TECHNICAL ASSESSMENT SUMMARY FOR GSI-191, "ASSESSMENT OF DEBRIS ACCUMULATION ON PWR SUMP PERFORMANCE"

Technical Basis

The GSI-191 technical assessment included data collection from operating PWRs, phenomenological testing, computational simulation, and engineering analyses. The following provides an overview of (1) parametric evaluation, (2) averted core damage frequency (CDF) estimates, and (3) benefit and cost estimates.

- 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 sump and accumulate on the screen. The debris that accumulates on the sump screen forms a bed that acts as a filter. Head loss across the debris bed may exceed the NPSH margin of the ECCS or containment spray pumps. For sump screens that are only partially submerged by water on the containment floor, head loss across the debris bed may prevent water from entering the sump. Thus, excessive head loss can prevent or impede ECCS operation during recirculation.

  From information collected during a survey of operating PWRs, two volunteer plants, and other readily available information, 69 cases were created that represented predominate variations (e.g., quantities of thermal insulation, different NPSH margin) among operating PWRs. For each case, the minimum amount of debris accumulation on the sump screen needed to exceed NPSH margin was estimated. Then, using favorable and unfavorable conditions, a range of debris that would be damaged, transported, and accumulated on the sump screen was estimated. If the calculated range was greater than the minimum amount of debris, then loss of NPSH margin was considered very likely. If the estimated range was less than the minimum amount of debris, then loss of NPSH margin was considered unlikely.

  Loss of NPSH margin to pumps taking suction from the sump is likely to occur in some PWRs because of debris accumulation on sump screens. Because of the large number of plant-specific variations, it is not possible to generically identify which plants will lose NPSH margin. However, the 69 cases in the GSI-191 parametric evaluation provide a reasonable representation of operating PWRs. The parametric evaluation results are presented in Table 1. A more complete description of the parametric evaluation methods and findings are provided in Attachment 2.

Table 1: Summary of Parametric Cases Potential for Loss of NPSH During Recirculation (an excerpt from Table 5-1 In Attachment 2)			
Tally	**SLOCA**	**MLOCA**	**LLOCA**
Very Likely	25	31	53
Likely	7	6	7
Possible	4	6	1
Unlikely	33	26	8
NOTE: SLOCA - small loss-of-coolant accident, MLOCA - medium loss-of-coolant accident, LLOCA - large loss-of-coolant accident			

- For the affected plants, the averted CDF associated with the increased potential for loss of NPSH margin caused by debris accumulation on ECCS sump screens was calculated. The accident sequences included (1) initiating events that would require recirculation from the sump to mitigate, (2) the need to go to recirculation, (3) the probability that the sump blocks and the ECCS recirculation fails, and (4) the success of actions to recover the sump. The quantification of the accident sequence considered the type of initiating event, the plant type, and containment type. The probability for sump blockage and ECCS recirculation failure was based on the GSI-191 parametric evaluation results. The averted CDF estimates by affected plant aggregates are presented in Table 2, and a detailed description of averted CDF estimates are provided in Attachment 3. Based on the parametric cases (Attachment 2), it was assumed that at least 25 and at most 37 units would benefit from modifications to prevent sump blockage.

Table 2: CDF contribution estimates by affected plant aggregates		
25 Plant Cases	31 Plant Cases	37 Plant Cases
8.84E-05/YR	8.65E-05/YR	7.78E-05/YR

- For both the benefit and cost estimates, it was assumed that the corrective action would involve increasing surface area of the sump screen.

  The benefits are the averted costs of an accident, if the sump screen blockage problem is fixed. Benefits are typically categorized as offsite and onsite averted costs. The benefits are dominated by averted onsite costs which include clean-up and decontamination at the site, and the incremental costs of replacing the power.

  The costs to physically modify the plant to increase the sump screen surface area are categorized as: (1) up-front analytical activities; (2) physical modification activities; and (3) other cost elements. The up-front costs include regulatory actions by NRC, development of generic guidance by industry, and plant-specific analyses by industry. The physical modification costs include administrative, engineering, testing, and waste disposal. Other costs include verification by NRC in the form of audits and inspections.

Based on these cost and benefit estimates, an increase of sump screen surface area to reduce the vulnerability to loss of NPSH margin caused by debris accumulation on sump screens is net beneficial (i.e., benefits exceed costs). For the evaluations performed in Attachments 3 and 4, the net benefits ranged from approximately $24.5M to $31.8M.

RES Recommendation

The 69 cases in the GSI-191 parametric evaluation provide a reasonable representation of operating PWRs, whose results form a credible technical basis for concluding that additional action, beyond the resolution of USI A-43 is warranted. If the NPSH margin for ECCS pumps taking suction from sump is lost, then licensees may not satisfy the requirements in 10 CFR 50.46. RES recommends that plant-specific analyses be conducted to determine whether debris accumulation in containment will impede or prevent ECCS operation during recirculation. If it is determined that debris accumulation will impede or prevent ECCS operation, then appropriate corrective actions should be implemented.

