume (a 1-ft x 1.5-ft cross section with a 10-ft length) and a large flume (a 3-ft x 4-ft cross section with a 20-ft length). Most of the

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[3] Final test data do not include vertical mixing velocity data because the tests showed that very high velocities would be needed to either resuspend debris or continuously keep debris in the flowing water.

debris transport tests were conducted in the large flume. The large flume was not designed to provide test data that is directly scalable to plant applications; instead, it was designed to serve as a test rig for simulating a variety of different flow conditions and studying the effect of these flow conditions on debris transport, i.e., suitable for conducting separate-effects testing. The large flume apparatus has the following design requirements.

1. The pumping loop was to have sufficient capacity and control to collect debris transport data over a linear velocity range of 0.05 ft/s to 1.5 ft/s. This covers the expected range of screen approach velocities based on data reported in an industry survey of key debris sources and plant features that may strongly influence debris generation, transport, and accumulation in PWRs (Ref. 8).
2. The flume was to be sufficiently wide to accommodate large-scale debris transport without wall effects.
3. The top surface had to be a free surface to simulate the containment sump flow accurately.
4. The flume geometry and physical features had to provide the experimenter with the capability of simulating the variety of flow patterns required by the experimental program.
5. The flume geometry was to provide the flexibility to allow an obstruction to be placed in the flow path (e.g., curbs) and to vary cross-sectional flow area (converging or diverging cross-sections).

As stated above, detailed test results for the separate effects tests are documented under a separate cover (Ref. 8). Insights on the behavior of fiberglass and calcium-silicate debris that were applied during development of the debris transport fractions used in the parametric evaluation include the following

1. Pieces of large fiberglass debris initially float for up to 30 min. While they are afloat, they can be transported by even small fluid velocities. After they become saturated and sink to the containment floor, very high velocities would be needed to move them. Therefore, transport of large debris is very plant-specific and must address issues such as switchover time and screen orientation.
2. Small fiber shreds can be transported at velocities as low as 0.1 ft/s (loosely attached fibers at 0.05 ft/s). Their settling velocities are lower, and small levels of turbulence can keep them in suspension for prolonged periods of time. (In 3-D tank tests, debris transport occurred for several hours.) Small shreds are also susceptible to further destruction during transport. Their transport can be treated generically.
3. Fiberglass insulation fragments (sizes between 1/2 and 1 in.) that have settled to the floor will begin to tumble and slide with a depth-averaged flow of approximately 0.12 ft/s. These fragments also can remain in suspension for prolonged periods of time. Furthermore, these fragments can easily degrade into finer fragments when they are subjected to turbulent mixing flows.
4. Calcium-silicate in fragmented form easily dissolves in hot water and transports as a suspended particulate up to physical diameters approaching 1/2 in.

These four findings were contributing factors to the decision to assess the effect of only small, fine fibrous debris (and particulate) in the parametric evaluation.

4.2 Integrated 3-D Tank Tests

Experiments were conducted at the UNM hydrology laboratory to investigate the integral containment pool transport behavior of various types of insulation debris under simulated LOCA conditions. To perform these tests, a tank was constructed to simulate a generic PWR containment similar to that shown in Fig. 2. The tank characteristics are shown in Table 1. Tank testing parameters were chosen to ensure that, on average, flow conditions in the tank setup are less severe (lower horizontal velocities and lower turbulence levels) than conditions expected to exist in actual containments.

The tests performed in the 3-D tank had several diverse objectives, including developing velocity profiles for various tank configurations that could be used as a benchmark for future CFD calculations. However, the objective that was key for developing transport fractions for use in the parametric evaluation was measuring debris transport to the sump screen for various floor configurations, source locations, and water source (i.e., simulated break) flow rates. As with the linear flume separate-effects tests, a complete description of the 3-D tank tests, including discussions of objectives, test methods, detailed apparatus

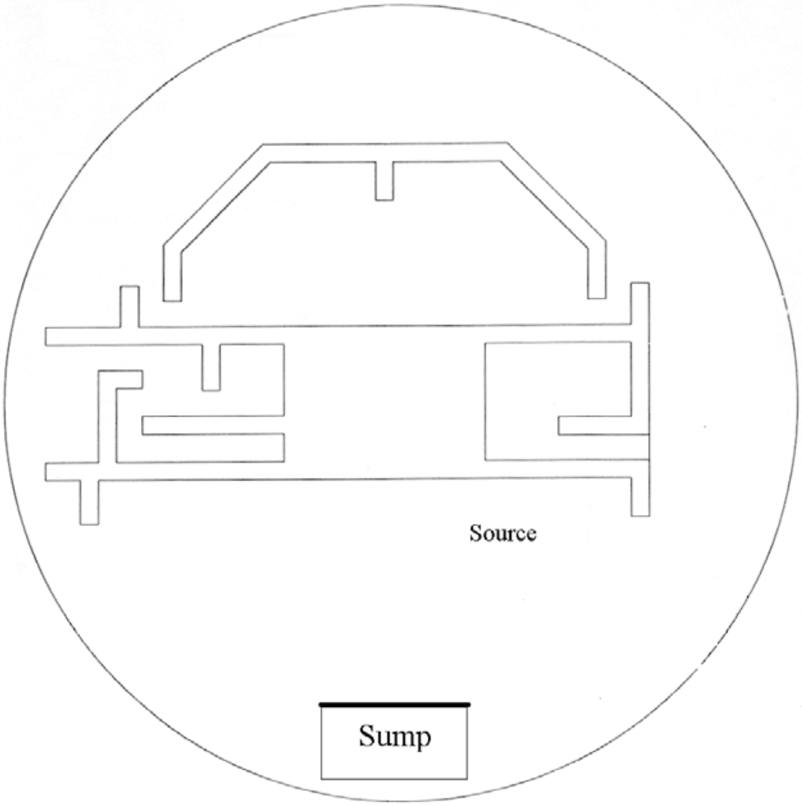

Fig. 2. Schematic of 3-D Tank Layout.

