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DEVELOPMENT OF DEBRIS-GENERATION QUANTITIES 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 in the vicinity of the break will be damaged and dislodged, and a fraction of this material will be transported to the ECCS recirculation sump. The debris that accumulates on the sump screen acts as a filter that impedes flow. Excessive head loss across the debris may exceed the net positive suction head (NPSH) margin of the ECCS or containment spray (CS) pumps.

A parametric evaluation was performed to determine whether sump failure is a plausible concern for operating PWRs. The research documented here was used directly in that generic assessment of the vulnerability of the PWR population to the sump blockage safety concern as presented in Los Alamos National Laboratory report LA-UR-01-4083, "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance." Details on the input data used, the methods applied, and the assumptions made in the parametric evaluation are provided in this report. The parametric evaluation included performing appropriate technical calculations supported by experimental data to provide estimates of debris-generation quantities. This report documents the methodology and assumptions used to determine the debris-generation quantities that were used in the parametric evaluation.

The approach to estimating the potential for sump failure for each case in the parametric evaluation was to first perform a debris estimate for a volunteer plant where sufficient detail was available to develop a credible estimate. Then, the limited insulation data of the other operating PWR units (on which the parametric cases were based) were used to essentially scale the results of the volunteer plant to each of these other units to form a credible debris-generation estimate for the 69 parametric cases. Because of information limitations, these estimates are not considered best-estimate plant-specific values. Instead, they represent a credible (but not bounding) range of debris-generation estimates for the industry as a whole. We assumed the same total insulation debris volume for each of the parametric cases (based on the volunteer plant analysis) and used plant-specific insulation composition fractions to scale those total volumes to determine type-specific debris volumes for each parametric case. The methodology is shown in Fig. ES-1. Even with the clear limitations associated with this approach, it was the best surrogate available to evaluate the industry-wide vulnerability to sump blockage using the limited plant-specific data that were available.

The debris-generation approach necessarily had to consider the extent of uncertainties resulting from both data unavailability and stochastic uncertainty in accident progression, but it had to do so in a manner that was not overly conservative. The approach, as implemented, tended toward best estimate-analysis while at the same time identifying the uncertainties. First, the experience and knowledge accumulated during the resolution of the issue for the boiling water reactor (BWR) plants were applied. Specifically, models recommended by the BWR Owners Group (BWROG) and approved by the Nuclear Regulatory Commission (NRC) were used. For example, the BWROG spherical zone-of-influence (ZOI) model was used but with an enhancement to compensate for the recent Ontario Power Generation (OPG) two-phase jet test data that indicate destruction of insulation at lower pressures for a two-phase jet than for an air jet.

With the approach described above, debris quantities were calculated for a number of potential break locations. The 95th percentile debris-generation volumes then were developed for application to each of the 69 parametric cases. These are shown in Table ES-1. The application of these values to each of the parametric cases is discussed in the body of the report with specific examples. Details of the values generated for each case are provided in the parametric evaluation report (LA-UR-01-4083, 2001).

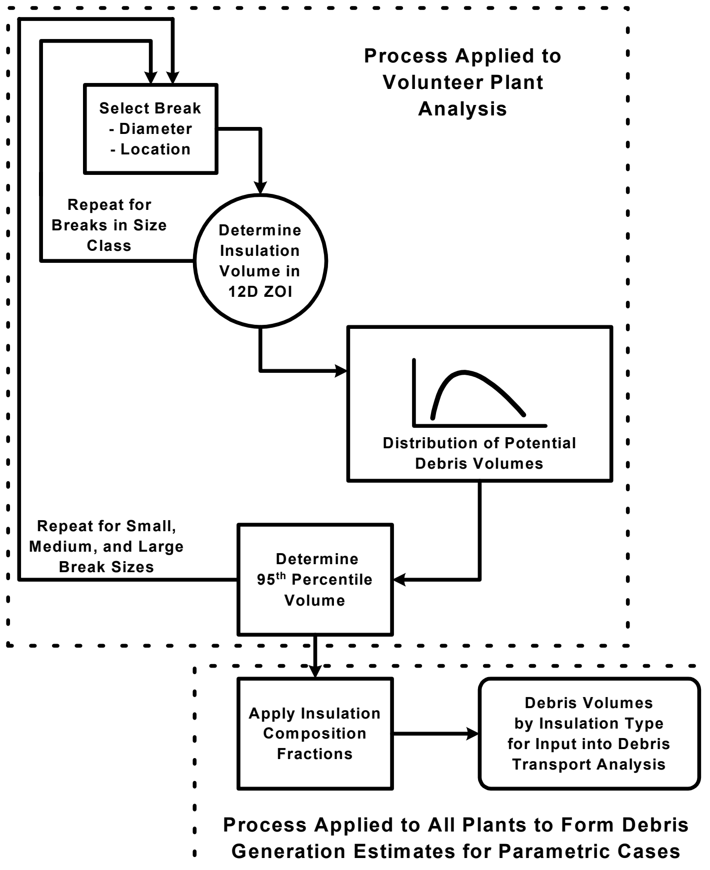

Fig. ES-1. Debris-Generation Methodology.

Table ES-1. Summary of Debris-Generation Volumes.

Break Size	95^{th} Percentile Debris-Generation Volumes (ft^3)
SLOCA	25
MLOCA	40
LLOCA	1700

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LIST OF ACRONYMS AND ABBREVIATIONS

AJIT	Air Jet Impact Testing
ANS	American Nuclear Society
ANSI	American National Standards Institute
BWR	Boiling Water Reactor
BWROG	BWR Owners Group
CAD	Computer-Aided Drafting
CFD	Computational Fluid Dynamics
CS	Containment Spray
DEGB	Double-Ended Guillotine Break
ECCS	Emergency Core Cooling System
GSI	Generic Safety Issue
HDFG	High-Density Fiberglass
LANL	Los Alamos National Laboratory
LDFG	Low-Density Fiberglass
LLOCA	Large Loss-of-Coolant Accident
LOCA	Loss-of-Coolant Accident
MLOCA	Medium Loss-of-Coolant Accident
NEI	Nuclear Energy Institute
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
OPG	Ontario Power Generation
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RMI	Reflective Metallic Insulation
SER	Safety Evaluation Report
SLOCA	Small Loss-of-Coolant Accident
TLR	Technical Letter Report
URG	Utility Resolution Guidance
USI	Unresolved Safety Issue
ZOI	Zone of Influence

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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 (Los Alamos National Laboratory report LA-UR-01-4083, 2001). 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. 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. Details regarding the input data used, methods applied, and assumptions made in the parametric evaluation are provided in this report.

The parametric evaluation included performing appropriate calculations supported by experimental data 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 quantities of debris generated that were used in the parametric evaluation and provides an explanation of the method and assumptions used beyond what was included in the parametric evaluation report.

The approach to the parametric evaluation, i.e., the methodology, assumptions, and key input data used in the parametric evaluation and the relationship to the overall objectives of the GSI-191 research program are discussed in Sec. 2. Section 3 discusses the rationale and justification for the assumptions used to estimate debris quantities. Section 4 provides an overall discussion regarding the methodology using these assumptions. Finally, Sec. 5 lists references cited in this TLR.

2.0 PARAMETRIC EVALUATION APPROACH

Estimating the quantities of insulation debris generated by a LOCA is a complex task, and substantial uncertainty is associated with the estimates. To make matters more difficult, the debris quantities were to be evaluated for all operating PWR plants to form the bases for the 69 parametric cases. One volunteer plant with sufficient information was evaluated in detail to estimate the amount of debris that could be generated following a LOCA at that plant. This estimate then was used as a basis for estimating the debris volumes for each of the 69 parametric cases in the generic vulnerability assessment. This section summarizes the methodology and assumptions used to estimate the debris-generation quantities used in the parametric evaluation. Section 2.1 presents a general discussion of the various accident phenomena considered while the debris-generation evaluation was performed. Section 2.2 details the methodology applied and identifies assumptions made in the parametric evaluation. Justifications for each of these key assumptions are discussed in Sec. 3.

2.1 Debris-Generation Phenomenology

Phenomena that control debris-generation estimates for a LOCA include a variety of potential pipe break locations, sizes, and orientations; the break effluent; the congestion of piping near the break; the variety of insulation types and insulation jackets; the orientation of the insulation relative to the break; and the shielding of the insulation by walls and equipment. Potential breaks range from small cracks to a double-ended guillotine break (DEBG). The shape of the break jet and the subsequent region of destruction depend on many factors, such as the separation of the broken pipe ends (both radially and axially). Potential break sizes range from those associated with small pipes (less than 2 in. in diameter) to those associated with the large primary and secondary pipes (as large as 42 in. in diameter).

Most, if not all, of the reactor coolant system (RCS) piping and auxiliary piping (e.g., service water piping) in PWRs is insulated. Estimating insulation debris generation from a LOCA is complicated by many factors, including, but not limited to, the following.

- The spatial arrangement of piping systems and equipment that can serve both as targets and as locations of high-energy breaks.
- The spatial distribution of insulation types and thickness.
- The relative potential of breaks occurring in various sizes of pipes and piping locations such as walls and elbows.
- The unknown destruction response of each insulation type and of concrete and coatings to a two-phase depressurization jet.
- The unknown range and shape of a two-phase depressurization jet in the presence of obstacles such as concrete structures and adjacent piping.
- The exact location, severity, and jet direction of a given LOCA event.

The high-energy piping in PWR plants is insulated with a variety of insulation types, generally categorized as fibrous insulation, reflective metal insulation (RMI), particulate insulations, foam insulations, and hardened materials (NEI, 1997). A variety of fibrous insulations are used, including low-density fiberglass (LDFG) such as Nukon®, high-density fiberglass (HDFG) such as Temp-Mat, fine mineral wool fibers, and miscellaneous fibers such as Kaowool. Several types of RMI insulation are used. The particulate insulations (referred to as “particulate” because particulate is produced when these insulations are destroyed) include calcium-silicate, Min-k, asbestos, Unibestos, and Microtherm. Foam insulations include neoprene, foamed plastic, flexible anti-sweat foam, and foamglass. Hardened material would include materials such as Marinate board. The foam insulations were screened out from further analysis in the parametric evaluation because foam debris tested in GSI-191 separate-effects tests tended to float on the water surface and therefore would not be likely to block the sump screens completely. Marinate-like materials were screened out because debris from these materials readily sank and would not be likely to transport to the sump screens.

The remaining insulations were categorized into one of three categories for the purposes of the parametric evaluation: fibrous, RMI, and calcium silicate. A variety of methods are used to secure the insulation materials to the piping and equipment. A covering material such as canvas or metal sheeting surrounds the insulating material. The covering material is secured in place by bands or straps such as canvas straps or steel bands; the straps and bands are in turn secured by a variety of latches. Before the jet stream can damage the insulation material, the jet must remove or deform the covering material, exposing the insulating material. The jet impingement load required to do this depends on the type of covering, banding, and latches used. Further, it depends on the jet impingement load on the cover seams, which in turn depends on the orientation of the seam with respect to the jet.

The shape of the break not only depends on the separation of the broken pipe ends but on the structures and other piping located within the jet region as well. For example, a wall or another pipe would deflect and redirect the jet. Pipe congestion could transform the shape of the DEGB jet destruction zone from the double-sided conical shape of a free jet to a more spherical shape. The jet impingement pressures depend on the distance from the jet (both centerline and offset distances) and on the effect of structures and piping congestion. The pressure required to damage an insulation cover depends on the orientation between the covering and the jet. The pressure varies along the seam and the covering surface. The pressure at the weak point tends to determine whether a covering fails. In reality, the boundary between damaged and undamaged material would not conform to a definite boundary volume. Some piping insulation closer to the break could remain intact, whereas other insulation further away could fail simply as a result of such details as the orientation of the seam relative to the jet.

Obviously, simplifying assumptions were needed to render this analysis tractable. These will be identified in the discussion of the methodology provided below.

2.2 Methodology

The primary methodology was plant-specific (Sec. 2.2.1) and designed to perform a detailed evaluation of the volunteer plant; a generic scaling methodology (Sec. 2.2.2) was used to evaluate each of the 69 parametric cases in the parametric evaluation. The overall methodology, which is discussed in this section, is shown in Fig. 2-1, and the assumptions are summarized in Table 2-1. Where the justification for these assumptions required substantial discussion, those discussions are located in Sec. 3.

2.2.1 Plant-Specific Methodology. The plant-specific methodology consisted of (1) defining a zone of influence (ZOI) around the postulated break, with the ZOI defined as the volume surrounding the break location in which insulation is expected to be damaged by the LOCA depressurization jet; (2) estimating the degree of insulation damage (specifically estimating the volumes of debris that can reasonably be transported to the sump screens); and (3) systematically performing a sampling of potential pipe breaks to determine the range of potential debris volumes (and constructing a cumulative distribution function). The 95th percentile of this distribution then was used in the parametric evaluation to assess the likelihood of sump screen blockage.

2.2.1.1 Zone of Influence. Specifying the ZOI required using an assumption about its shape and orientation around the break and its size. The shape of the ZOI associated with a free jet would resemble the shape of the jet effluent, and the jet impingement force anywhere within this ZOI could damage insulation. A DEGB with separated pipe ends could form two free jets in opposite directions. In a congested area, which is common in nuclear containments, piping and structures would tend to deflect the jet into different directions, perhaps forming a ZOI that was more spherical.