Attachment 2

LA-UR-01-4083

GSI-191: PARAMETRIC EVALUATIONS FOR PRESSURIZED WATER REACTOR RECIRCULATION SUMP PERFORMANCE

TECHNICAL LETTER REPORT

AUGUST 2001, REVISION 1

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EXECUTIVE SUMMARY

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

As part of the GSI-191 study, the parametric evaluation documented in this report was performed to demonstrate whether sump failure is a plausible concern for operating PWRs. The results of the parametric evaluation form a credible technical basis for making a determination of whether sump blockage is a generic concern for PWRs. However, the parametric evaluations have a number of limitations that make them ill-suited for making a determination of whether a specific plant is vulnerable to sump failure.

Approach

PWR sump and containment design features vary widely between plants. The focus of this parametric evaluation was to examine the range of conditions present in operating PWRs and to incorporate variations such as insulation type in proportion to their occurrence in the population so that the plausibility of sump blockage could be assessed generically for the PWR population as a whole. This objective necessitated an adequate representation of individual plant features, so parametric cases were developed to represent specific plants. Although the best information available to Los Alamos National Laboratory (LANL) was applied for each parametric case, it is recognized that these cases do not provide a complete perspective of the sump-blockage potential at the corresponding plants. However, the cases do provide a reasonable description of operating PWRs, and they focus parametric evaluations on a realistic range of conditions. The development of the parametric cases was a key feature of this study.

Two primary sources of information were used to construct the parametric cases.

(a) Licensee responses to a recent industry survey on sump and containment design related to GSI-191
(b) Licensee responses to Nuclear Regulatory Commission (NRC) Generic Letter (GL) 97-04.

As appropriate, this information was augmented by plant-specific information from

(a) the Unresolved Safety Issue (USI) A-43 study (Serkiz, 1985),
(b) Updated Final Safety Analysis Reports (UFSARs), and
(c) Individual Plant Examinations (IPEs).

Another key feature of this study involves the use of "reasonable" parameter ranges. These ranges were defined through the judicious application of completed and ongoing test results from the GSI-191 study and test results from the NRC-sponsored Boiling Water Reactor (BWR) Strainer Blockage Study. Also, results from tests and analyses that were sponsored by the Boiling Water Reactor Owner's Group

(BWROG) during the recent modification of BWR ECCS strainers[1] were used to establish "reasonable" parameter ranges. Parameter values that reduced the potential for sump blockage were considered to be "favorable," whereas parameter values that increased the potential for sump blockage were viewed as "unfavorable." An example of this approach is the designation of design ECCS flow as "unfavorable" because it would increase the head loss caused by a debris bed and designation of 1/2 of the maximum flow (i.e., one train of the ECCS operating) as a "favorable" assumption because it would decrease the head loss caused by a debris bed. Both flow rates are realistic and reasonable.

Final determination of the sump failure likelihood for each parametric case was expressed with a qualitative grade of **unlikely**, **possible**, **likely**, and **very likely**. Under this approach, a parametric case with debris-bed head losses that exceed the sump failure criterion when evaluated under favorable conditions indicates that blockage is **very likely** to occur for the assumed plant configuration. A case that meets the sump failure criterion even under unfavorable assumptions indicates that blockage is **unlikely** to be a concern. Intermediate cases that fail over part of the parameter range and succeed over the remainder of the range are more difficult to judge. These require consideration of features of the parametric case like the orientation of the screen, the location of the sump, and the predominance of insulation types in the containment. Qualitative grades of **likely** and **possible** were assigned to this intermediate spectrum of cases using engineering judgment based on associated calculations and related test data.

Results

Table ES-1. Summary of Sump Failure Potential for 69 Parametric Cases.

Sump Failure Potential	SLOCA	MLOCA	LLOCA
Very Likely	25	31	53
Likely	7	6	7
Possible	4	6	1
Unlikely	33	26	8
Total	69	69	69

Table ES-1 summarizes the results of the parametric evaluation. The 69 parametric cases developed for this evaluation provide a reasonable representation of operating PWRs, so the results form a credible technical basis for making a determination of whether sump blockage is a generic concern for PWRs. However, the parametric evaluations have a number of limitations that make them ill-suited for making a determination of whether a specific plant is vulnerable to sump failure.

Some of these limitations include the following.

(a) The locations of thermal insulation and other debris sources for the various plants that the parametric cases are based on were not modeled.
(b) Changes in $NPSH_{Margin}$ for the various plants that the parametric cases are based on were not modeled.
(c) The variability in responding to SLOCAs for the various plants on which the parametric cases are based was not modeled.

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[1] ECCS strainers in BWRs perform the same function that recirculation sump screens do in PWRs.

(d) Only the thermal insulations and other debris sources that are widely used were included in the evaluation.

Useful Insights

(a) Accumulation of very large quantities of damaged reflective metallic insulation (RMI) would be necessary to cause sump failure by the assumed head-loss criteria. The potential for sump failure caused by transport of RMI debris was found to be unlikely for all parametric cases except 3 out of the 69.