Table 1. Characteristic of 3-D Tank Compared to Generic PWR

	Generic Plant	3-D Tank
Diameter	130 ft	13 ft
Water Height	5 ft	9–16 in.
LLOCA Flow	>10,000 gpm	140–150 gpm
SLOCA Flow	2750–10,000 gpm	40 gpm

descriptions, test results and test insights, is documented separately (Ref. 9). Key points used for development of transport fractions used in the parametric evaluation include the following.

1. On average, 35% of added debris was transported to the sump screen in 3-D tank tests within the first 15–30 minfor flow rates representative of a LLOCA.
2. On average, 15% of added debris was transported to the sump screen in 3-D tank tests within the first 15–30 min for flow rates representative of a SLOCA.
3. Much of the added debris was transported to, and collected in, fairly stagnant areas of the containment pool. As a result, the long-term tests did not show significant increases in transport to the sump screen after the first 30–60 min.

4.3 Debris Accumulation Tests

Three basic assumptions must be made to apply the NUREG/CR-6224 head-loss correlation to the evaluation of potential head loss for PWR sump screens. These are (a) a uniform 1/8-in.-thick bed (minimum) would form on the screen surface and filter out particulate debris passing through it, (b) the beds can survive significant head losses across them, and (c) buildup of such beds is possible even for a screen mesh clearance size of ¼ in. A series of debris accumulation tests was performed in the large linear flume to address the applicability of these assumptions to a typical PWR sump screen. Tests were performed for flow rates that would produce screen approach velocities representative of the range expected in the PWR population for response to SLOCA, medium LOCA (MLOCA) and LLOCA events. Tests were performed using fiberglass[4] and calcium-silicate debris (separately and mixed).

Significant findings from the debris accumulation tests include those below.

1. The debris accumulation tests demonstrated that small shreds of fiberglass and fines would create a uniform debris bed on a 1/8-in.-mesh vertical screen at pool velocities as low as 0.1 ft/s. Further, measurable head loss was observed when these debris beds were as thin as 1/10 in.
2. Very small approach velocities (<0.05 ft/s) are sufficient to keep a piece of fiberglass debris attached to a vertical sump screen. Buildup of thicker (1- to 2-in.) fiber beds would be necessary to induce the high head losses necessary to overwhelm the $\mathrm{NPSH}_{\mathrm{Margin}}$. However, fibrous debris readily detaches from the screen when flow through the screen is terminated.
3. Fibrous debris buildup in the presence of calcium-silicate is very similar to buildup in its absence (see Fig. 3). Close inspection of the debris bed shown in Fig. 3 reveals very small to microscopic calcium-silicate granules imbedded in a complex fiber mat. The broken bed to the right of the photo was damaged during screen removal. The nominal fiber bed thickness is 1/10 in. Although a debris bed made up of calcium-silicate looks similar to a pure fiber bed, the calcium-silicate and fiber beds behave differently. Very small quantities of fibrous debris may induce very large pressure drops if calcium-silicate is present. In fact, a very thin bed could induce large pressure drops. For example, the bed shown in Fig. 3 caused a head loss in excess of 1 ft-water (and still increasing when the experiment was terminated[5]). However, upon termination of flow, the debris remained intact on the screen instead of crumbling as noted in the case of pure fiber beds.
4. Figure 4 shows the initial growth of a fiber bed on a ¼-in.-mesh screen. Note how individual fibers are able to stretch across the corners of the mesh and gradually reduce the effective opening. At this point of bed development, the solid patches of fiber represent the larger flocks of debris that were suspended in the water flow. After several minutes, the fiber mat becomes contiguous, causes significant head loss, and is virtually indistinguishable from similar beds formed on 1/8-in.-mesh screens.

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[4] Only small shreds of fiberglass and fines were introduced to the flume for these tests.

[5] The experiment was terminated because a temporary arrangement was used to perform these ‘quick-look’ experiments. There was a concern that this screen may fail. Besides, head-loss measurement was not part of this set of experiments.

Fig. 3. Screen of 1/8-in. Mesh Opening Obstructed by Calcium-Silicate.