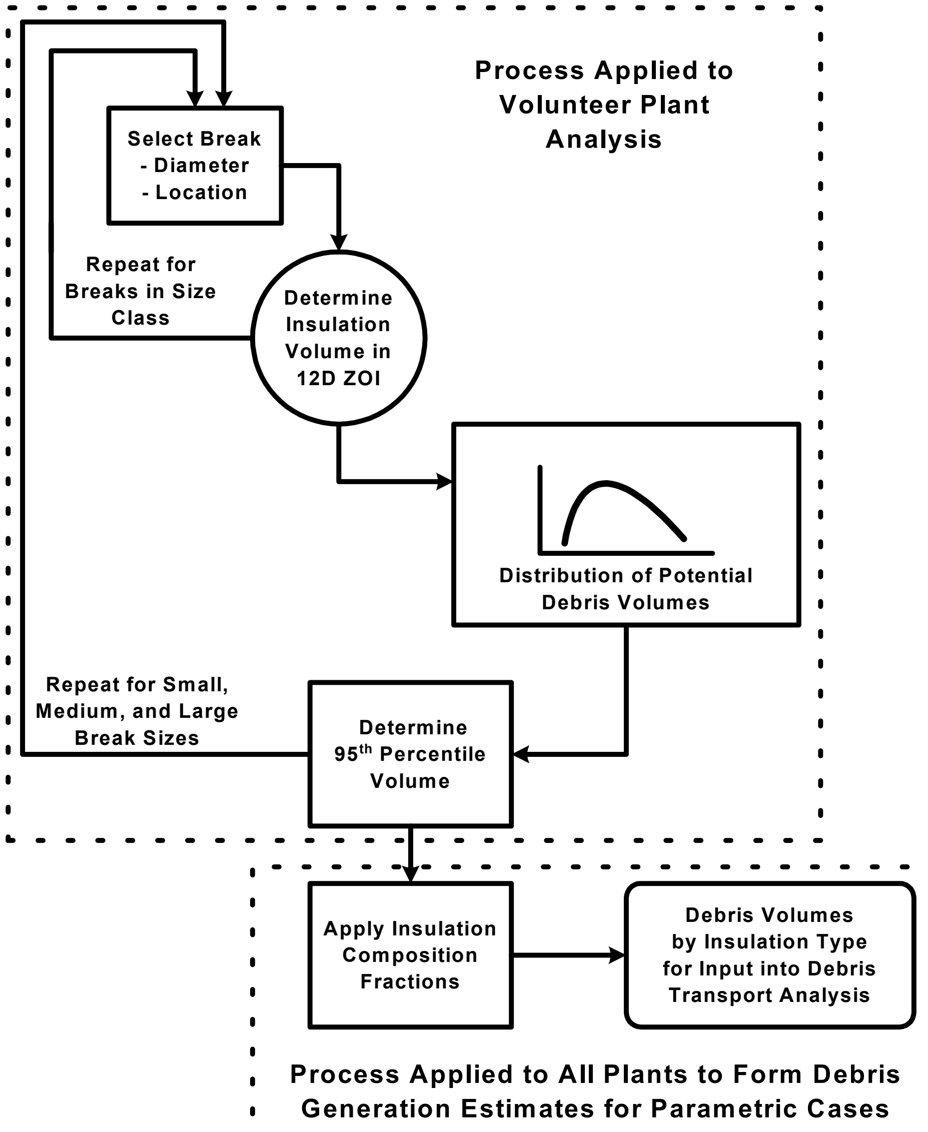

Fig. 2-1. Summary of Debris-Generation Methodology.

Table 2-1. Summary of Debris-Generation Assumptions.

No.	Assumption	Basis of Assumption	Discussion of Justification
1	The ZOI has a spherical shape with same volume as that of a free jet.	Best accepted method of accounting for variable pipe break separation geometries and effect of piping congestion.	Section 3.1.1
2	Minimum damage pressure used to define ZOI corresponded to destruction pressure for a typical LDFG insulation.	LDFG common in PWR plants, easily damaged, and substantial data exist regarding its destruction.	Section 3.1.2
3	Spherical ZOI Radius was 12D.	Boiling Water Reactor Owner's Group (BWROG) and Ontario Power Generation (OPG) jet impact testing.	Section 3.1.3
4	33% of the insulation within the ZOI was damaged into small debris that could transport relatively easily.	BWROG and OPG jet impact testing.	Section 3.2
5	67% of the insulation within the ZOI was damaged but either remained blanketed insulation (intact or damaged) or became larger debris that would not likely transport following the completion of blowdown.	BWROG and OPG jet impact testing.	Section 3.2
6	10% of the remaining intact insulation and large debris was eroded by post-LOCA flows, forming additional small transportable debris.	BWR resolution research.	Section 3.2
7	Only breaks in high–energy (>500 psig) piping were evaluated.	Break effluent from low-energy pipe breaks would not likely generate significant debris.	Section 3.3.1
8	Pipe diameters were subdivided into ranges associated with small, medium, and large LOCAs (Table 2-2).	Generally accepted pipe diameter ranges.	Section 3.3.2
9	insulation on pipes smaller than 2 in. in diameter was neglected.	Insulation quantities considered negligible for the purposes of the parametric evaluation.	Section 3.3.2
10	Pipe shielding by walls and other piping was neglected.	Necessary to keep analysis tractable.	Section 3.3.3
11	The 95th percentile of debris volume distributions was used as the basis for the strainer blockage vulnerability assessment (before the transport analysis)	Avoids the extreme conservatism of using the debris volume of the single worst break while still compensating for uncertainties in the analyses.	Section 3.4
12	Insulation within containment was uniformly distributed, i.e., homogenized.	Other than the volunteer plants, the plant-specific data consisted of containment-wide volume distribution fractions. Therefore, nonuniform distributions were not possible with available data.	Section 3.5.1
13	The volunteer plant was representative of PWR industry.	There was no other reasonable alternative for the parametric evaluation. The variability of piping congestion and insulation distributions cannot be fully assessed without substantial additional plant-specific information. However, all plants have much the same inventory of systems and likely have similar levels of congestion.	Section 3.5.2
14	Where insulation composition fractions were unavailable, ranges of values (favorable to unfavorable) were used to bracket results.	Method used to bracket results where plant-specific input was unavailable.	Section 3.5.3

Method 2 from the BWROG Utility Resolution Guidance (URG) (BWROG, 1998) was adopted for use in the PWR parametric evaluation. In Method 2, a ZOI is defined by determining the spatial volume enveloped by a specific damage pressure of interest for a jet expanding in free space and mapping that volume into a spherical ZOI of equal volume surrounding the break (i.e., an equivalent spherical destruction zone). The spherical-shaped ZOI was used as the best means of accounting for the effect of drywell congestion, drywell structural interactions, and the dynamic effects of pipe separation. Because the ZOI is spherical, its orientation does not have to be specified. This method was endorsed by the US Nuclear Regulatory Commission (NRC) as being an acceptable method for identifying a ZOI in the Safety Evaluation Report (SER) to the URG (NRC-SER-URG, 1998).

Assumption 1: The ZOI has a spherical shape with the same volume as that of a free jet.

The volume of the spherical ZOI was determined by estimating the volume within a free jet that would be expected to damage insulation. The minimum jet impingement pressure for which insulation within the ZOI would be damaged was assumed. The jet stream isobar for this pressure defined the volume of the ZOI. Insulation outside the ZOI was assumed to be undamaged because the jet impingement loads would be too low to cause significant damage. Although a ZOI frequently would contain more than one type of insulation and each insulation damage pressure would define a different ZOI volume, a single damage pressure was used to simplify the analysis. Therefore, the damage pressure was selected for the most vulnerable type of insulation commonly found in PWR plants. The destruction pressure for a typical LDFG insulation was used to determine the ZOI volume.

Assumption 2: The minimum damage pressure used to define the ZOI corresponded to the destruction pressure for a typical LDFG insulation.

LDFG is common in PWR plants and is destroyed by pressures of 10 psid (or less) (NRC-SER-URG, Appendix B, 1998). Because LDFG insulation also was common in BWR plants, substantial data exist regarding its destruction, transport, and head-loss characteristics.

The radius of the spherical ZOI was determined using a volume mapping method developed by the BWROG based on data from the BWROG Air Jet Impact Testing (AJIT) [BWROG, 1998]. This radius then was scaled to a larger value based on data from two-phase jet impact testing that was performed as part of the GSI-191 research program (OPG, 2001). The BWROG model estimated the radius at 10.4 times the break diameter, which is referred to as 10.4D. The two-phase scaling resulted in a spherical radius of 12D.

Assumption 3: The radius of the spherical ZOI was 12 times the diameter of the break.

The ZOI for all breaks in the volunteer plant analysis performed for the parametric evaluation was a sphere with a radius of 12 times the diameter of the broken pipe. The justifications for the use of the BWROG URG Method 2 used and Assumptions 1, 2, and 3 are discussed in Sec. 3.1.

2.2.1.2 Insulation Destruction within the ZOI. For a specific break, the analysis identifies the insulation volumes within the ZOI associated with the break. All insulation within the ZOI was assumed to be damaged to some extent, but determining the fraction of this damaged insulation that can transport to the sump screens required an estimate of its size distribution. Estimating the damage to insulation caused by a LOCA jet is also a complex process that depends on many factors (discussed in Sec. 3.2). For the parametric evaluation, the fraction of the insulation within the ZOI that was destroyed into small, easily transportable debris was estimated generically based on available experimental data. Although the large debris and relatively intact insulation would not be expected to transport easily to the sump screens, it would be subject to potential erosion by break overflow, containment sprays, and condensate drainage.

Thus, a portion of the large debris subsequently would erode and transport toward the sump screens. It was assumed that one-third of the ZOI insulation would be damaged into the small debris category and that 10% of the remaining two-thirds of the damaged insulation would erode away from the large pieces and become transportable debris. Hence, 40% of the total insulation located within a pipe break ZOI was assumed to form transportable debris.

Assumption 4: 33% of the insulation within the ZOI was damaged into small debris that could transport relatively easily.
Assumption 5: 67% of the insulation within the ZOI was damaged but either remained blanketed insulation (intact or damaged) or became larger debris that would not likely transport following the completion of blowdown.
Assumption 6: 10% of the remaining intact insulation and large debris was eroded by post-LOCA flows, forming additional small transportable debris.

2.2.1.3 Systematic Plant-Specific Debris-Generation Analysis. The quantities of debris associated with each potential break were evaluated to determine the range and distribution of debris that could be transported to the sump screens following a small LOCA (SLOCA), medium LOCA (MLOCA), and large LOCA (LLOCA). In theory, the location of the break could occur at any location on a high-energy pipe. Only high-energy piping would likely have a sufficient jet force to significantly damage insulation. The amount of debris generated for each potential pipe break needed to be evaluated, and each pipe break was associated with a different arrangement of piping congestion and insulation within its ZOI. A set of criteria and associated considerations for selecting the systems of interest for postulated break analysis was established. The criteria for a system to be included as a potential for a break or target were (1) the system must be typical of other PWR plants, (2) a break in the system has the potential to damage surrounding materials, (3) a break in the system may lead to operating conditions that require the ECCS, and (4) all piping in the containment was considered regardless of location, including secondary systems.

Assumption 7: Only breaks in high–energy (>500 psig) piping were evaluated.

For the volunteer plant analysis, break locations were postulated systematically using a sampling method along all of the high-energy piping (i.e., ≅ 500 psi or higher) for all pipes greater than 2 in. in diameter (approximately 1350 break locations were simulated). Computer-aided drafting (CAD) data for a volunteer plant (a Westinghouse four-loop RCS with an ice-condenser containment) describing the relative spatial locations of piping systems, equipment, and insulation applications were used as the basis for this evaluation. Figure 2-2 shows the level of detail incorporated in the CAD model of the volunteer plant. Insulation on large tanks and equipment is subdivided into panels as shown in the figure, and all insulated pipes are divided into discrete segments represented by point insulation targets that can be enveloped by a damage zone. The large sphere in the lower right-hand corner of the figure identifies the ZOI surrounding a large pipe break.

An objective of the parametric evaluation was to examine the potential for sump blockage as a function of pipe break size, i.e., small, medium, or large breaks. For the parametric evaluation, break sizes were defined as shown in Table 2-2. Pipes less than 2 in. in diameter were neglected in the analyses.

Assumption 8: Pipe diameters were subdivided into ranges associated with small, medium, and large LOCAs (Table 2-2).
Assumption 9: Insulation on pipes smaller than 2 in. in diameter was neglected.