(b) Transport and accumulation of small quantities of fibrous and particulate debris are sufficient to cause sump failure by the assumed head-loss criteria. Approximately 1/2 ft^3 of fibrous insulation combined with only 10 lb of particulates would be sufficient to raise sump blockage concerns for 30 out of 69 parametric cases. This finding is a direct reflection of the fact that a significant number of parametric cases included sump-screen areas less than 100 ft^2 and $NPSH_{Margins}$ less than 4 ft-water.

(c) In numerous parametric cases, the estimated quantities of debris reaching the sump far exceeded the minimum amount of debris necessary to cause sump failure. The actual number of parametric cases where failure was predicted varied depending on the break size. In general, a large LOCA (LLOCA) tended to generate and transport substantially larger quantities than the failure-threshold debris loadings. Although estimates for the quantity of debris transported following a small LOCA (SLOCA) depended strongly on assumptions related to CS actuation, a small subset of parametric cases was capable of transporting quantities of debris sufficient for failure even without sprays. In these parametric cases, recirculation sumps are located inside the missile shield and have special features such as horizontal screens at or below the containment floor level.

(d) For many parametric cases, head-loss estimates (evaluated using both favorable and unfavorable assumptions) exceeded the $NPSH_{Margin}$ for the ECCS and/or CS pump(s). Typically, head-loss estimates following a LLOCA were much larger than the $NPSH_{Margin}$.

(e) Greater uncertainties and variability in SLOCA accident sequences introduce greater uncertainties in the conclusions of this study for SLOCA. Large debris volumes and more standard plant responses to medium LOCAs (MLOCAs) and LLOCAs increase the confidence placed in the conclusions for these accidents.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHU	Air Handling Unit
AJIT	Air-Jet Impact Testing
B&W	Babcock and Wilcox
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners' Group
CCW	Component Cooling Water
CE	Combustion Engineering
CFD	Computational Fluid Dynamics
CP	Corrosion Products
CS	Core Spray
DBA	Design Basis Accident
DEGB	Double-Ended Guillotine Break
ECCS	Emergency Core Cooling System
EOP	Emergency Operating Procedure
EQ	Equipment Qualification
ESF	Engineered Safeguard Feature
FSAR	Final Safety Analysis Report
FTDL	Failure-Threshold Debris Loading
FY	Fiscal Year
GL	Generic Letter
GSI	Generic Safety Issue
HDR	Heissdampfreaktor
HEPA	High-Efficiency Particulate Air
HPSI	High-Pressure Safety Injection
IPE	Individual Plant Examination
L/D	Range-of-Damage Zone Divided by Pipe Diameter
LANL	Los Alamos National Laboratory
LDFG	Low-Density Fiberglass
LLOCA	Large LOCA
LOCA	Loss-of-Coolant Accident
LPSI	Low-Pressure Safety Injection
MLOCA	Medium LOCA
NEI	Nuclear Energy Institute
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NRR	Nuclear Regulatory Research
PORV	Power-Operated Relief Valve
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RMI	Reflective Metallic Insulation
RWST	Refueling Water Storage Tank
SAT	Spray Additive Tank
SER	Safety Evaluation Report
SI	Safety Injection

SLOCA	Small LOCA
SRS	Savannah River Site
UFSAR	Updated Final Safety Analysis Report
URG	Utility Resolution Guidance
USI	Unresolved Safety Issue
ZOI	Zone of Influence

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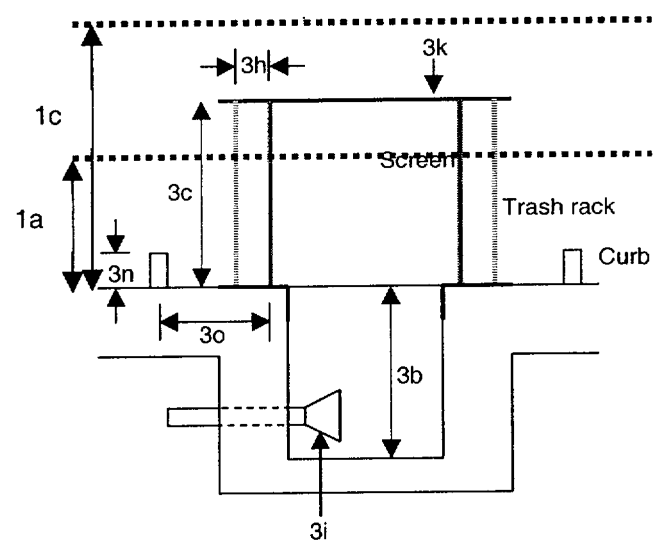
1.0 INTRODUCTION

1.1 Description of Safety Concern

In the event of a loss-of-coolant accident (LOCA) within the containment of a pressurized water reactor (PWR), piping thermal insulation and other materials in the vicinity of the break will be dislodged by break-jet impingement. A fraction of this fragmented and dislodged insulation and other materials such as paint chips, paint particulates, and concrete dust will be transported to the containment floor by the steam/water flows induced by the break and by the containment sprays. Some of this debris will eventually be transported to and accumulated on the recirculation sump suction screens. Debris accumulation on the sump screen may challenge the sump's capability to provide adequate, long-term cooling water to the emergency core cooling system (ECCS) and to the containment spray (CS) pumps. The Generic Safety Issue (GSI) 191 study titled "Assessment of Debris Accumulation on PWR Sump Performance" addresses the issue of debris generation, transport, and accumulation on the PWR sump screen, and its subsequent impact on ECCS performance. Los Alamos National Laboratory (LANL) has been supporting the U.S. Nuclear Regulatory Commission (NRC) in the resolution of GSI-191.