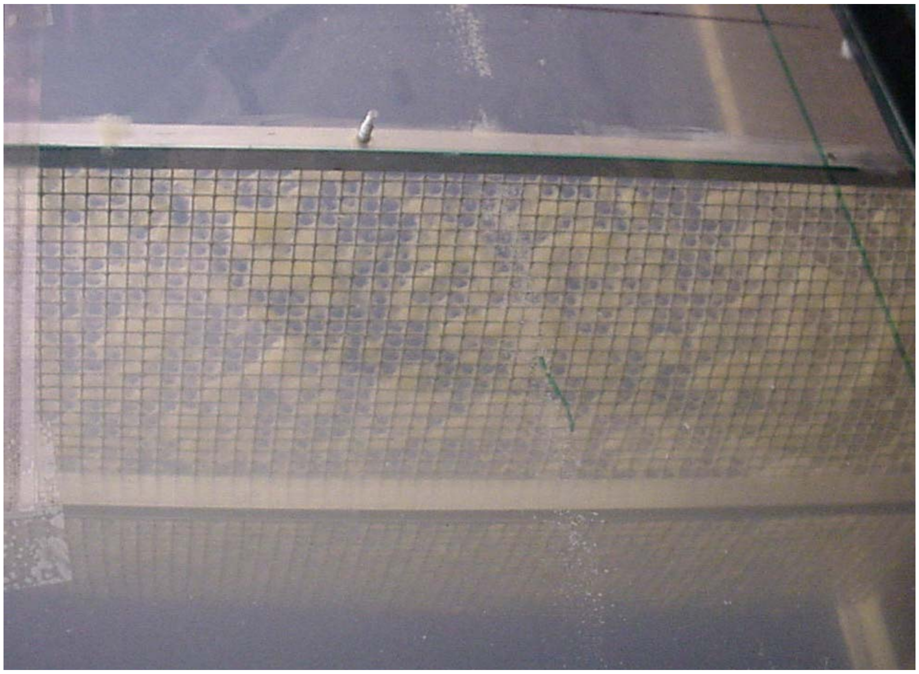

Fig. 4. Thin Fiber Bed Beginning to Build on Vertical Screen of 1/4-in. Mesh Opening.

5.0 DERIVATION OF INTEGRAL TRANSPORT FRACTIONS

Different LOCA phenomena that would influence debris transport must be considered to develop transport fractions for use in the parametric evaluation. It should be reiterated here that this discussion focuses on the transport of small shreds and individual fibers from fiberglass insulation and calcium-silicate insulation debris. Figure 5 shows the different phenomena that may influence debris transport during a LOCA and describes what tools might be used to perform a detailed assessment of debris transport behavior. For the parametric evaluation, a more generalized approach was used to assess reasonable values for an integral debris transport fraction for the various LOCA sizes. A logic tree (Fig. 6) was applied to quantify the three primary transport phenomena: (a) air transport during **blowdown**, (b) **washdown** transport from erosion and containment sprays during the injection phase of the accident, and (c) **water transport** in the containment pool after recirculation is established. Sections 5.1 through 5.3 address the quantification of the logic tree for these three transport phenomena. Note that the size of debris generated is important in determining an integral transport fraction because large debris is assumed not to transport in this analysis. The debris that is assumed to be generated in transportable form is 40% of the total debris generated as shown in Fig. 6 (see Assumption 4 in Sec. 3.0).

Although many of the numbers derived in the following sections are based on experimental evidence or phenomenological analysis or are inferred from previous debris transport studies performed during the BWR strainer studies, engineering judgment is a significant contributor to the quantification of the debris transport fractions for use in the parametric evaluation. Every attempt was made to arrive at reasonable and defensible values for each parameter addressed. Care was taken not to develop conservative values for transport fractions, but rather reasonable "best-estimate" values based on information available. One exception to this practice was the quantification of water transport fractions (see Sec. 5.3). In this case, the range of transport values based on GSI-191 experimental evidence was relatively large. As such, minimum (or favorable) and maximum (or unfavorable) transport values were estimated to bound the problem.

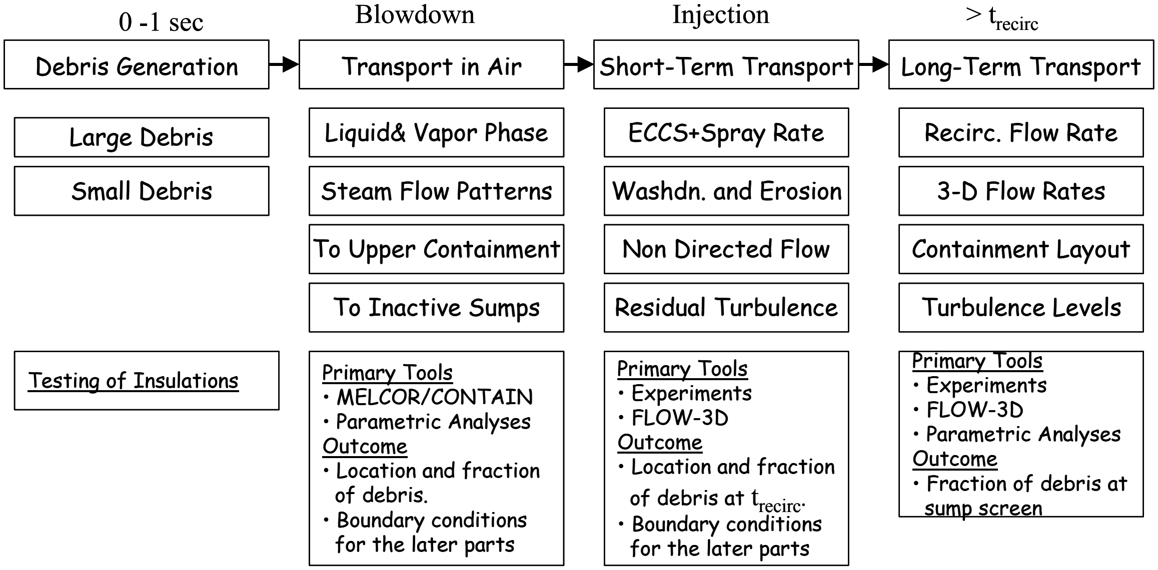

Fig. 5. Debris Transport Phenomenology.