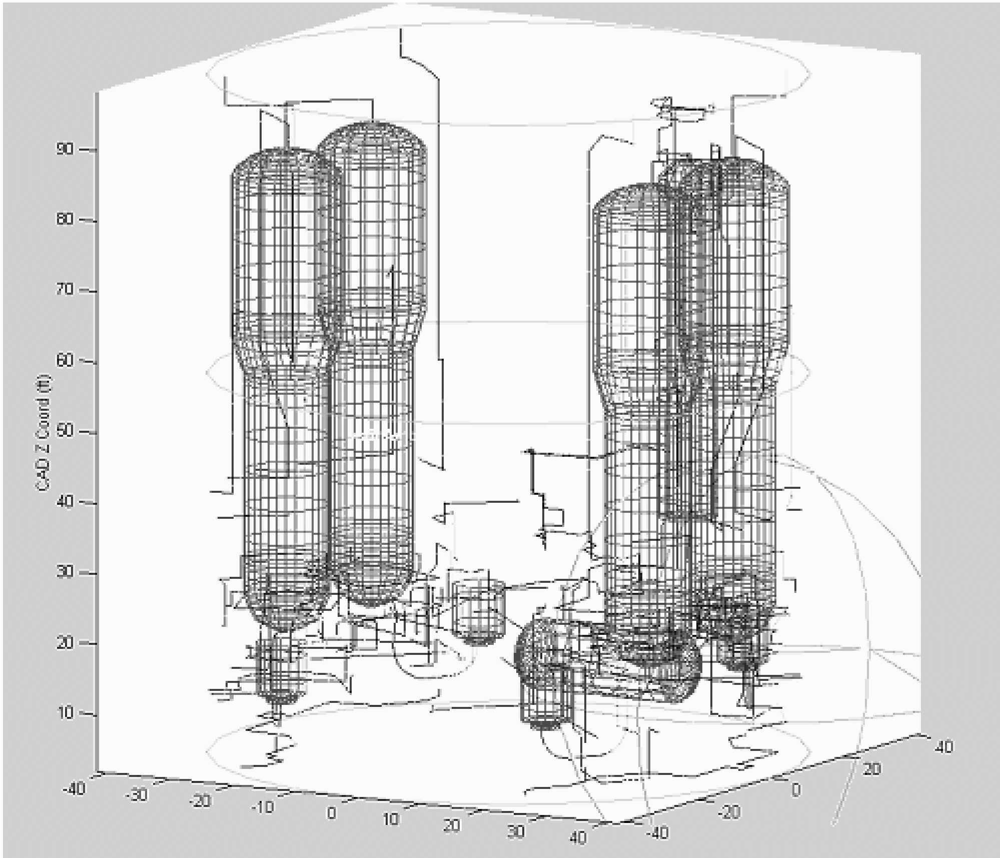

Fig. 2-2. Graphic of Volunteer Plant Piping and Equipment Data.

Table 2-2. Break Diameter Classifications.

Break Classification	Diameter Range (in.)
Small	$4 > d \geq 2$
Medium	$6 > d \geq 4$
Large	$d \geq 6$

To keep the parametric evaluation tractable, the systematic evaluation model did not consider potential shielding that might exist between a break and an insulation target, such as a wall. Further, the analysis did not model potential shadowing by adjacent piping. This simplifying limitation could result in a high-energy break inside the crane wall, for example, being predicted to damage insulation outside the crane wall. On the other hand, had that same break been deflected by the crane wall, the jet would damage insulation inside the crane wall that otherwise would not have been affected. It is difficult to assess the effect of this modeling limitation.

Assumption 10: Pipe shielding by walls and other piping was neglected.

The thickness of insulation on the volunteer containment piping components was required to calculate debris volumes. The thickness for each section of insulation was obtained from the volunteer plant CAD model.

The plant-specific analysis of the volunteer plant resulted in a distribution of debris volumes for each of the break size categories (SLOCA, MLOCA, and LLOCA). The distribution for LLOCAs is shown in Fig. 2-3, the corresponding cumulative distribution is shown in Fig. 2-4, and the 95th percentile of these distributions is given in Table 2-3.

Rather than evaluating the vulnerability to strainer blockage associated with each break, one value for each break size distribution (small, medium, and large) was used. The 95th percentile debris volumes were used in the parametric evaluation to assess the potential for strainer blockage at the volunteer plant (25, 40, and 1700 ft^3 for small, medium, and large breaks, respectively). Use of the 95th percentile as an upper estimate avoids the extreme conservatism of reporting the debris volume of the single worst break. Note that the method used to arrive at these values is considered appropriate for development of a reasonable debris-generation estimate for use in a generic study such as the parametric evaluation. It is expected that plant-specific analyses might yield results vastly different than these “generic” numbers. Therefore, any vulnerability assessment for a specific plant should include a plant-specific debris-generation evaluation.

Assumption 11: The 95th percentile of debris volume distributions was used as the basis for the strainer blockage vulnerability assessment (before the transport analysis).

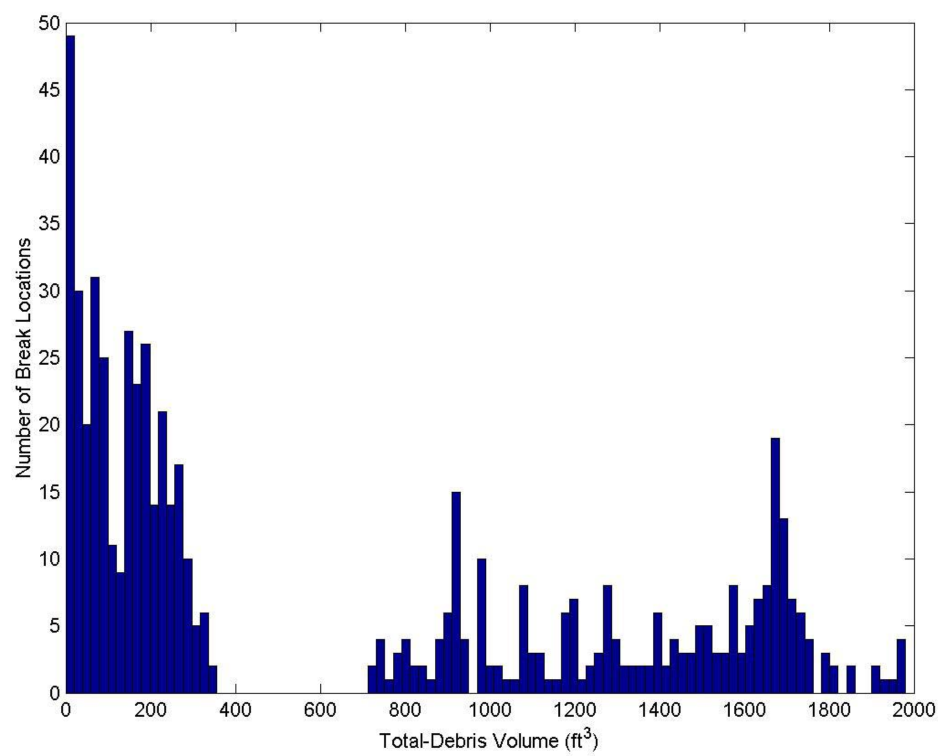

Fig. 2-3. Frequency Distribution of Possible Breaks from Large-Pipe Breaks in the Volunteer Plant.

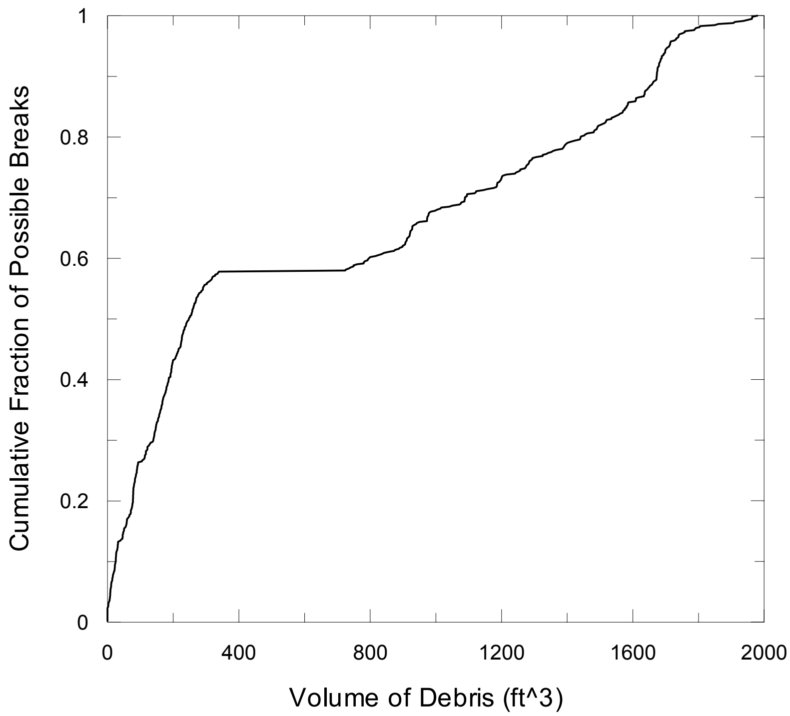

Fig. 2-4. Cumulative Distribution of Debris Volumes for LLOCA Occurring in the Volunteer Plant.

Table 2-3. Summary of Debris-Generation Volumes.

Break Size	Diameter Range (in.)	Debris Volume (ft^3)		
		5th Percentile	50th Percentile	95th Percentile
SLOCA	$2 < d \leq 4$	1	4	25
MLOCA	$4 < d \leq 6$	8	18	40
LLOCA	$6 < d$	20	250	1700

The detailed volunteer plant evaluation determined that the volunteer plant used fibrous (21%), RMI (33%), and calcium silicate (46%) insulations (i.e., 21% of all the insulation within the entire containment was fibrous insulation, etc.). The total volume of insulation in the volunteer plant is approximately 7200 ft^3. For the parametric evaluation, it was assumed that the relative composition of the insulation was homogenized throughout the containment[1]. In other words, in any given ZOI within the containment of the volunteer plant, 21% of the insulation would be fibrous insulation, 33% would be RMI, and 46% would be calcium silicate. Therefore, the quantities of insulation by type that are postulated to be available for transport to the sump screen were determined by multiplying the 95th percentile volumes by the homogenized composition fractions. The debris volumes for the volunteer plant are shown in Table 2-4.

Assumption 12: Insulation within the containment was uniformly distributed, i.e., homogenized.

[1]Although this assumption is not realistic, no better method for estimating insulation locations could be identified, short of completing a plant-specific insulation inventory for each of the 69 PWRs that formed the bases for the parametric cases.

Table 2-4. Summary of Volunteer Plant Debris-Generation Volumes.

Break Size	Diameter Range (in.)	95th Percentile Debris Volume from Cumulative Distribution Function (ft^3)			
		Fibrous	RMI	Calcium Silicate	Total
SLOCA	2 < d ≤ 4	5.3	8.2	11.5	25
MLOCA	4 < d ≤ 6	8.4	13.2	18.4	40
LLOCA	6 < d	357	561	782	1700

2.2.2 Generic Scaling Methodology. After the debris-volume distributions were determined for the volunteer plant, a method was needed to estimate the potential for debris blockage in the 69 parametric cases. It was assumed that the same total quantities of debris would be generated in each of the PWR plants as was generated for the volunteer plant, i.e., the volunteer plant was representative of the PWR industry.

Assumption 13: The volunteer plant was representative of the PWR industry.

However, the volumes for each type of insulation would vary from plant to plant according to the relative volume of each type of insulation reported in the plant survey. In this manner, the 95th percentile numbers for the volunteer plant were used to scale the debris volume for the other 68 plants based on the plant-specific insulation composition fractions.

Three specific implications of the assumption that the volunteer plant can be used in a generic way to represent the other PWR plants are listed below.

- The lengths, sizes, and complexity of the piping and equipment presented in the volunteer plant are representative of all PWR designs. This assumption extends to the relative proportion of piping sizes. The validation of this assumption would require spatial plant-specific data not available to the parametric evaluation.
- The thickness of insulation applications and the reactor systems to which they are applied in the volunteer plants are representative of typical applications of thermal insulation throughout the industry. The validation of this assumption would require spatial plant-specific data not available to the parametric evaluation.
- Where volumetric fractions of several insulation types have been provided, the fractions can be assumed to be distributed in those proportions homogeneously throughout the containment.

Debris-generation estimates for parametric cases based on plants that did not provide insulation fractions[2] required those fractions to be assumed. For example, if a plant simply stated that fibrous and RMI insulation were both present, then a fraction was estimated for each insulation type (totaling 1), and the fraction for calcium silicate would be 0. The approach taken was to assume two distributions, a distribution that favored the plant (i.e., estimated lower strainer head losses) and a distribution that did not favor the plant (referred to as “unfavorable”). In this manner, an attempt was made to bracket the debris volumes relative to insulation types. Vulnerability assessments were made in the parametric evaluation using both the favorable and unfavorable debris quantities in an attempt to bracket the effect of this uncertainty.

[2]These insulation fractions were provided by the licensees in response to an industry survey of plant data (NEI, 1997).

Assumption 14: Where insulation composition fractions were unavailable, ranges of values (favorable to unfavorable) were used to bracket results.

A favorable distribution would assume that a high fraction of the plant insulation was RMI insulation rather than fibrous or calcium silicate because head losses associated with RMI are much smaller than those for either fibrous or calcium silicate. Conversely, an unfavorable distribution would have little RMI insulation. The typical distributions used in the parametric evaluation are shown in Table 2-5.

There is, of course, a wide range of distributions possible, and different analysts would most likely choose somewhat different distributions. Because the parametric evaluation resources did not allow an exhaustive study of the possible insulation distributions, plausible distributions were simply chosen to keep the evaluation on track. In this manner, the range of potential debris volumes was bracketed reasonably well.

Table 2-5. Typical Assumed Insulation Fractional Distributions.

Insulation Category	Favorable	Unfavorable
Fibrous	0.05	0.5
RMI	0.85	0.01
Calcium Silicate	0.1	0.49

3.0 JUSTIFICATION OF KEY ASSUMPTIONS

Several assumptions were required to render the debris-generation analysis sufficiently tractable for the parametric evaluation. Key assumptions were identified in Sec. 2. The rationale for each of these key assumptions is discussed in this section.

3.1 Zone of Influence

This section discusses the rationale that justified the use of Assumptions 1, 2, and 3.