In the GSI-191 study, the sump is defined as the space enclosed by the trash rack (see Fig. 1-1), and the space enclosed by the sump screen is referred to as the sump pit or sump region. Figure 1-1 is a generic representation of a pressurized water reactor (PWR) sump layout. Actual sump designs vary significantly from this figure, but all share similar geometric features. The purpose of the trash rack and sump screen is to prevent debris that may damage or clog components downstream of the sump from entering the ECCS and reactor coolant system (RCS). The area outside of the sump is referred to as the containment floor or pool.



Symbol	
3b	Sump depth
3c	Height above floor
3h	Distance between trash rack and screen
3i	Vortex suppressor
3k	Solid plate
3n	Debris curb height
3o	Distance between debris curb and screen
1a	Height of water pool on containment floor at time of switchover
1c	Max. Height of water pool on containment floor

Fig. 1-1. Illustration of Sump Parameters Queried in the GSI-191 Industry Survey.

An examination of plant drawings, preliminary analyses, and ongoing tests suggests that a prominent mechanism for recirculation sump failure involves pressure drop across the sump screen induced by debris accumulation. However, sump-screen failure through other mechanisms is also possible for some configurations. Three failure mechanisms were considered as part of the GSI-191 study.

(1) Loss of net positive suction head (NPSH) margin caused by excess pressure drop across the screen resulting from debris buildup. This concern applies to all plant units having sump screens that are completely submerged in the containment pool in combination with other plant features that permit generation and accumulation of debris on the sump screen.

(2) Loss of the static head necessary to drive recirculation flow through a screen because of excess pressure drop across the screen resulting from debris buildup. This concern applies to all plant units having sump screens that are not completely submerged in combination with other plant features that permit generation and accumulation of debris on the sump screen.

(3) Blockage of water-flow paths may (a) cause buildup (and retention) of water in some regions of the containment and result in lower water levels near the sump and thus lower $NPSH_{Margin}$ than estimated by the licensees or (b) altogether prevent adequate water flow through these openings.

Realistically, only the licensees are capable of judging their plant's vulnerability to the third safety concern because (a) vulnerability to this mechanism is highly plant-specific and (b) the plant-specific data necessary to make such a judgment are not widely available. Although plant vulnerability to debris accumulation on the sump screen (i.e., the first two safety concerns) is also plant-specific, the NRC and industry groups have compiled much of the information that is necessary to effectively judge the vulnerability of ECCS systems during recirculation following specific accidents [e.g., large LOCA (LLOCA), medium LOCA (MLOCA), and small LOCA (SLOCA)] and to draw insights regarding the potential severity of the problem for classes of reactors with similar design features (e.g., sub-atmospheric containments, ice condenser containments, etc.). The focus of the present study is to perform "representative" parametric analyses to address the following safety questions for each plant to the extent possible.

If a LOCA of a given break size were to occur, would the amount and type of debris generated from containment insulation and other sources of debris cause significant buildup on the ECCS recirculation sump? If so, would such blockage be of sufficient magnitude to challenge the ECCS function either by reducing the $NPSH_{available}$ below the $NPSH_{required}$ or by reducing flow through the sump screen below the ECCS pump flow demand?

Other concerns related to debris generated during postulated accidents are beyond the scope of the GSI-191 study and the parametric analyses presented in this report. Examples of such concerns include (a) the potential for debris to pass through the sump screen, enter the RCS, and damage or block ECCS or RCS components and (b) structural failure of sump screens as a result of loads from debris or direct jet impingement.

1.2 Scope and Objectives of the Parametric Calculations

The present study has two objectives.

1. Perform parametric analyses that can be used effectively to judge the potential for sump-screen blockage following postulated LLOCA, MLOCA, and SLOCA events in representative PWRs. This includes performing appropriate technical calculations that provide estimates for debris generation, debris transport, debris accumulation, and the resulting head loss across the sump screen. This effort also includes providing defensible bases for all of the assumptions made in the

analyses and explanations of how some of the prominent calculational uncertainties were factored into the decision process.

2. Interface with the ongoing probabilistic risk assessment (PRA) study [LANL, 2001f] and provide a conditional probability range for loss of recirculation caused by LOCA-generated debris that can be used to estimate the risk-significance of this issue for the overall PWR population.

Clearly, this safety concern is plant-specific in nature, and a firm determination of the vulnerability of any individual plant could require a plant-specific evaluation. Such an evaluation may have to incorporate plant features such as

- physical layouts of primary and auxiliary piping in the containment;
- possible locations of the postulated breaks and the likely ECCS response to these breaks;
- locations, types, and quantities of insulation used on each piping system and equipment component;
- physical layouts of intervening structures that may inhibit debris transport;
- a physical description of the sump geometry and its location in containment; and
- the time until switchover to recirculation and the required flow rates through the sump.