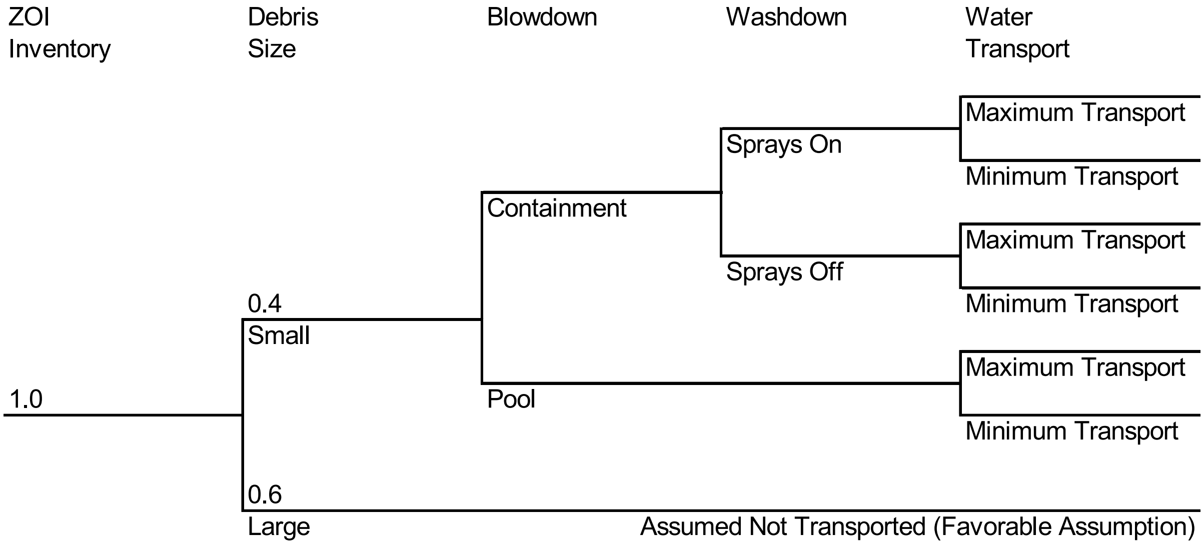

Fig. 6. Logic Tree for Quantification of Debris Transport During a LOCA.

5.1 Transport During Blowdown

During the blowdown phase of the accident, transport will occur as debris is entrained in air and steam moving throughout the containment. Figure 7 show debris transport during the blowdown phase of the LOCA. Containment atmospheric flows have no dominant direction during blowdown. Thus, when higher atmospheric velocities exist, it is expected that debris will be deposited throughout the containment. MELCOR analyses have been performed in support of the GSI-191 research program that characterize containment response for the full range of postulated LOCA sizes (Ref. 6). These calculations showed that atmosphere velocities in excess of 100 ft/s could be expected during the blowdown phase of a LLOCA, which would likely result in wide dispersal of destroyed insulation. Further, even for SLOCA events, velocities as high as 30 ft/s can be expected in the containment atmosphere. Therefore, some dispersal of small insulation fragments into the upper and lower containment annulus can be expected for any LOCA event that would generate significant amounts of insulation debris, although dispersal will increase with higher atmospheric velocities. Note that larger debris pieces may be trapped on containment floor surfaces, gratings, or equipment. For this analysis, it was assumed that no large insulation debris was transported to the containment pool. MELCOR calculations confirm that the large containment atmosphere velocities associated with the blowdown phase of a LOCA will subside after approximately 30 s.

Based on information obtained from the BWR drywell debris transport study (Ref. 5) and engineering judgment, the fraction of small debris that is assumed to be entrained by steam and transported to the upper portions of containment is 60% for LLOCA events and 25% for SLOCA events. For large atmospheric velocities, such as those calculated by MELCOR for LLOCA events, it is expected that the majority of the small debris fragments and fines will be entrained in the steam (or mist) and be distributed throughout the containment. However, it is expected that the small fragmented debris would be wet and therefore be more likely to fall to the containment pool than to be carried elsewhere unless those very high velocities exist. With SLOCA atmosphere velocities of 30 ft/s, the majority of debris is expected to fall to the pool, although significant deposition of debris throughout containment cannot be ruled out. These transport fractions, 0.60 to the “containment” and 0.40 to the “pool” for the LLOCA and 0.25 to the “containment” and 0.75 to the “pool” for the SLOCA, will be reflected in the partially quantified logic tree in Figs. 8 and 9.