3.1.1 Spherical ZOI Model (Assumption 1). The BWROG recommended four options for estimating the ZOI in a BWR plant. Method 2 documented in Sec. 3.2.1.3.2, "Method 2 – Target Based Analysis Using Limiting Size Zones of Influence," of the URG (BWROG, 1998) was selected for the parametric evaluation. The other three methods were considered either overly conservative or too unwieldy for the parametric evaluation. In Method 2, a ZOI was defined by determining the spatial volume enveloped by a specific damage pressure of interest for a jet expanding in free space and mapping a spherical ZOI of equal volume surrounding the break, i.e., equivalent spherical destruction zone. It was assumed that all of the insulation contained within that spherical volume is damaged (but not necessarily damaged to the extent that it can be transported to the recirculation screens). Method 2 assumed full separation of both ends of a DEGB, thereby not crediting the effect of pipe restraints and not requiring an evaluation of the axial and radial offsets consistent with those restraints. The NRC evaluated these methods and generally accepted Method 2 as an acceptable method for determining the ZOI (NRC-SER-URG, 1998). The staff concurred with the URG's recommended use of the spherical model as the best means to account for the effect of drywell congestion, drywell structural interactions, and the dynamic effects of pipe separation. Piping and structures would tend to deflect the jet in different directions, i.e., a ZOI more spherical than conical.

This method (i.e., Method 2 from the BWROG URG) was adopted for use in the PWR parametric evaluation with a slight modification. The radius of the spherical ZOI used in the parametric evaluation was 12 times the diameter of the pipe break or 12D (higher than the 10.4 D radius used for the BWRs). The following sections describe how this radius was determined.

3.1.2 Insulation Destruction Pressure (Assumption 2). The volume of a freely expanding jet with sufficient pressure to damage insulation is bounded by a pressure isobar that corresponds to the experimentally determined damage pressure for that particular insulation. Therefore, determining the ZOI first requires the determination of the applicable damage pressure. To keep the analysis tractable, a single conservative damage pressure was used in the parametric evaluation. The single conservative damage pressure was based on an insulation type in common use in PWR plants and most vulnerable to destruction. PWR plants have substantial quantities of LDFG, and debris from this type of insulation would form a debris bed on the recirculation sump screens. A damage pressure of 10 psid was assumed, which is generally applicable to both jacketed and unjacketed LDFG.

The NRC SER provided a table of insulation destruction pressures applicable to BWR insulation types (NRC-SER-URG, Table B-1). This table, reproduced in part in Table 3-1, includes the pressures recommended by the BWROG and those estimated by NRC confirmatory analysis.

Experimental data for certain insulations are not very comprehensive because testing was conducted for only a limited number of distances from the nozzle. For example, in the case of stainless-steel-jacketed NUKON®, the AJIT report documented damage at distances up to 50D with 12% of the insulation destroyed into fines and 29% destroyed into larger pieces, but the BWROG did not explore damage beyond distances of 50D. Similarly, in the case of unjacketed NUKON®, significant damage occurred at 60D with no damage at 119D, but the BWROG did not report any data points in between. As discussed in Sec. 3.1.3, recent data indicated that the pressures needed to damage insulations could well be less than those determined by the BWROG.

Table 3-1. Selected Insulation Destruction Pressures.

Insulation Material	BWROG Recommendation	NRC Confirmatory Analysis Recommendation
Calcium Silicate with Aluminum Jacket	160	150
K-Wool	40	40
Temp-Mat with SS Wire Retainer	17	17
Knaupf®	10	10
Jacketed NUKON®	10	6
Unjacketed NUKON®	10	6
Min-K	4	<4

3.1.3 Radius of Spherical ZOI (Assumption 3). The radius of the spherical ZOI was determined using a volume mapping method developed by the BWROG based on data from its AJIT (BWROG, 1998) but scaled to a larger value based on data from two-phase jet impact testing (OPG, 2001).

3.1.3.1 BWR-Based ZOI. The BWROG estimated the volumes of expanding jets bounded by pressure isobars using computational fluid dynamics (CFD) calculations run with the NPARC computer code. These volumes then were converted to an equivalent spherical volume. The volumes were estimated for variety of DEGB break-separation radial and axial offset distances and insulation destruction pressures. These results were correlated as coefficients, A, for the following equation where D is the inside diameter of the postulated break.

$$V_{ZOI} = A D^3 \qquad \text{(Eq. 3-1)}$$

For an insulation destruction pressure of 10 psid and a freely expanding jet, the appropriate value of coefficient A was 4708. The radius of spherical ZOI is then.

$$r_{ZOI} = \left[\frac{3\,V_{ZOI}}{4\pi}\right]^{1/3} = \left[\frac{3\,A}{4\pi}\right]^{1/3} D = 10.4\,D \quad . \qquad \text{(Eq. 3-2)}$$

The volumes also were estimated using an analytical model sponsored by the American Nuclear Society (ANS), the American National Standards Institute (ANSI)/ANS-58.2 model (ANSI/ANS-58.2, 1988). The NRC reviewed and evaluated this work and believes NPARC to be a more capable method to model steam jets than the ANSI/ANS-58.2 model. Further, the NRC concluded that the URG-predicted jet volumes are conservative or reasonable in the pressure ranges of interest, depending on the impingement load. Their use is acceptable if properly justified.

3.1.3.2 ZOI Enlargement Based on Recent Data. Recent debris-generation testing has indicated that the ZOI should be somewhat larger than the ZOI determined by the BWROG. The BWROG's AJIT program provided valuable information regarding the jet impingement pressures (or loads) that would be necessary to generate debris from insulation materials that are commonly used in U.S. nuclear power plants. However, that information was obtained using air as the working fluid. Therefore, it is not directly applicable to PWR blowdown conditions, where blowdown consists of steam and water mixtures at higher pressures than for BWRs. In addition, the AJIT testing was not comprehensive.

The current understanding is that debris generation occurs initially as a result of blast effects or passing of the initial shock wave that emerges from the pipe rupture and after onset of blowdown as a result of erosion caused by jet impingement. Different insulation materials may display different degrees of sensitivity against each of these two phases of accident. Research performed as part of the BWR

ECCS Strainer Blockage Study (NUREG/CR-6224, 1995, and BWROG, 1998) concluded that debris generation resulting from blast effects would be confined to a small region surrounding the break location, and that the major contributor to debris generation is jet impingement. Other contributors, such as pipe whip and impact, have been studied and shown to be of secondary importance [NUREG-0897, 1985].

A series of two-phase jet impingement tests was carried out at OPG as part of their ongoing resolution of potential strainer blockage in Canadian nuclear plants. The NRC and Los Alamos National Laboratory (LANL) supported these tests as part of the GSI-191 study. An OPG report describes these tests and lists the insights gained from this test program (OPG, 2001). The preliminary results of these tests were available to the parametric evaluation. The testing program was designed to address debris generation by two-phase jets created during a PWR blowdown through postulated breaks. The insulations of primary concern are aluminum-clad calcium silicate and jacketed fiberglass. An NRC objective was to compare the insulation damage behaviors between the two-phase OPG tests and the BWROG air-jet tests.

The test data were used in the GSI-191 parametric evaluation to further refine a generic ZOI that would allow the amount of debris that could be generated by a postulated PWR LOCA to be estimated. These analyses relied on qualitative comparison of damage caused by two-phase jets with that previously measured using air as the working fluid.

The OPG test rig and test results are described in Appendix A. Briefly, the OPG jet impact test rig consisted of a tank with a capacity of approximately 2.2 m^3 filled with heated, pressurized water. A 3-in. Schedule 160 nozzle (2.87-in. inside diameter) was connected to the tank by a rupture-disk triggering mechanism, associated piping, and instrumentation. A debris catch cage approximately 12 ft^3 in volume surrounded the nozzle to capture the insulation debris for analysis. The cage was constructed of 1-in.-square wire mesh. Each of these tests simulated a 10-s blowdown for a 10-MPa saturated water jet.

A typical tank pressure during depressurization is shown in Fig. 3-1, where it is compared with a RELAP code prediction for the OPG test apparatus. The RELAP code prediction was in good agreement with the test pressure. To help put the OPG tests into perspective with the needs of the parametric evaluation, the pressure also was compared with a RELAP prediction for a typical PWR system blowdown.

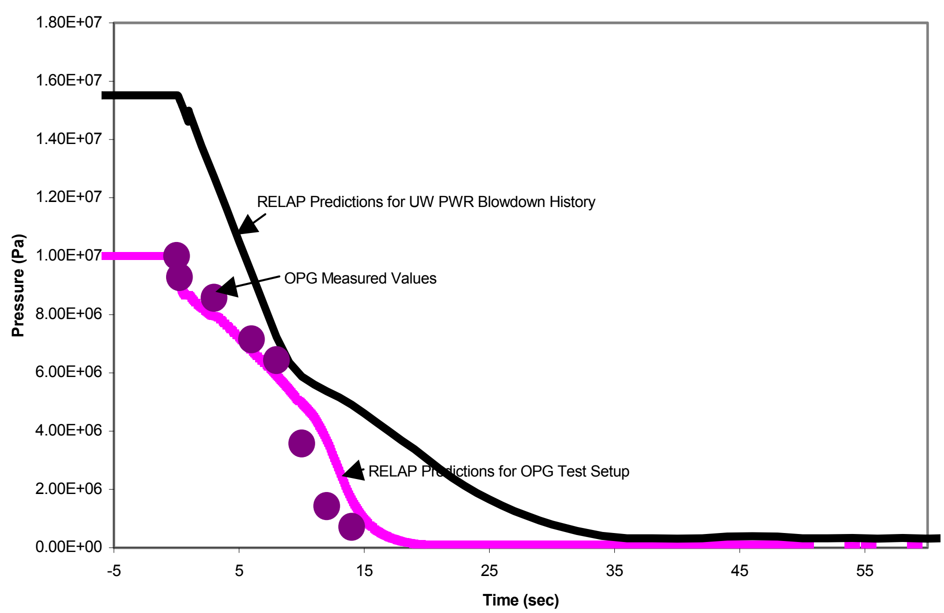

Fig. 3-1. Comparison of RELAP Predictions with OPG Measurements for the Tank Pressure During Blowdown.

Applicable test data examined for the parametric evaluation consisted of seven tests with calcium-silicate targets and one test with a LDFG target. All these targets were jacketed with 0.016-in.-thick aluminum clad. For the calcium-silicate targets, the clad was constrained with 0.020-in.-thick stainless-steel bands and standard crimp connectors. For the fiberglass target, the clad was constrained with 0.0-50-in.-thick stainless-steel bands. The calcium-silicate insulation targets were 1 in. thick and 48 in. long and were mounted in front of the jet on a 2-in. Schedule 160 pipe.

The variable test parameters for the calcium-silicate tests were the distance between the nozzle and the target and the orientation of the jacket seam with respect to the jet. In one test, the target was offset in the radial direction. Three of the tests had a second jacket, referred to as over-cladding, where the seam of the over-cladding was oriented 180^o from the seam of the first clad. The general idea was to vary the distance between the target and the nozzle for a given target configuration to determine the threshold distance for the onset of damage to the target. This distance then could be correlated to the pressure on the target and compared with the damage pressures from the AJIT testing.

Experimentally measured pressures for the OPG tests were not available for the parametric evaluation analysis, so the ANSI/ANS-58.2 model was used to estimate the jet pressures. The pressure estimates for the OPG tests are compared with the AJIT pressures in Fig. 3-2. Because the OPG initial pressure of 1450 psia was different from the AJIT initial pressure of 1100 psia, the compared pressures are actually the target pressures (gage) divided by the initial tank pressure (gage). The AJIT pressures were estimated using the NPARC CFD code with a few experimental pressures (at distances >20D).

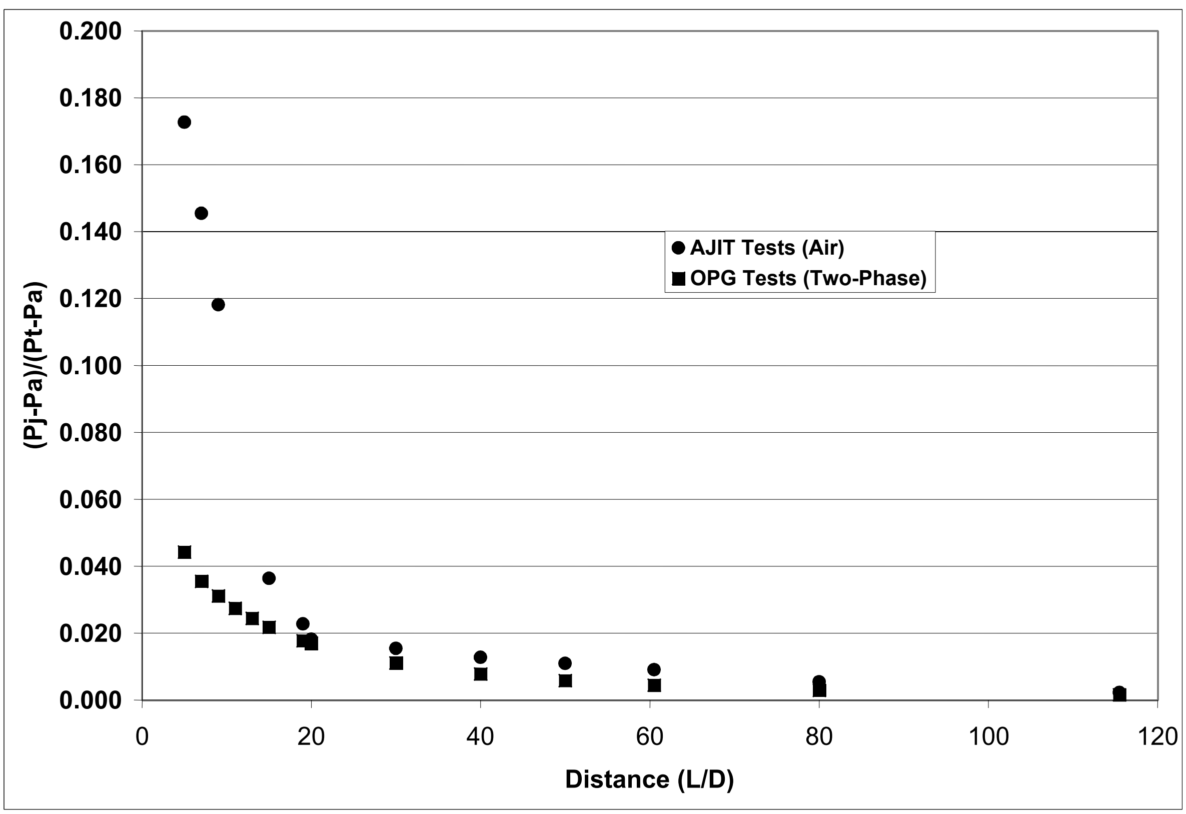

Fig. 3-2. Comparison of OPG and AJIT Target Pressures.