Detailed plant-specific analyses are complex and unique, and performing them for each of the 69 operating PWRs is beyond the present scope of work.[2] The objective of this parametric study is to examine the range of possible conditions present in the industry and to incorporate variations such as insulation type in proportion to its occurrence in the population so that the plausibility of sump blockage can be assessed. This objective necessitates approximations of individual plant features, so throughout the parametric analysis, individual cases are developed to represent specific plants in the industry. Although the best information available to LANL was used for each unit, it is recognized that these cases do not describe conditions at any single plant in great detail. Therefore, the individual entries for each unit will be referred to as "cases" or as "parametric cases" rather than as "plant analyses" so that it is understood that the individual cases do not provide a complete perspective of sump-blockage risk at the corresponding plants.

Even with the necessary approximations, valuable insights regarding the relative potential for plant susceptibility to sump-screen blockage can be drawn by performing representative parametric evaluations. This can be demonstrated by considering the following examples.

1. Consider two plants that have sump screens with flow areas of only 11.64 ft^2 and use fibrous insulation on essentially all of their piping.[3] A LOCA in these plants would almost certainly result in thick beds of fibrous insulation on the screen. With or without the addition of some particulate materials (e.g., concrete dust and paint chips), a substantial head loss would result that could easily overcome the plant's NPSH margin (estimated to be about 2.6 ft-water based on plant responses to NRC GL 97-04 [US NRC, 1997]). Several representative parametric evaluations can be performed in this case to demonstrate that sump-screen blockage and loss of $NPSH_{Margin}$ are **very likely** for these plants.

2. There is a set of plants whose primary piping is insulated with large quantities of both calcium silicate (cal-sil) and fibrous insulation (e.g., fiberglass or mineral wool). The combination of cal-sil and fibrous insulation is known to induce very large head losses across a sump screen (even at very small debris loadings), and hence, this class of plants would be susceptible to sump-

[2]Plant-specific analyses are underway as part of the continuing GSI-191 study for two volunteer plants and six USI A-43 reference plants (for which detailed drawings are available).
[3]Source of information: Plant submittal to Industry Survey.

screen blockage. Representative parametric evaluations also can be performed in this case to judge the potential for blockage.

3. Finally, consider a plant that has a screen area of 330 ft^2. Its insulation consists of 90% reflective metallic insulation (RMI) and 10% fibrous insulation, and it has a relatively large $NPSH_{Margin}$ of 5.25 ft. RMI debris is known to cause substantially less strainer blockage than other types of insulation debris. Also, recent testing has shown that RMI is less likely to transport to the sump in significant quantities. Given these facts, parametric evaluations can be used again to show that this plant is **unlikely** to have a strainer head-loss problem. Despite the conclusions of a parametric evaluation, only a thorough analysis can confirm that this plant is not susceptible to sump-screen blockage.

The terms "very likely" and "unlikely" are described in Sec. 3 along with the rationale used to assign these grades to each parametric case.

1.3 Description of Relevant Plant Features and Other Parameters

Some general conclusions regarding important plant features that influence accident outcome are listed below.

Sump Design and Configurations

- The ECCS and/or CS pumps in nearly one-third of the plants have an $NPSH_{Margin}$ less than 2 ft-water, and another one-third have an $NPSH_{Margin}$ between 2 ft-water and 4 ft-water. In general, PWR sumps have low $NPSH_{Margins}$ compared with the head-loss effects of debris accumulation on the sump screen.
- PWR sump designs vary significantly, ranging from horizontal screens located below the floor elevation to vertical screens located on pedestals. The sump-screen surface areas vary significantly from unit to unit, ranging from 11 ft^2 to 700 ft^2 (the median value is approximately 125 ft^2). Some plants employ curb-like features to prevent heavier debris from accumulating on the sump screen, and some do not have any noticeable curbs. All these plant-specific features should be captured adequately in the parametric cases.
- In 19 PWR units, the sump screen would not be completely submerged at the time that ECCS recirculation starts. As described in Sec. 1.4, the mode of failure is strongly influenced by sump submergence.
- Sump-screen clearance size varies considerably. A majority of the plants used a sump-screen opening size of 0.125 in., reportedly to ensure that the maximum size of the debris that can pass through the sump screen is less than the smallest clearance in the RCS and the CS system. However, 26 PWR units indicated that sump-screen clearance is higher than 0.125 in., reaching up to 0.6 in. Two units reported not having fine screens, other than the standard industrial grating used to filter out very large debris.

Sources and Locations of Debris

- US PWRs employ a variety of types of insulation and modes of encapsulation, ranging from non-encapsulated fiberglass to fully encapsulated stainless-steel RMI. A significant majority of PWRs have fiberglass and cal-sil insulations in the containment, either on primary piping or on supporting systems.[4] The types of fibrous insulation varied significantly, but much of it is in the form of generic low-density fiberglass (LDFG) and mineral wool. It appears that many of the newer plants (or plants replacing steam generators) have been replacing RMI insulation on the primary systems with "high-performance" fiberglass. In general, the smaller pipes and steam generators are more likely to be insulated with fiberglass and cal-sil than the reactor pressure vessel or the hot leg or cold leg. Other sources of fibrous materials in the containment for some plants include up to 12,985 ft^2 of filter media on the air-handling units (AHUs) and up to 1500 ft^3 of fibrous insulation (e.g., Kaowool) used as fire barrier materials. Given that (a) very small quantities of fibrous insulation would be necessary to induce large pressure drops across the sump screens (less than 10 ft^3) and (b) most plants have comparatively very large inventories of fibrous insulation, it is not clear that any plant can be screened out from this safety evaluation without the benefit of detailed evaluations.