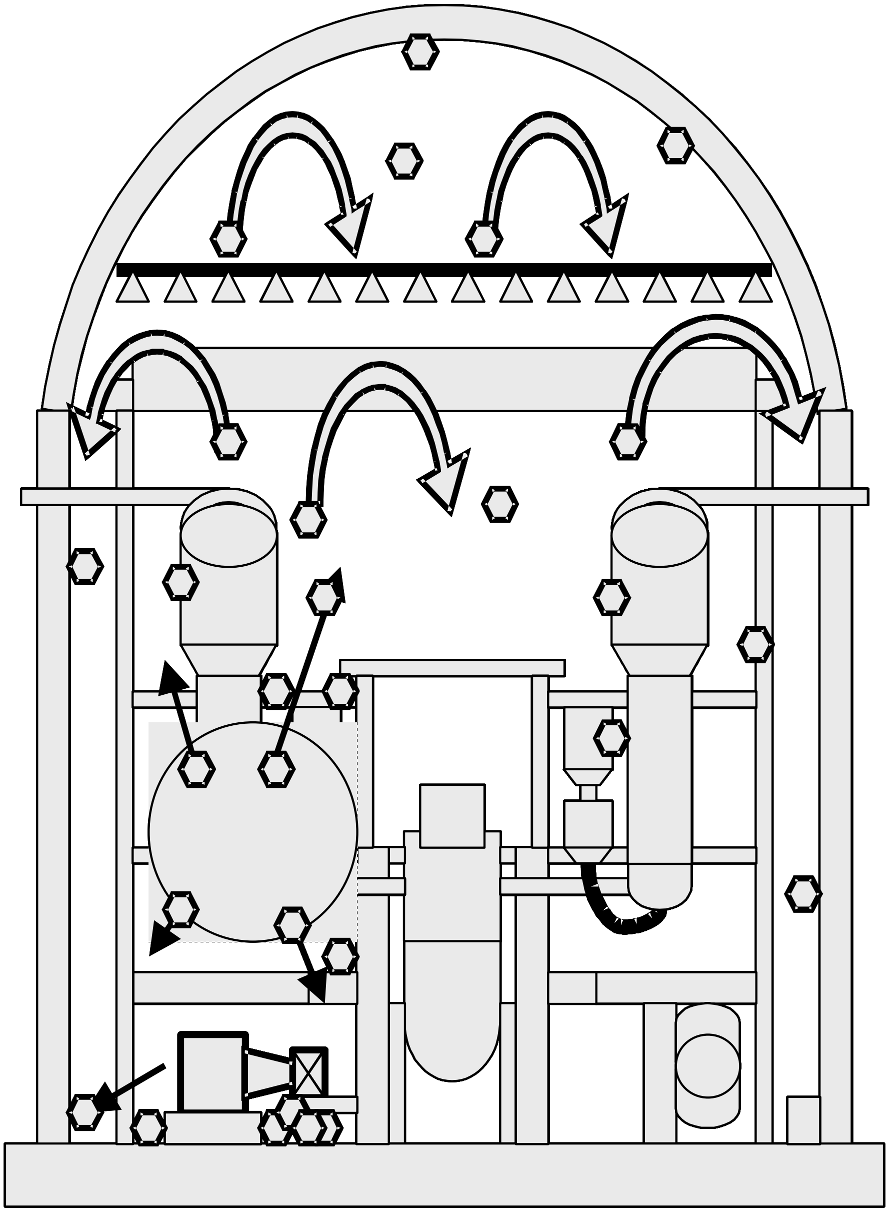

Fig. 7. Debris Transport During LOCA Blowdown.

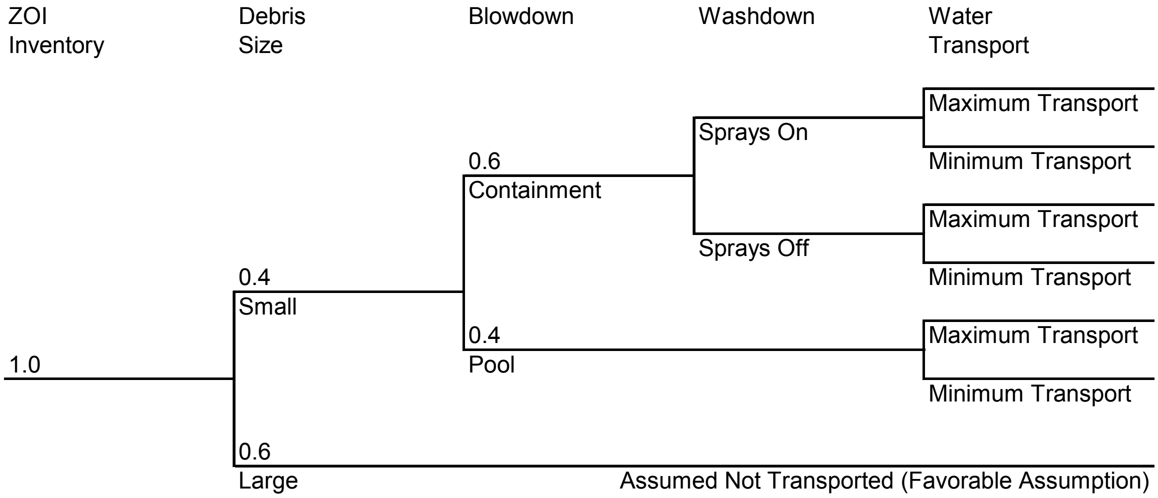

Fig. 8. LLOCA Logic Tree—Blowdown Transport Quantified.