OPG found that the orientation between the clad seam and the jet is critical to the damage mechanism.

- With the seam at 0^o (directly facing the jet), the threshold of damage was found to be located at a distance of between 5 and 7 jet diameters (5D-7D).
- With the seam at 180^o (away from the jet), no damage was found at 3D (over-clad) and no damage was found at 5D (single-clad).
- With the seam at 45^o from the jet, damage occurred out to 20D, the furthest tested.

When comparing the damage thresholds for the OPG and the AJIT tests, it is clear that the seam orientation and the distance from the target must be the same between the compared tests. However, none of the AJIT tests were conducted with a 45^o seam angle. The direct comparison of an OPG test with an AJIT test was not practical because of the differences in test parameters. Insulation destruction pressures also depend somewhat on the type and placement of bands.

The single OPG fiberglass test available to the parametric evaluation was conducted at a distance of 10D with the seam at 45^o and with banded aluminum cladding. Approximately half of the fiberglass was turned into debris. The ANSI/ANS-58.2 model pressure at 10D is 6.4 psid. This indicates that the fiberglass destruction pressure was significantly less than 6 psig. As shown in Table 3-1, this pressure is significantly less than the BWROG-recommended pressure and probably is less than the NRC recommendation. This result indicates insulation destruction at a lower pressure for a two-phase jet than for an air jet.

The tests with calcium silicate also indicate destruction at a lower pressure than that determined by the AJIT tests. The calcium-silicate destruction pressures were determined for comparison with the AJIT pressures again using the ANSI/ANS-58.2 model to determine test pressures. These results are compared in Table 3-2.

As shown, the calcium-silicate destruction pressures determined by the OPG two-phase tests are substantially less than the corresponding pressures determined by the AJIT. Further, it appears that the optimum seam angle for maximum destruction is near 45^o, an angle not tested by the BWROG. In reality, the envelope of destruction would not be a distinct uniform sphere; i.e., some targets within the ZOI with the seam away from the jet would survive intact, and some targets outside the ZOI with the seam 45^o with respect to the jet would be damaged.

Figure 3-3 shows the radius of the equivalent ZOI sphere as calculated using the BWROG model for the volume of a freely expanding jet as a function of the pressure isobar corresponding to a specific insulation destruction pressure. For example, the destruction pressure for calcium-silicate insulation as determined from the AJIT data ranges in the neighborhood of 150 to 160 psid. A bar shown on the figures at these pressures shows that the ZOI radius would be in the neighborhood of 6.4D. The calcium-silicate destruction pressures as determined by the OPG data ranged in the neighborhood of 50 to 65 psid (with perhaps an even wider range). Thus, the equivalent radius at the OPG pressures would be around 7.8D.

Table 3-2. Calcium Silicate Destruction Pressures.

OPG Destruction Pressures		AJIT Destruction Pressures	
Seam at 0^o	51 to 64 psid	BWROG	160 psid
Seam at 45^o	< 24 psid	NRC	150 psid
Seam at 180^o	> 64	Seams at 90^o and 270^o to the jet	

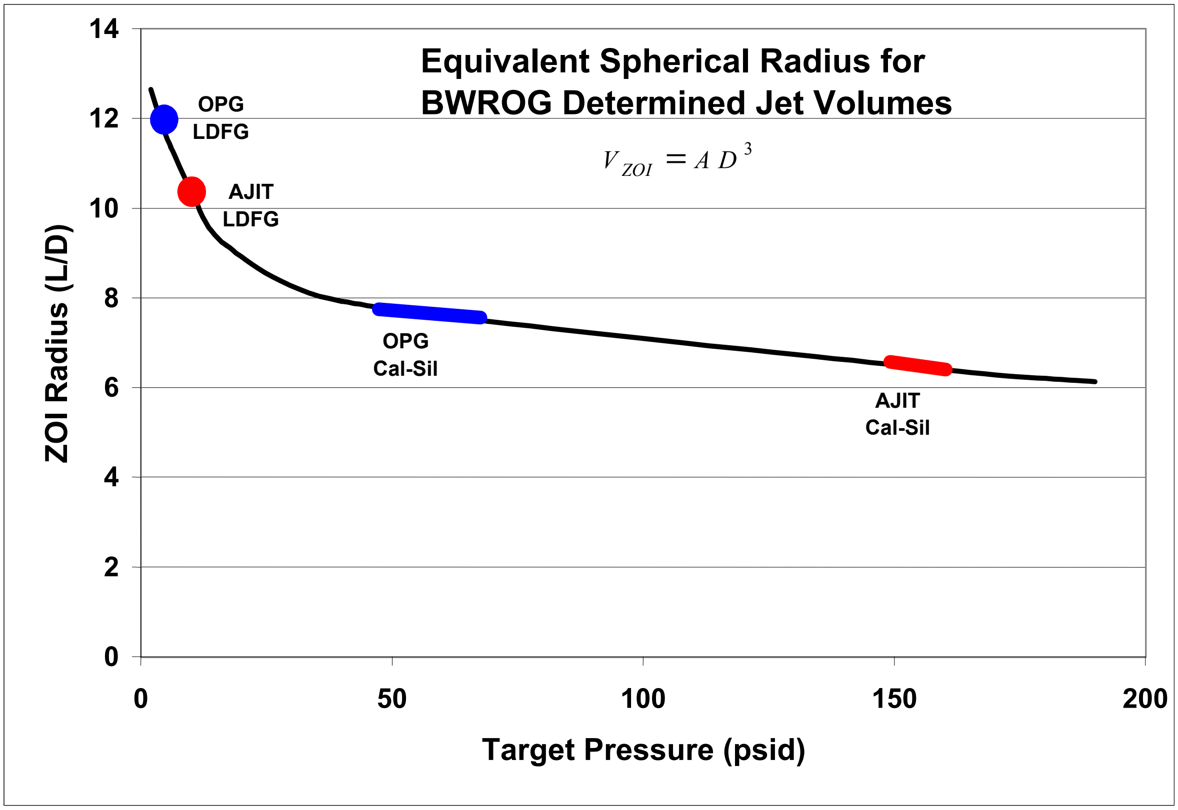

Fig. 3-3. Equivalent Spherical Radius Dependence on Insulation Destruction Pressure.

However, the parametric evaluation focused on fiber debris forming a debris bed on the screens, but there were insufficient data to determine the OPG destruction pressures for LDFG. The data did indicate a destruction pressure less than 6 psid, whereas the BWROG recommended 10 psid. The equivalent radius corresponding to 10 psid is also shown in Fig. 3-3.

For the parametric evaluation, the LDFG destruction pressure was scaled using the available calcium-silicate pressures. The scaling process is shown in Eq. 3-3. The ranges of pressures previously cited (i.e., 6 to 10 psid for the LDFG AJIT, 150 to 160 psid for the calcium-silicate AJIT, and 51 to 64 for the calcium-silicate OPG tests) resulted in a range of destruction pressures of 1.9 to 4.3 psid for LDFG with two-phase flow. A nominal destruction pressure of 4 psid was selected for use in the parametric evaluation, and this pressure corresponds to a ZOI radius of 12D.

$$P_{LDFG}^{OPG} = \frac{P_{AJIT}^{LDFG}}{P_{AJIT}^{Cal-Sil}} P_{OPG}^{Cil-Sil} = \frac{10}{160} 64 = 4 \qquad \text{(Eq. 3-3)}$$

3.2 Insulation Destruction (Assumptions 4, 5, and 6)

After the radius of the spherical ZOI was estimated at 12D, the degree of damage to the insulation within the ZOI had to be estimated so that the quantities of debris transported to the sump screens could be estimated (LA-UR-01-5965, 2001). Estimating the damage to the insulation resulting from a LOCA jet is a very complex process that depends on many factors and requires the use of simplifying assumptions to make the estimate tractable. Damage depends on factors such as the location of the insulation in the jet, the type of insulation, the covering protecting the insulation, the orientation of the cover seams relative to the impinging jet, and the type and number of bands holding the insulation in place.

Damage estimates usually assume that all the insulation within the ZOI is damaged to some degree and can be categorized into one of three damage categories.

- Small debris that is relatively transportable.
- Large debris that is relatively nontransportable but is subject to erosion by ECCS flows.
- Insulation still contained within its covering material so that subsequent erosion is not likely. In fact, this insulation may still be attached to the piping.

Debris damage estimates depend on data obtained from small-scale experiments, such as the BWROG AJIT tests and the OPG tests. In these tests, an insulation target was placed in front of a jet at a specified distance from it and with the insulation seams oriented as specified. Following the test, the resulting debris was collected, and the fractions of the original insulation that fit the above three categories were determined. With sufficient test data, the fractions for small and large debris can be correlated with the distance of the insulation from the jet and then with the jet impingement pressure. Using the BWROG method to determine jet volumes within pressure isobars (Eq. 3-1), the average debris fractions for the entire test jet can be determined as shown by Eq. 3-4. This average then can be applied to the spherical ZOI.

$$F_{ZOI} = \frac{\sum_{i=1}^{N} F_i \ \Delta V_i}{\sum_{i=1}^{N} \Delta V_i} \quad , \qquad \text{(Eq. 3-4)}$$

where

F_{ZOI} = the debris fraction for the entire ZOI,
F_i = the debris fraction for increment i,
ΔV_i = the volume of increment i, and
N = the number of increments.

The ZOI debris fractions depend on the type of insulation, the types of jacketing materials, the banding, and the orientation of seams relative to the jet.

The BWROG [BWROG, 1998] recommended debris fractions for a number of insulation materials and jacketing arrangements. For jacketed and unjacketed NUKON®, the BWROG recommended that 23% of the insulation within the ZOI be considered in the strainer head-loss evaluations. The remainder of the insulation was assumed to not be transportable to the strainers, i.e., either large debris or jacketed insulation. Erosion of large debris is not considered in this 23% estimate.

The NRC reviewed the BWROG recommendations and documented their findings in an SER (NRC-SER-URG, 1998). Although the NRC had some reservations regarding the BWROG method for determining the debris fractions, the NRC believed the debris fractions to be conservative primarily because the blanket seams were arranged in the AJIT tests to maximize the destruction of the blankets. Specifically, the seams were placed 180^{o} away from the jet so that more damage would occur before the blanket could be torn from the target holder.

The OPG test data indicated somewhat higher small-debris fractions than did the AJIT test data. (The OPG tests were described briefly in Sec. 3.1.3.) It was difficult to make a meaningful comparison of the one OPG fiberglass test available to the parametric evaluation with the AJIT test data; however, this one comparison illustrated the potential for more small debris to be generated than was indicated by the AJIT data. In this one test, 53% of the initial insulation was removed from the target and 48% was either collected as debris less than 1 in. or the debris passed through the cage and thus was not collected. The pressure on target for the test was estimated at 42.1 psid. In the AJIT tests, a target located at the same pressure (but not the same distance) probably would not have produced more than about 40% small debris.

Two major test conditions differed between the two test series, and each would have affected the debris fractions. First, the OPG tests used two-phase steam/water, whereas the AJIT tests used air. Second, the jacket seams were oriented differently with respect to the jet. For the tests that used jacketed calcium-silicate insulation for the target, the seams in the available OPG tests (with one exception) were oriented 45° from the incoming jet flow. In the AJIT tests, the seams were oriented on the top and bottom (i.e., 90°) of the target. Before debris was generated in significant quantities, the jacket seams were broken so that a portion of the jacket was removed from the calcium silicate. It appears likely that the 45° orientation of the OPG tests is more severe than the AJIT orientation. The difference between the OPG and AJIT test small-debris fractions is shown in Fig. 3-4.

In the AJIT tests, the jackets remained relatively intact, even at high pressures, leading to low destruction fractions. In the OPG tests, the jackets typically were peeled back, exposing insulation on the backside of the target to erosion.

The qualitative conclusion of comparing these two sets of test data was that the small-debris fraction should be increased from the BWROG recommendation. It was an engineering judgment to increase the recommended destruction fraction for small debris from 23% to 33%.

The remaining 67% of the insulation would be assumed to be large debris either exposed or enclosed in its covering material. This debris was considered in the parametric evaluation as generally non-transportable. However, exposed insulation would be subject to subsequent erosion by break overflow, containment sprays, and condensate drainage, especially insulation located in the vicinity of the break. Tests confirmed that exposed insulation subjected to water flow would erode at a reasonably constant rate. In the tests, insulation pieces subjected to simulated break overflow eroded about 9.2% of the insulation per hour (NUREG/CR-6369, 1999). An estimate of the eroded debris must consider plant-specific features to correlate debris exposure to erosion flows. If a significant portion of the 67% large debris were subject to erosive flows for several hours, it is not unreasonable to assume that 10% of the large debris could be eroded into very transportable debris, i.e., either particulate or individual fibers.