- Other sources of debris in the PWR containments include cement dust and dirt (either present in the containment *a priori* or generated by a LOCA), particulate insulations used on the fire barriers (e.g., Marinite), failed containment coatings (a median PWR has approximately 650,000 ft^2 of coated surfaces in the containment), and precipitants (zinc and aluminum precipitation by-products).[5] Estimates for this type of debris ranges from 100 lb to several 1000 lb; either of these bounds would result in very large head losses when combined with fibrous material .

Containment Features Affecting Debris Transport

- CS set points typically are defined based on LLOCA and equipment qualification (EQ) considerations. Consequently, sprays may not (automatically) actuate during SLOCAs[6] because peak containment pressures are expected to be lower than for an LLOCA. CS actuation following an SLOCA event plays an important role in the transport of debris to the sump, and at the same time, it affects the timing of sump failure. Set points for CS actuation vary considerably and span a wide range: 2.8 psig to 30 psig. Consistently lower values are observed in sub-atmospheric and ice condenser containment designs, as would be expected. Nevertheless, values at or below 10 psig[7] are observed for several plants, including large dry containments.

1.4 Criteria for Evaluating Sump Failure

The sump failure criterion applicable to each plant is determined primarily by sump submergence. Figure 1-2 illustrates the two basic sump configurations of fully and partially submerged screens. Although only vertical sump configurations are shown here, the same designations are applicable for inclined screen designs. The key distinction between the fully and partially submerged configurations is that partially submerged screens allow equal pressure above both the pit and the pool, which are potentially separated by a debris bed. Fully submerged screens have a complete seal of water between the pump inlet and the containment atmosphere along all water paths passing through the sump screen. The effect of this difference in evaluation of the sump failure criterion is described below.

[4]About 40 PWR units have in excess of 10% of the plant insulation in the form of fiberglass and another 5-10% in the form of cal-sil. A typical plant has approximately 7500 ft^3 of insulation on the primary pipes and supporting systems pipes that are in close proximity to the primary pipes.

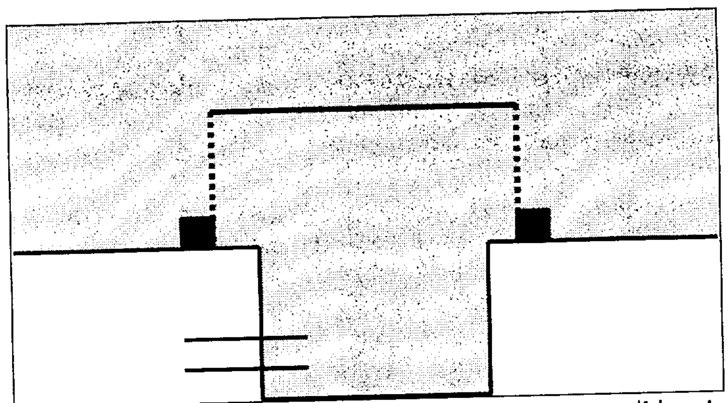
[5]PWR DBAs evaluate the potential for precipitation of aluminum and zinc when they are subjected to high-pH, hot, borated water because these chemical reactions generate H_2.

[6]Fan cooler response to LOCAs also plays a vital role in determining spray actuation following SLOCA. These concerns are not applicable to LLOCA or MLOCA, where automatic actuation of sprays is expected in every plant.

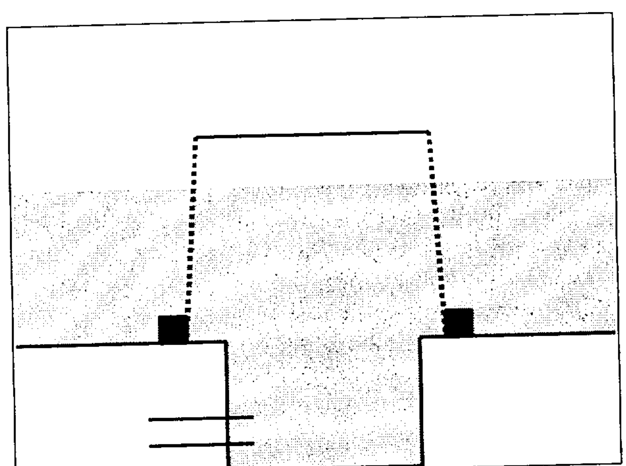
[7]The 10-psig set point is important because MELCOR simulations showed that if both fan coolers in a large dry containment are not operating at full capacity, containment pressure could exceed 10 psig for breaks $\geq$ 2 in [LANL, 2001b].