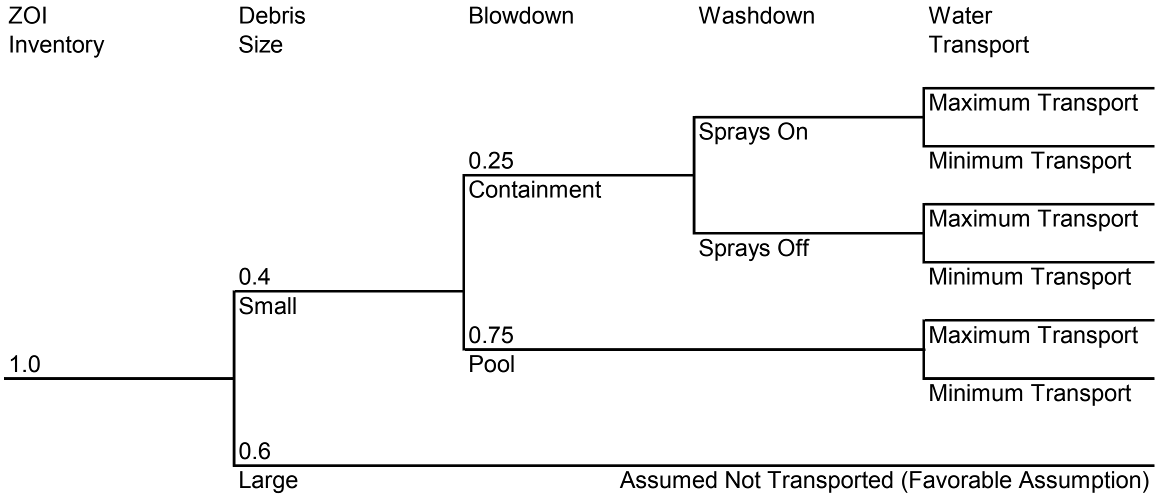

Fig. 9. SLOCA Logic Tree—Blowdown Transport Quantified.

5.2 Washdown Transport During the Injection Phase

During the injection phase of the LOCA, debris that initially was deposited in the upper regions of the containment may be transported to the pool as a result of erosion caused by the high steam environment. This effect is not expected to contribute significantly to debris transport. However, information documented during BWR analysis of debris transport (Refs. 4 and 5) suggests that erosion of debris in the vicinity of the break may result in as much as 5% debris transport to the pool. This will be reflected as a transport fraction of 0.05 on the "Sprays Off" branch of the quantified logic tree under the "Washdown" category. When containment sprays operate, water is introduced to the containment at flow rates exceeding 8000 gpm (Ref. 8). These sprays form liquid films on containment surfaces where debris may have been deposited. MELCOR film drainage models have been developed as part of the assessment of the containment response to LOCA events. These models were designed to identify spaces and surfaces where insulation debris would not likely be washed away by sprays or drainage flow (e.g., an area that is not affected by sprays or that has too little drainage flow to transport debris). Based on these models, washdown of up to ¾ of the debris deposited on containment surfaces cannot be ruled out. This will be reflected as a transport fraction of 0.75 on the "Sprays On" branch of the quantified logic tree under the "Washdown" category. This value is independent of the LOCA size and is solely a function of whether or not sprays operate. Figures 10 and 11 show the partially quantified logic trees including the washdown fractions for LLOCA and SLOCA, respectively. Note that the washdown transport fraction is 1.0 for debris that has already been relocated to the pool during blowdown.

5.3 Transport During the Recirculation Phase

The results from the ongoing GSI-191 debris transport test program played a key role in determining the containment transport fractions and thus the quantity of insulation expected to reach the sump. The principal basis for the water transport estimates was the series of 3-D tank transport tests discussed in Sec. 4.2. Given the results of the transport tests for recirculation flow rates representative of LLOCA and SLOCA events, it was concluded that minimum transport fractions of 0.35 and 0.15 could be supported for LLOCA and SLOCA events, respectively. Further, because of increased recirculation requirements for SLOCA events where sprays operate, it was judged that transport for SLOCA events with sprays would fall between these two values. Therefore, we defined a minimum transport fraction of 0.25 for this condition.

CFD simulations of various plant configurations suggest that, in many containments, transport velocities could be much higher than those representative of the 3-D tank tests. For LLOCA events, a maximum water transport fraction of 0.75 was assigned to reflect the potential effects of these higher velocities. Maximum water transport fractions were also increased for SLOCA events. A maximum transport fraction of 0.65 was assigned when sprays operate, and a value of 0.35 was assigned when sprays do not operate. These minimum and maximum transport fractions are applied in the completed logic trees shown in Figs. 12 and 13 for the LLOCA and SLOCA events, respectively.

Based on the information shown in the logic trees in Figs. 12 and 13, the sequence transport fractions can be summed based on the sequence characteristics, arriving at the integral transport fractions shown in Table 2.