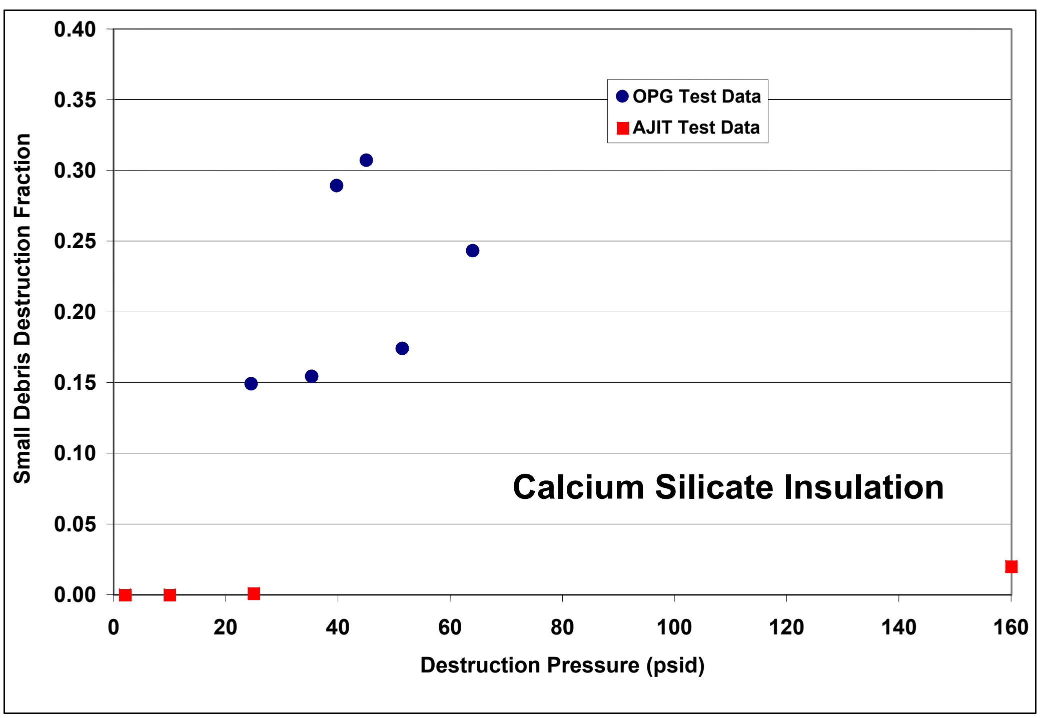

Fig. 3-4. Small Debris Destruction Fractions for Calcium-Silicate Insulation.

Adding 10% of the 67% large debris to the 33% assumed that small debris results in approximately 40% of the insulation damaged into small or fine insulation debris. This 40% debris fraction was used in the parametric evaluation.

3.3 Systems Evaluated

The quantities of debris that potentially could be generated depend on the location of the break; the size of the break; and the displacement, type, and thickness of insulation in the neighborhood of the break. The location of the break could, in theory, occur at any location of a high-energy pipe. The displacement of insulation depends on the congestion of the piping. Each of these factors is very plant-specific. For a specific break, the analysis identifies the insulation volumes by insulation type within the ZOI associated with the break. A complete analysis requires the evaluation of all potential breaks, which of course necessitates a systematic approach. To render such an approach tractable, some engineering assumptions were required. This section discusses those assumptions.

3.3.1 High Energy Piping (Assumption 7). CAD data describing the relative spatial locations of piping systems, equipment, and insulation applications for a volunteer plant were used in a systematic evaluation of debris potential. Break locations were sampled, and insulation volumes within a 12D ZOI of each break were calculated. Insulated pipes were discretized into linear segments and equipment blankets were discretized into panels. All insulation within the ZOI was assumed damaged to some degree.

Breaks were postulated only in high-energy (i.e., >500 psig) lines (based on design pressure). An evaluation was conducted to determine the high-energy piping in the volunteer plant evaluation. A set of criteria and associated considerations for selecting the systems of interest for postulated break analysis was established. The following criteria for a system to be included as a potential for a break or target were used.

- The system must be typical of other PWR plants.
- A break in the system has the potential to damage surrounding materials.
- A break in the system may lead to operating conditions that require the ECCS.
- All piping in the containment was considered regardless of location, including secondary systems.
- A system was included in the model as a potential target if it is insulated and in the vicinity of a potential break location. This included volunteer plant systems insulated with RMI that may be covered with other materials at other plants.
- Low-energy, noninsulated systems were not included in the model when the configuration was considered typical of other plants in the industry.

An example of a system included in the parametric evaluation was the Chemical Volume Control System because it contained insulated high-energy piping typical of PWR plants. This system could potentially break, and it could be a source of insulation debris should another system break. On the other hand, the CS system was not included in the model because the system was not a high-energy one and was not insulated; therefore, if it were to break, it would not generate debris and could not serve as a target for the break of another system.

3.3.2 Pipe Size Classifications (Assumptions 8 and 9). An objective of the parametric evaluation was to examine the potential for sump blockage as a function of pipe break size, i.e., small, medium, or large breaks. For the parametric analyses, a range of generally accepted diameters fitting into each relative sized break was used as shown in Table 2-2. In addition, these ranges tended to fit natural size groupings in the volunteer plant data.

Pipes less than 2 in. in diameter were neglected in the analysis as breaks in pipes this size are not likely to result in a need for the ECCS to operate. However, these pipes could be insulated and therefore be a source of debris for a break in another pipe. It was judged that the quantities of insulation on the small neglected piping would not alter the conclusions of the parametric evaluation. Therefore, in the interest of keeping the analysis tractable, this source of insulation was not evaluated. However, whether small piping can be screened from the analysis should be reevaluated on a plant-specific basis.

3.3.3 Pipe Shielding (Assumption 10). The systematic evaluation model did not consider shielding that might exist between a break and an insulation target, such as a wall. Further, the analysis did not model potential shadowing by adjacent piping. This simplifying limitation could result in a high-energy break inside the crane wall, resulting in damage to insulation outside the crane wall. Also, breaks outside the crane wall were postulated to occur in high-energy lines such as feedwater or steam lines.

It is recognized that, for a specific plant, this could result in overly conservative results for evaluations of SLOCA because of the plant's ability to isolate small breaks outside the crane wall and thus prevent transition to recirculation. Because the debris-generation calculations were performed for a single volunteer plant and were applied to the PWR population in general, this detail is not considered important to the overall results. It is fully expected that if plant-specific debris-generation analyses were performed, the limiting debris-generation cases might vary greatly from those applied in the generic parametric evaluation. One of the largest uncertainties in the parametric evaluation is the spatial location of insulation and other potential debris sources (in each containment) in relationship to the potential break locations. This plant-specific variability could produce results that vary greatly from the debris-generation quantities used in the parametric evaluation. It is conceivable, on one extreme, that insulation could be concentrated in such a way around any given break location such that a plant-specific estimate would yield much higher debris-generation estimates than those produced for the parametric evaluation. However, it is also possible that (fibrous) insulation locations in containment could be separated from small piping so that no single break could be postulated that would result in enough fibrous debris to produce a measurable head loss across the sump screen. Only plant-specific evaluations can answer this question.

It should be noted that the present inclusion of breaks in small pipes outside of the crane wall probably skews the distribution of possible debris volumes to lower values because less insulation exists in these areas. If these breaks are removed from consideration, the 95th percentile debris volume used to characterize small breaks may increase.

3.4 Selection of Debris Quantities for Transport to Sump (Assumption 11)

The systematic evaluation of the debris generated on a break-by-break basis results in a distribution of volumes of damaged insulation. That is, a break at one location could generate relatively little debris simply because there is little insulation within the ZOI associated with that break; conversely, a break at another location could generate a relatively large volume of damaged insulation. Volume distributions were obtained for SLOCA, MLOCA, and LLOCA breaks. The parametric evaluation selected the 95th percentile damage volume from each of these three distributions for subsequent transport to the sump screens to determine the likelihood of sump blockage.

General Design Criterion 35 of 10CFR50 Appendix A requires an ECCS to provide abundant emergency core cooling to transfer heat from the reactor core following any loss of reactor coolant at a rate that prevents core damage with suitable redundancy to ensure that the system safety function can be accomplished assuming a single failure. The criterion requires the ECCS to function for as long as its function is needed and for *any* amount of debris that can be transported to the sump screens. However, because of the uncertainties in the debris-generation analyses, it was considered unreasonable to use the largest debris volume from the distributions. Some precedence has been set for using the 95th percentile of a probability distribution in safety analyses. For example, the NUREG-1150 risk study (NUREG-1150, 1990) used the 95th percentile to characterize the upper end of probability distributions. The 95th percentile concept was adapted to the parametric evaluation to estimate essentially worst-case debris loadings on the screens without the penalty of using the extreme tail of the distribution.

The parametric evaluation was intended to provide a picture of the vulnerability of the PWR population (as a whole) to the sump-screen blockage issue. Limitations exist when performing such evaluations in a generic sense, such as the issue of binning debris-generation results into three discrete sizes. However, it is clear that this limitation in no way invalidates the conclusion that a sump-screen-blockage safety concern cannot be ruled out by the results of the parametric evaluation. This is clear simply from examining the results presented in the Executive Summary to the parametric evaluation report. Even if the LLOCA results were completely discounted, nearly half of the units in the PWR population were ranked as "Very Likely" to be susceptible to sump screen blockage for MLOCA events.

3.5 Adapting Volunteer Plant Results to Representative Industry

The objective of the parametric evaluation was to demonstrate whether sump failure is a plausible concern for the PWR industry as a whole. The information available to determine plausible debris volumes for each of the 69 parametric cases consisted of the debris volume distributions determined for a single volunteer plant and a few applicable plant-specific data obtained from the PWR plant survey (NEI, 1997). The plant-specific data (nonvolunteer plants) included a listing of insulation types within each plant and plant-wide estimates of the relative fractions for each insulation type; i.e., the fraction of the plant-wide insulation that was fibrous, that was RMI, and that was calcium silicate. However, even this limited database was incomplete. Many plants simply indicated that a certain type of insulation was or was not present (no fractions provided). One plant did not provide any information relative to estimating debris generation. Obviously, some gross assumptions were required to complete the parametric evaluation.

3.5.1 Homogeneous Insulation Distributions (Assumption 12). Because of the nature of the plant-specific information, it was necessary to assume that the insulation composition was homogeneous throughout the plant's containment. That is, at any location in the containment, the fraction of fibrous insulation was assumed to be the same regardless of the piping system or location. The 95th percentile results for the volunteer plant were multiplied by the plant-wide debris fractions to estimate the debris volumes for each type of insulation. The reality that the types of insulation are often grouped by systems was not factored into the analysis. For example, RMI insulation tends to be used more around the reactor vessel and larger primary system piping, whereas small piping would tend to be insulated with fibrous and particulate types of insulation.

The justification for the homogenous insulation assumption was an absolute necessity; no other reasonable course of action was available to complete this study with the available information. The uncertainties associated with this assumption must be kept in mind when drawing conclusions from the results. Further, the need for this assumption highlights the need for plant-specific analyses for each of the 69 operating PWR plants.

This assumption regarding the homogeneity of insulation types is perhaps the most limiting condition of the parametric evaluation. Careful inspection of detailed insulation layout data available for six Unresolved Safety Issue (USI) A-43 plants (Kolbe, 1982) and the GSI-191 volunteer plants confirms that this assumption is not accurate for most regions of the plants' containments. Preferential application of fiber insulation to smaller pipes and auxiliary pipes is more common, whereas RMI is used primarily on large components such as the reactor vessel and steam generators. This spatial dependency of the insulation application means that the fiber on small pipes is more likely to be affected by breaks in small pipes. Thus, the local proportion of fiber near a small break may be much higher than the containment-averaged proportion. Although the assumption of homogeneity guarantees that each insulation type is represented in every postulated break, it may de-emphasize the potentially higher volumes of "problematic insulation" that actually could be generated by a break in a specific location of the plant. The potential spatial correlation between insulation types and break locations that may exist in a plant were not addressed in the parametric analyses because only approximate volumetric proportions were provided in the industry survey. As a result, it is possible that the risk of sump failure following a SLOCA may have been underestimated for some of the parametric cases. Because large breaks already generate and transport large quantities of debris, this issue is not likely to affect the assessment of the vulnerability to sump failure for LLOCAs.

Even with the clear limitations associated with this approach, it was the best surrogate available to the parametric evaluation of industry-wide vulnerability to sump blockage. The approach was validated somewhat by comparing the debris volumes for the volunteer plant with other estimates of LOCA debris volumes that have been reported for several PWR power plants (Kolbe, 1982). These volumes are summarized in Table 3-3. In general, the total debris volumes summed over all insulation types agree

Table 3-3. Comparison Debris Volumes for Limiting Breaks in Several PWRs.