1.4.1 Fully Submerged Sump Screens

Figure 1-2(a) is a schematic of a sump screen that is fully submerged at the time of switchover to ECCS. Sump failure is likely to occur for sumps in this configuration because of cavitation within the pump housing when head loss caused by debris accumulation exceeds the $NPSH_{Margin}$. For this set of plants (in which sump screens are fully submerged at the time of switchover), the onset of cavitation is determined by comparing the plant $NPSH_{Margin}$, as reported by plants responding to NRC Generic Letter (GL) 97-04 [US NRC, 1997] with the screen head loss calculated in the parametric study. Therefore, for this case, the sump failure criterion (ΔH_f) is assumed to be reached when $\Delta H_{screen} \geq NPSH_{Margin}$.



(a) Fully submerged screen configuration showing solid water from pump inlet to containment atmosphere.



(b) Partially submerged screen configuration showing containment atmosphere over both the external pool and the internal sump pit with water on lower portion of screen.

Fig. 1-2. Sump-Screen Schematics.

1.4.2 Partially Submerged Sump Screens

Figure 1-2(b) is a schematic of a sump that is partially submerged at the time of switchover. Failure can occur for sumps in this configuration in one of two ways: by pump cavitation as explained above or when head loss caused by debris buildup prevents sufficient water from entering the sump. This flow imbalance occurs when water infiltration through a debris bed on the screen can no longer satisfy the volumetric demands of the pump. Because the pit and the pool are at equal atmospheric overpressure, the only force available to move water through a debris bed is the static pressure head in the pool. Numeric simulations confirm that an effective head loss across a debris bed approximately equal to ½ of the pool height is sufficient to prevent adequate water flow. For all partially submerged sump screens, the sump failure criterion (ΔH_f) is assumed to be reached when

$$\Delta H_{screen} \geq NPSH_{Margin} \text{ or } \Delta H_{screen} \geq \tfrac{1}{2} \text{ of pool height.}$$

After switchover to ECCS recirculation, some plants can change their sump configuration from partially submerged to fully submerged. This can occur for a number of reasons, including accumulation of CS water, continued melting of ice-condenser reservoirs, and continued addition of refueling water storage tank (RWST) inventory to the containment pool. As the pool depth changes during recirculation, the "wetted area" (or submerged area) of the sump screens can also change. The wetted area of the screen determines the average approach velocity of water that may carry debris. Because information about time-dependent pool depths is difficult to obtain and because the most significant debris transport will occur early in the scenario when the pool is shallow, only the pool depth at the time of switchover to the ECCS was used in the parametric evaluations.

1.5 Industry Survey and Other Sources of Information

Based on the findings of the boiling water reactor (BWR) ECCS strainer blockage study, e.g., BWR Utility Resolution Guidance (URG) [BWROG, 1998], review of updated safety analysis reports (UFSARs), and several plant visits, the NRC and LANL identified a set of plant design features (e.g., sump design) and sources of debris (e.g., insulation materials and containment coatings) that were judged to strongly influence debris generation, transport, and accumulation in PWRs. One of the tasks under GSI-191 is to compile a database of insulation, containment, and recirculation sump design and operation information for each of the operating US PWRs.

The NRC (and LANL) formulated a set of questions that captured some of the information needs and forwarded them to the industry groups formally organized by Nuclear Energy Institute (NEI). The licensee response to these survey questions was voluntary and consisted of written responses and engineering drawings (as deemed necessary by the individual licensees). This information is contained in the NEI database *Results of Industry Survey on PWR Design and Operations* [NEI, 1997]. LANL performed a thorough review of the industry responses to draw inferences regarding the plant designs and features that affect the generation, transport, and accumulation of debris on the sump screen. From this data base, LANL also compiled the most up-to-date information on insulations, other sources of debris, and containment and sump configurations at each of the operating PWRs. This database is the primary source of information for the parametric evaluations described here [LANL, 2001a]. This information was supplemented, as necessary, using two sources of additional information.

1. PWR licensee responses to Generic Letter 97-04, "Assurance of Sufficient Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Pumps" [US NRC, 1997]. These provide the $NPSH_{Margin}$ and licensing-basis ECCS flow rate for each plant following a postulated LLOCA.

2. PWR UFSARs, individual plant examination (IPE) submittals, and emergency operating procedures (EOPs) for selected plants. These provided information regarding plant accident progression and the basis for recirculation sump flow rates following a SLOCA.

1.6 Integration of Parametric Calculations with Ongoing GSI-191 Research

The parametric analysis documented in this report took advantage of the following aspects of the ongoing GSI-191 research program.

Preliminary results from ongoing debris generation testing [LANL, 2001e] were used to define the zone of influence (ZOI)[8] for fiberglass and cal-sil insulations in this parametric study. The preliminary findings suggest that two-phase jets with a stagnation pressure of approximately 1400 psia (290°C and 20-s blowdown duration)[9] can inflict significant damage at distances much farther away than those measured either in USI A-43 studies or the BWR air-jet impact test (AJIT) program. Further testing is under way to collect similar test data for other insulations (other than fiberglass and cal-sil) and to examine the effect of larger nozzle sizes and longer blowdown duration on insulation damage.