Transport fractions were developed for use in the parametric evaluation based on the information in Table 2. First, it was determined, based on RELAP5 calculations, that the break flow rates for MLOCA events were similar enough to those for LLOCA events to treat them as equal for the purposes of defining integral debris transport fractions. Although distinctions between LLOCA and MLOCA events could be made with plant-specific analyses, the generic application of these values to the PWR population as a whole, along with the fact that engineering judgment was a large factor in developing these values, made development of separate MLOCA transport fractions unwarranted. Second, based on the MELCOR-calculated containment pressure response for MLOCA and LLOCA events, it was determined that CS actuation would always be required for these events. The typical spray system failure probability is sufficiently low that analysis of LLOCA/MLOCA events with no sprays was neglected as part of the parametric evaluation. Finally, the actual values for use in the parametric evaluation were approximated (i.e., rounded off to the nearest 5%) based on the values in Table 2. The resulting integral transport fractions used in the parametric evaluation are shown in Table 3.

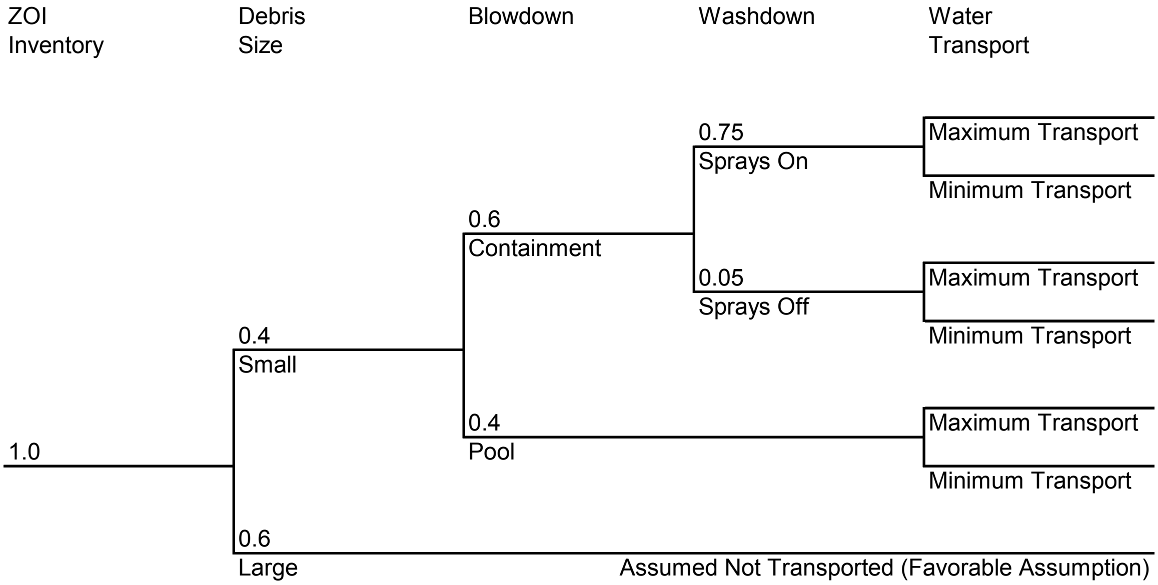

Fig. 10. LLOCA Logic Tree—Washdown Transport Quantified.

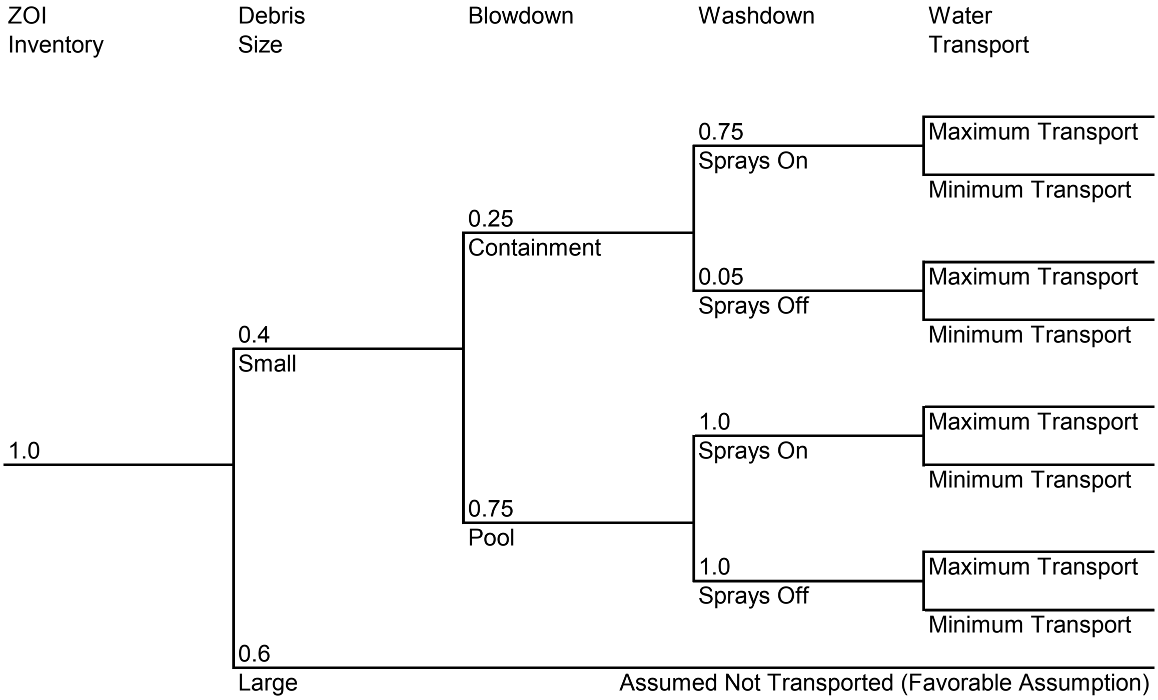

Fig. 11. SLOCA Logic Tree—Washdown Transport Quantified.