Plant	Break	RMI ft^3	Fiber ft^3	Cal-Sil ft^3	Total ft^3
Salem 1 (W-Dry)	Hot Leg	391	353	0	744
	Cold Leg	**598**	**685**	**0**	**1283**
ANO 1 (CE-Dry)	**Main Steam Line**	**726**	**0**	**1157**	**1883**
Maine Yankee (CE-Dry)	**Main Steam Line**	**0**	**66**	**785**	**851**
(No Longer Operating)	Hot Leg 1	0	49	246	295
	Hot Leg 2 or Crossover 1	0	41	384	425
	Crossover 2	0	86	317	403
	Cold Leg	0	53	50	103
	Pressurizer (6-in. line)	0	26	7	33
Sequoyah 2 (W-Ice)	Pressurizer (6-in. line)	31	0	0	31
	Hot Leg	751	0	0	751
	Coolant Pump	241	0	0	241
	Steam Generator 4	141	0	0	141
	Steam Generator 1	852	0	0	852
	Loop Closure	**1419**	**0**	**0**	**1419**
Prairie Island 1 (W-Dry)	Main Steam Line	1149	40	0	1189
	Feedwater	316	40	0	356
	Hot Leg	1099	40	0	1139
	Cold Leg	338	0	0	338
	Crossover	**1341**	**40**	**0**	**1381**

well with the 95th percentile value of 1700 ft^3 that can be generated from large breaks in the volunteer plant. Further, this table provides confirmation that LOCAs can damage a significant fraction of the insulation present in the containment.

3.5.2 Volunteer Plant Representative of PWR Industry (Assumption 13). The debris volumes estimated for the volunteer plant were assumed to represent all the other plants in the PWR industry. There was no other reasonable alternative for the parametric evaluation. The variability of piping congestion and insulation distributions cannot be assessed fully without substantial additional plant-specific information. Again, only plant-specific analyses can eliminate uncertainty in the vulnerability of a specific unit.

3.5.3 Favorable/Unfavorable Ranges (Assumption 14). Debris-generation estimates for plants that did not provide insulation fractions required those fractions to be assumed (as discussed in Sec. 2.2.2). Plausible distributions were formulated so the analysis could proceed for these parametric cases. This approach was necessary because there was no other reasonable alternative for the parametric evaluation. In this manner, an attempt was made to bracket the debris volumes relative to insulation types. Although additional uncertainty is associated with these parametric cases, useful information was generated.

4.0 ASSESSMENT OF DEBRIS-GENERATION METHODOLOGY

As part of the GSI-191 study, the parametric evaluation demonstrated a plausible concern regarding potential sump failure for operating PWR plants. A credible technical basis was formed that determined that sump blockage was a generic concern for the PWR population. The methodology used to estimate quantities of insulation debris generated by a LOCA depressurization jet was an essential part of the parametric evaluation. As discussed in Secs. 2 and 3, estimating the quantities of insulation debris generated is a complex task that requires several simplifying assumptions to render the analysis tractable. Further, the analysis requires substantial plant-specific data that were only available for two volunteer plants. The plant-specific data for the PWR population were quite limited. Inherent to the complexity and incompleteness of debris-generation testing and plant-specific information, substantial uncertainty is associated with the debris-generation estimates.

The approach to estimating the vulnerability to sump failure for each parametric case was to first perform the estimation for a volunteer plant where sufficient detail was provided for a credible estimate. Then, the limited insulation data of the other plants was used to essentially scale the results of the volunteer plant to each of these other plants, which then formed the basis for the debris-generation estimates for the 69 parametric cases. After assuming that all plants would generate the same total volumes of insulation debris, the plant-specific insulation composition fractions were used to scale those total volumes to determine plant-specific volumes for each type of debris for each plant. (The approach is shown in Fig. 2-1.) Recognizing the clear limitations associated with this approach, it was the best surrogate available to evaluate the industry-wide vulnerability to sump blockage using the limited plant-specific data available to the study.

The uncertainties associated with the debris-generation aspect of the parametric evaluation include the following.

- Limited plant-specific data (except for the volunteer plants).
  - Specifically, the insulation composition fractions, and even these were not available for 14 of the PWR plants.
- Variability of insulation types, protective covers, and restraints.
- Limited and incomplete debris-generation testing.
  - Determining the onset of insulation destruction pressures and the effect of cover seam orientation with respect to the jet.
  - Determining debris size distributions.
- Applicability of the spherical ZOI model has not been evaluated experimentally.
- Spherical ZOI model based on jet impingement pressures that were evaluated using analytical models, rather than experimental test measurements (except for four data points in the air-jet impact tests).

The debris-generation approach necessarily had to consider the extent of the uncertainties but do so in a manner that was not overly conservative. The approach, as implemented, tended toward identifying “reasonable” debris quantities while at the same time identifying the uncertainties. First of all, the experience and knowledge accumulated during the resolution of the issue for the BWR plants was applied. Specifically, models recommended by the BWROG and approved by the NRC were used. The spherical ZOI model (BWROG URG Method 2) was used with an enhancement to compensate for the recent OPG two-phase jet test data that indicate the destruction of insulation at lower pressures for a two-phase jet than for an air jet (i.e., the ZOI radius was increased from the BWR model result of 10.4D to 12D). Note that preliminary OPG test data reviewed by the NRC indicated that insulation destruction would occur at lower pressures than indicated by the BWROG AJIT test data and that more of the insulation would be destroyed into the small transportable debris category.

The limitation of only one insulation destruction pressure, specifically, 10 psid for LDFG, was an unfavorable assumption for plants with little LDFG. For example, many plants have substantial HDFG in their containments, which requires a higher pressure for damage and therefore a smaller ZOI. However, with so little plant-specific data, it was not realistic to attempt to factor this into the parametric evaluation, whereas a plant-specific evaluation can.

Also, the insulation destruction pressures determined by the AJIT and OPG testing focused on placing the jacket seams at orientations where the jackets were more easily deformed or removed. In a realistic scenario, the jacket seam orientation with respect to the jet would be a distribution of possible orientations. So, the test data included a built-in conservatism that was unfavorable to the plants in the parametric evaluation.

The parametric evaluation did not consider wall shielding and/or pipe shadowing that may (or may not) have been unfavorable to the plant. Certainly the systematic approach of the parametric evaluation may have included damage to pipe insulation physically located on the other side of a wall, such as the crane wall. However, a redirected jet flow could impact insulation outside the normal ZOI. It is difficult to conclude whether this assumption increased or decreased the assessed vulnerability to sump blockage.

On the other hand, the assumptions that neglect piping less than 2 in. in diameter, neglect foam and marinite types of insulation debris, and neglect nontypical piping are assumptions favorable to the plants. Likely, these assumptions had a lesser effect on the parametric evaluation. However, an evaluation of the impact was not performed.

The plant ECCS sump screen should function following any loss of reactor coolant at a rate that prevents core damage with suitable redundancy to assure the system safety function can be accomplished assuming a single failure (General Design Criterion 35). Therefore, using the 95th percentile debris -volumes was more than a reasonable assumption. Using the absolute worst-break debris-generation volumes might have been unrealistic, given all the uncertainties associated with the evaluation.

The assumptions leading to the conclusion that 40% (small debris plus large debris erosion) of the damaged insulation was transportable was an engineering judgment tempered by the available test data. Whether this number is an over-estimate or even an under-estimate would be difficult to determine without more test data and analysis. However, the number is reasonable and applicable for the purposes of the parametric evaluation.

Assuming that the debris-generation volumes of the volunteer plant represent each and every one of the PWR plants and that the insulation types throughout each of these plants can be specified by containment-wide average composition fractions are perhaps the assumptions of greatest uncertainty. These assumptions were necessitated by the lack of plant-specific data. Nevertheless, the goal of determining whether a generic problem may well exist in the PWR industry was achieved. Now, only plant-specific analyses can refine the individual evaluations to determine debris-generation volumes with more certainty.

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APPENDIX A
DESCRIPTION OF ONTARIO POWER GENERATION TESTS

A.1 INTRODUCTION

The parametric evaluation relied heavily on research conducted to resolve the strainer blockage issue for the BWR plants. The debris-generation models used in the BWR resolution were based on the AJIT program carried out by the BWROG, which provided valuable information regarding the jet impingement pressures (or loads) that would be necessary to generate debris from insulation materials that are commonly used in US nuclear power plants. However, that information was obtained using air as the working fluid, and therefore, it is not directly applicable to PWR blowdown conditions where blowdown consists of steam and water mixtures. Although limited experimental data on two-phase jet impingement is available from European sources, it was primarily obtained for insulations that are not prevalent in US PWRs.

A series of two-phase jet impingement tests were carried at OPG as part of their ongoing resolution of potential strainer blockage in Canada. The NRC and LANL, as part of GSI-191 study, supported these tests to obtain debris-generation data for two-phase jets and to determine the relative effect of the working fluid on debris generation, i.e., two-phase vs air. An OPG report describes these tests and lists the insights gained from this test program (OPG, 2001). The preliminary results of these tests were available to the parametric evaluation. This appendix summarizes the aspects of the OPG report that were applicable to the parametric evaluation, specifically, the test objectives, test apparatus, test data, and insights gained from this test program.

The test data were used in the GSI-191 parametric evaluation to further refine a generic ZOI to estimate the amount of debris that would be generated by a postulated PWR LOCA. These analyses relied on qualitative comparisons of damage caused by two-phase jets with damage previously measured using air as the working fluid. Such analyses were carried out for two insulations: (1) calcium-silicate insulation with aluminum cladding and (2) a LDFG insulation. The ZOIs were defined following methods and assumptions similar to those developed for BWR Study.

A.2 TEST OBJECTIVES

The testing program is designed to address debris generation by two-phase jets created during a PWR blowdown through postulated breaks. The insulations of primary concern are aluminum-clad calcium silicate and jacketed fiberglass. When OPG conducted their tests, they had the following broad test objectives in mind.

- Obtain debris-generation data regarding the ZOI and debris size distribution for various materials found in the vicinity of the primary heat transport system piping in OPG's nuclear facilities, in particular, standard calcium-silicate insulation.
- Develop a methodology for applying the debris-generation data to OPG nuclear facilities, e.g., scaling small-scale test data to larger breaks.
- Assess the potential reduction in size of the current 10D ZOI.

In addition to gaining debris-generation data directly applicable to two-phase jets, an NRC objective was to compare the insulation damage behaviors between the two-phase OPG tests and the BWROG AJIT tests. The insulations of primary concern are aluminum-clad calcium silicate and jacketed fiberglass. The comparison would compare measured damage pressures, damage mechanisms, and size distributions of debris generated by the jets. The damage pressure is the minimum measured jet impingement pressure to induce incipient damage on the tested insulation. Hopefully, such a comparison would qualify the air jet data for application to PWR plants.

A.3 TEST APPARATUS

The OPG jet impact test rig consisted of a tank with a capacity of approximately 2.2 m^3 filled with heated pressurized water. The water in the tank was heated by an approximately 200-kW heater and was filled and drained by a system of fill and bleed lines. A 3-in. Schedule 160 nozzle (2.87-in. inside diameter) was connected to the tank by a rupture disk triggering mechanism, associated piping, and instrumentation. A robust sample-holding frame held the insulation in front of the nozzle at a predetermined position and orientation. The test apparatus is shown schematically in Fig. A-1. A debris catch cage approximately 12 ft^3 in volume surrounded the nozzle and target to capture the insulation debris for analysis. The cage was constructed of 1-in.-square wire mesh. Wire cloth could be used to reduce the screen size further if required.

With the 3-in. nozzle, the duration of the blowdown was approximately 10 s when the tank was initially filled with saturated water at a pressure of 10 MPa. A typical vessel pressure time history during a high-temperature test is shown in Fig. A-2. (The test started at approximately 37 s where single-phase steam is discharging.) The initial conditions for the tests were 311°C and 1417 psig.

The target insulation was mounted on two 2-in. Schedule 160 pipes. The insulation targets were 48 in. long and 1 in. thick. Thus, the target outer diameter was 4.375 in. A 0.016-in.-thick aluminum cladding surrounded the insulation. The cladding and banding specifications were based on the large-scale piping used in OPG's nuclear plants. Two or three sections of cladding (depending on the test) were required because the standard cladding length was 24 in. Thus, each target had one or two circumferential seams in addition to a longitudinal seam running the entire length of the target. For calcium-silicate targets, the bands were stainless steel with a thickness of 0.020 in. and standard crimp connectors. For the single fiberglass test available to the parametric evaluation, the bands were 0.5 in.

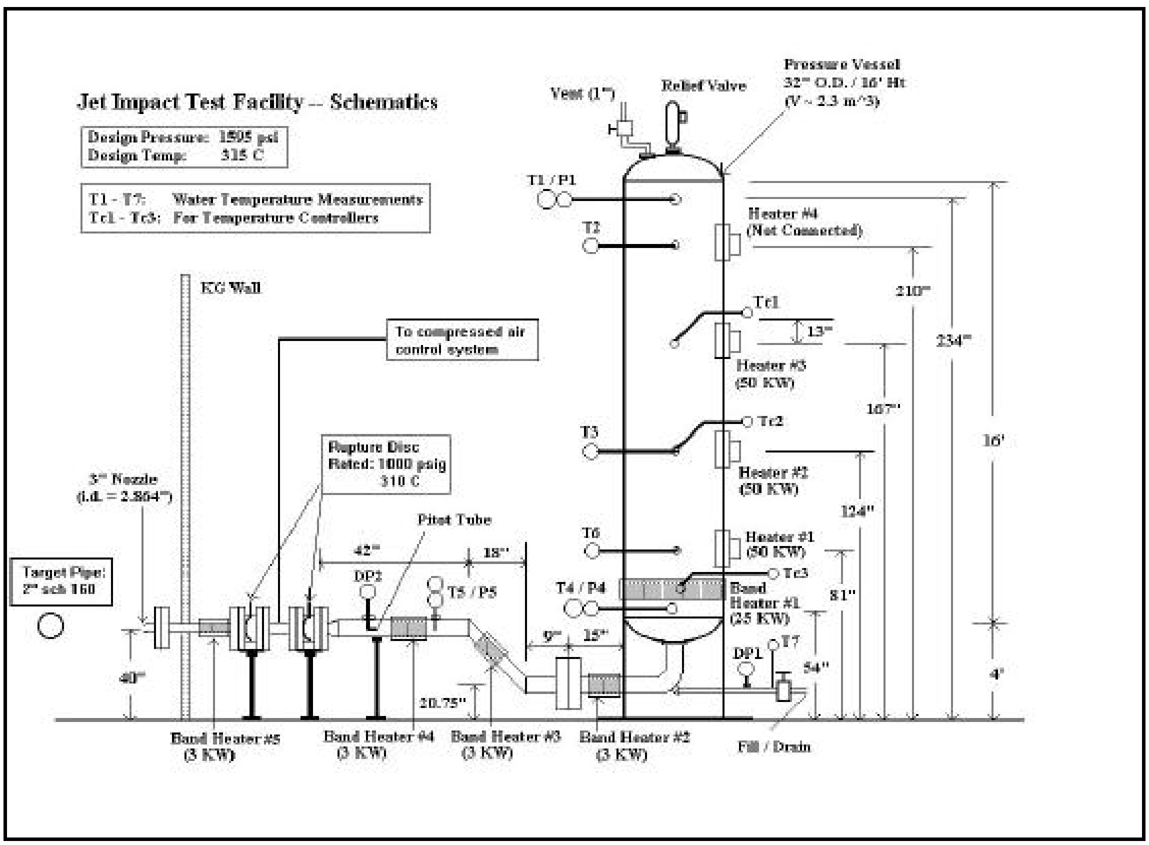

Fig. A-1. Schematic of Test Facility.

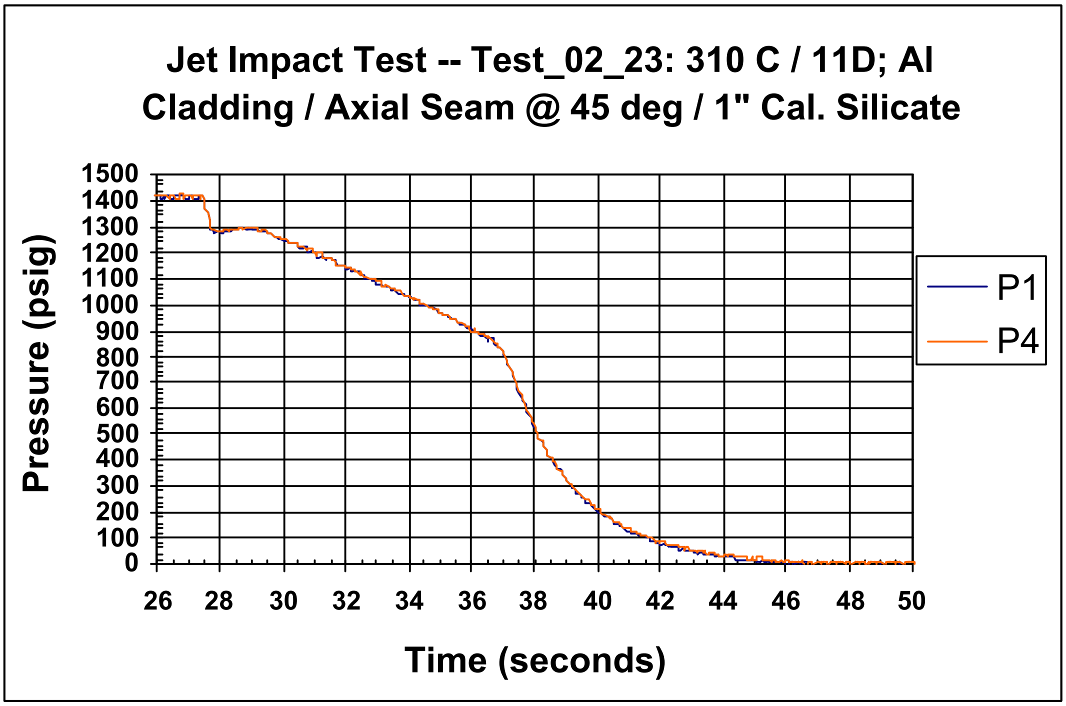

Fig. A-2. Typical Tank Pressure History.

Wide and 0.05 in. thick and also made of stainless steel. The average spacing between bands was greater than 6.5 in. For tests where the jet was centered between the bands (circumferential seam offset from the jet center), the spacing was 8 in. The maximum spacing was 8.25 in. The target-jet geometry is shown in Fig. A-3, and a typical band configuration is shown in Fig. A-4. Figure A-5 is a photo of a mounted target.

The longitudinal seam was oriented at an angle relative to the jet centerline. Note that the targets were mounted with their centerlines perpendicular to the jet centerline. The convention used was 0^{o} at front, 90^{o} on top, 180^{o} at rear, and 270^{o} at bottom. Most tests were conducted at an angle of 45^{o}, i.e., between the front and the top.

In selected tests, a second layer of cladding was added to the target with the longitudinal seam of the outer clad at 45^{o} from the jet and that of the inner clad 180^{o} from the outer clad. Because clad failure was found to be sensitive to the seam angle, the idea behind the second layer was that if the outer layer failed, perhaps the inner layer would not simply because the inner seam would be away from the jet.

A.4 TEST PARAMETERS

The test parameters for the calcium tests, which are summarized in Table A-1, included the four listed below.

- The distance of the target from the jet (in terms of the actual distance divided by the nozzle diameter). Note that one test also had a radial offset distance.
- Whether an over-cladding was used.
- The orientation of the longitudinal seam relative to the jet.
- The relative location of the circumferential seam, i.e., at jet centerline or offset.

Whether insulation material was liberated from the protection of the target cladding also is noted in the table.

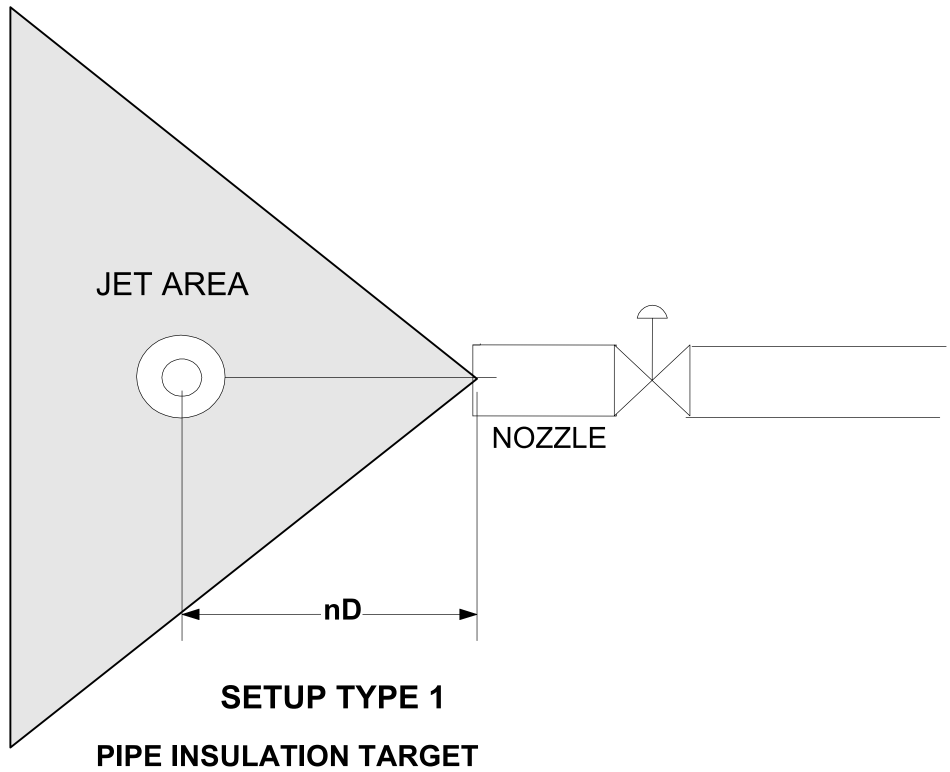

Fig. A-3. Target Mount Geometry.

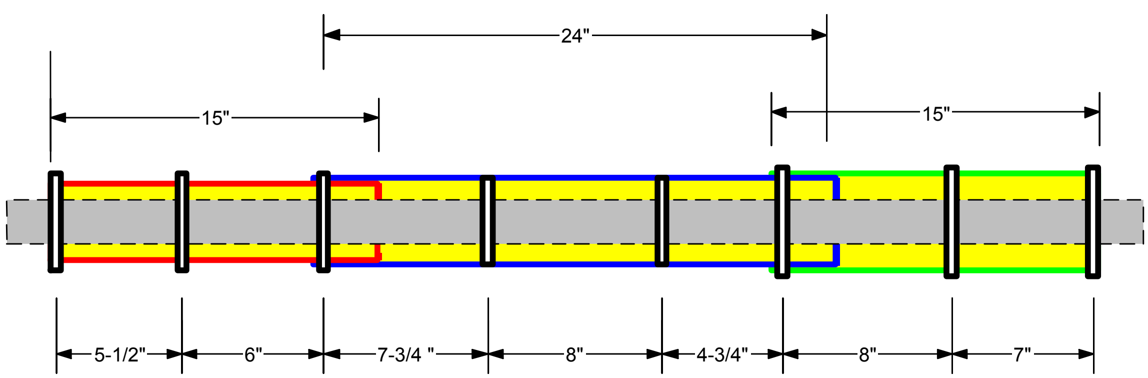

Fig. A-4. Typical Band Configuration for Seam Offset Tests.

Fig. A-5. Photo of a Mounted Target.

Table A-1. Summary of Test Parameters.

TEST	DISTANCE	OVER-CLADDING[2]	LONGITUDINAL SEAM	CIRCUMFERENTIAL SEAM	INSULATION LIBERATED
1[3]	7D	No	0°	Jet Centre	Yes (small amount)
2	7D	No	0°	Jet Centre	No
3	5D	No	0°	Jet Centre	Yes
4	7D	No	0°	Jet Centre	No
5	5D	No	0°	Jet Centre	Yes
6	5D	No	180°	Jet Centre	No
7	5D, offset 2D	No	0	Jet Centre	Yes
8	7D	No	45°	Offset[4]	Yes
9	4D	Yes	45°	Offset	No
10	3D	Yes	45°	Offset	No
11	4D	Yes	45°	Offset	No
12	9D	No	45°	Offset	Yes
13	11D	No	45°	Offset	Yes
14	13D	No	45°	Offset	Yes
15	20D	No	45°	Offset	Yes

For the single fibrous test, the target was located 10D from the jet and the longitudinal seam was oriented 45^o with respect to the jet.

A.4 TEST RESULTS

The actual debris masses generated in the tests are shown in Table A-2. It was found that the orientation between the seam and the jet is critical to the damage mechanism. The following was determined.

- With the seam directly in line with the jet (at 0^o), the threshold of damage was found to be located at a distance of between 5 and 7 jet diameters (5D to 7D).
- When the seam was on the backside (at 180^o), no damage was found at 3D for an over-clad test or at 5D for a test without over-clad (Test 6).
- When the seam was at 45^o, damage occurred out to 20D, the furthest distance tested.

When failure occurred, the mode of failure was exclusively tearing of the cladding caused by pressure acting on the edge, thus exposing the insulating material to the jet. Further, the liberated insulation tended to come from the far side from the nozzle. This was because of the cladding being "unwrapped" by the jet from the exposed edge to the backside. The insulation remaining on the near side of the target is protected from the jet by the remaining cladding. In all cases, the amount of insulation liberated was less than 50% of original mass.

Example post-test photos are shown in Figs. A-6, A-7, and A-8. Figure A-6 shows a target destroyed at a distance of 5D with the seam orientated in front. Figures A-7 and A-8 (front and rear views) show a destroyed target at a distance of 9D with the seam orientated at 45^o with respect to the jet.

Debris was collected by hand and sorted into three size ranges as reported in Table A-2. These ranges were (1) less than 1 in., (2) between 1 and 3 in., and (3) over 3 in. Typical debris is shown in Fig. A-9. Substantial quantities of debris were too small to be collected. The uncollected debris was termed dust (listed in Table A-2), and its mass was calculated by subtracting collected mass from the initial target insulation mass.

For a test conducted with the target close to the nozzle (5D for example), the damage region was focused at the center of the target, as shown in Fig. A-6. That is, the jet had not expanded sufficiently to reach the ends of the target. For tests with target distances from 7D to 13D, it was found that the zone of damage extended to one or both ends of the target. This is an important consideration with respect to scaling the damage to other size breaks. In the 5D case, it appears that nearly all of the insulation within the jet path was destroyed, whereas less than half of the target total was destroyed.

Table A-2. Actual Debris-Generation Results for Tests Where Insulation Was Liberated From Target.

Test Number[5]	Target Distance	Initial Weight gm	Remaining on Target gm	Debris Classification			
				Over 3" gm	1" – 3" gm	Under 1" gm	Dust gm
5	5D	2109	1112	238	247	31	481
7	5D, offset 2D	2074	1325	75	160	49	465
8	7D	2116	1578	52	118	34	334
12	9D	2089	1263	48	136	55	587
13	11D	2090	1252	114	120	37	567
14	13D	2143	1700	53	61	23	306
15	20D	2130	1654	98	60	17	301

Fig. A-6. Target at 5D and Seam at 0 Degrees.

Fig. A-7. Target at 9D and Seam at 45 Degrees (Front View).

Fig. A-8. Target at 9D and Seam at 45 Degrees (Back View).

Fig. A-9. Typical Debris.