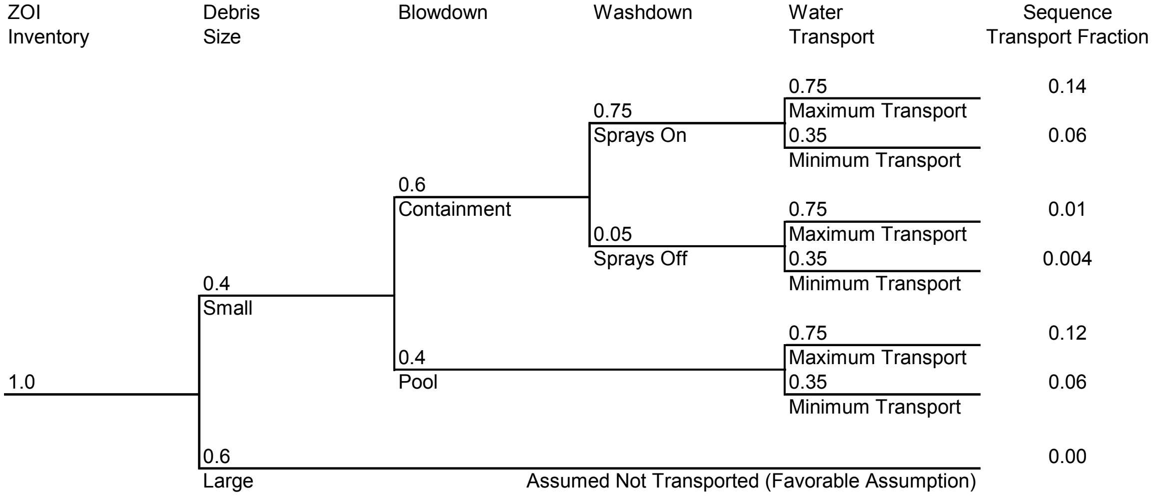

Fig. 12. Quantified LLOCA Logic Tree.

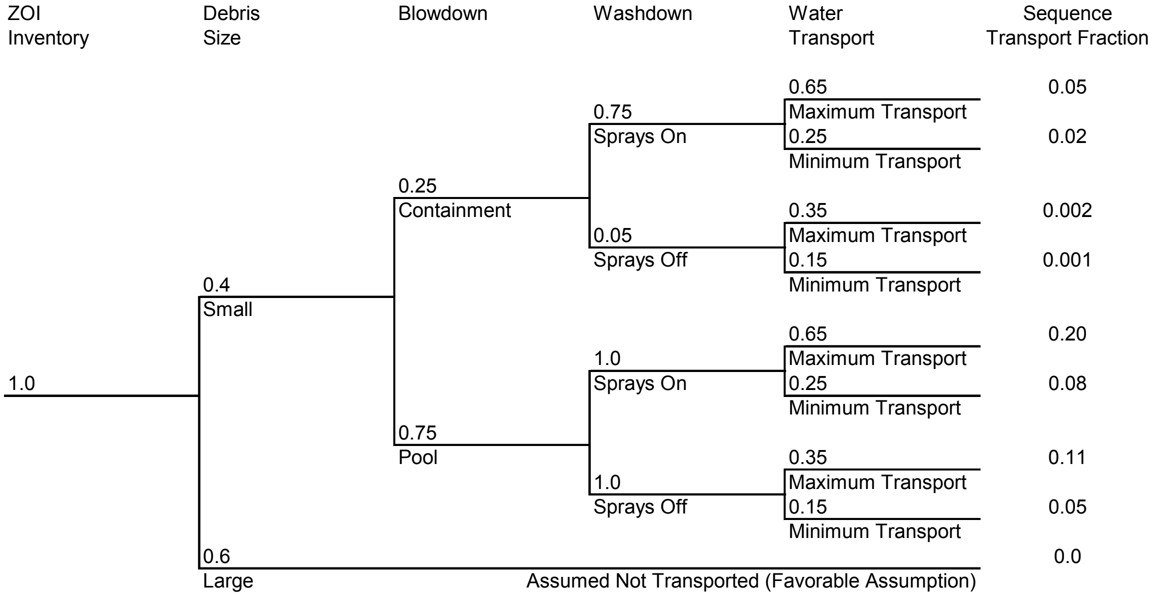

Fig. 13. Quantified SLOCA Logic Tree.

Table 2. Integral Transport Fractions Based on Logic Trees

Transport Conditions	Favorable Estimate	Unfavorable Estimate
SLOCA with No Sprays	0.05	0.11
SLOCA with Sprays Active	0.09	0.24
LLOCAs with No Sprays	0.06	0.13
LLOCA with Sprays Active	0.12	0.26

Table 3. Integral Transport Fractions for Use in Parametric Evaluation

Transport Conditions	Favorable Estimate	Unfavorable Estimate
Small LOCA (SLOCA) with Sprays Inactive	0.05	0.10
SLOCA with Sprays Active	0.10	0.25
All Medium LOCAs (MLOCAs) and Large LOCAs (LLOCAs)	0.10	0.25

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