Results from the ongoing transport testing program [LANL, 2001c; LANL, 2001d] played a key role in determining the containment transport fractions and thus the quantity of insulation expected to reach the sump. Given the preliminary nature of the results coupled with the fact that computational fluid dynamics (CFD) simulations of the parametric plant containment floors is lacking, the experimental results were used to deduce "favorable" and "unfavorable" estimates rather than best estimates. A set of transport tests using a three-dimensional tank facility were conducted to specifically obtain transport data that can be used to define "favorable" and "unfavorable" bounds.

The results from head-loss modeling activities were used to estimate the head-loss effects of debris accumulation on the sump. The primary basis for head-loss models is a BWR study [Zigler, 1995] that provided a semi-theoretical model for head-loss estimation. This correlation is known to under-predict head loss for cal-sil beds for which head-loss data were not measured in the NRC test apparatus (these experiments are currently in progress). Once again, the head-loss model was used to deduce "favorable" and "unfavorable" estimates for cal-sil contribution.

A set of tests was specifically designed and carried out in support of this parametric study [LANL, 2001d]. These tests examined the ability of small fiberglass insulation shreds and loosely attached fibers to build a contiguous and uniform debris bed on the simulated sump screens with openings of 1/4 in. and 1/8 in., respectively. These tests confirmed that at a "nominal" or "theoretical" thickness of approximately 1/10-in. fiberglass beds can be built on a vertical sump screen and that the beds can start to filter out cal-sil passing through them. In addition, these tests confirmed that cal-sil insulation can form debris beds by itself even without presence of fiberglass.

It also should be noted that this parametric study took full advantage of (a) containment and RCS analytical models developed as part of GSI-191 (see Sec. 2 and [LANL, 2001b]) and (b) a debris generation CAD model, also built to support the GSI-191 study (see Sec. 3).

Finally, the study results were provided to both LANL and NRC PRA analysts for use in their determination of the risk significance of GSI-191 to US PWRs. The PRA studies benefited significantly from the thermal-hydraulics simulations described in the following sections.

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

[9]These conditions are significantly less severe than those expected in a PWR (2250 psia and 300°C).

2.0 DESCRIPTION OF POSTULATED ACCIDENTS

2.1 Overview

This section presents the results of thermal-hydraulic simulations performed to achieve the following objectives.

1. Identify important RCS and containment thermal-hydraulic parameters that influence the generation and/or transport of debris in PWR containments.

2. Perform plant simulations using NRC-approved computer codes to the determine the value of each parameter as function of time and, where applicable, as a function of the assumed system's response. Of particular interest are plant simulations of small and medium LOCAs for which information regarding accident progression is not readily available.

3. Use the calculated plant response information to construct accident progression sequences that form the basis for strainer blockage evaluations and probabilistic risk evaluations.

Originally, evaluations were made for seven accident scenarios: (1) LLOCA (cold- and hot-leg breaks), (2) MLOCA (6-in. cold leg), (3) SLOCA (2-in. cold leg), (4) small-small LOCA (1/4-in. cold leg), (5) pressurizer surge line break, (6) loss of offsite power with simultaneous failure of feedwater, and (7) false lifting and stuck-open power-operated relief valve (PORV).

Figure 2-1 shows the major steps involved in the calculational effort. These include the following.

- RELAP5/MOD3.2 [Lockheed, 1995] was used for simulating the RCS response to each of the postulated accident sequences. The RELAP5 simulations incorporated realistic initial and boundary conditions and a full representation of a Westinghouse four-loop RCS design. Selected simulations were also performed for Combustion Engineering (CE) plants. No RELAP simulations were performed for Babcock and Wilcox (B&W) plants. Information regarding B&W plants was obtained primarily from their IPEs.

- MELCOR Version 1.8.2 [Summers, 1994] was used for simulating the response of the ice condenser containment, large dry containment, and sub-atmospheric containment to a release of steam/water into the containment as a result of each accident sequence (as predicted by RELAP5).

The parameters tracked for each code simulation are shown in Fig. 2-1. These parameters were limited to those that could influence debris generation and transport following a LOCA. A brief description of each of the important parameters and their potential effect is provided in Table 2-1.

Brief discussions of the simulation results are provided in Secs. 2.2 through 2.4 for an LLOCA, an MLOCA, and an SLOCA, respectively. An examination of the data summarized in these sections reveals that accident progression differs markedly with event type and containment type. The important differences are as follows.

Table 2-1. Important Parameters Tracked and Their Relevance to the Study.

RCS PRESSURE AND TEMPERATURE: The flow through an RCS breach would be choked as long as the RCS temperature (and hence pressure) remain elevated. The critical (choked) flow rate through the breach would depend strongly on upstream pressure and temperature, which define the thermodynamic state of the fluid. The state of the fluid largely determines the expansion characteristics of a two-phase flashing jet as evident from Ref. 5.
BREACH FLOW CONDITIONS (FLOW RATE, VELOCITY, AND QUALITY): The destructive potential of a break jet depends strongly on break flow conditions. The velocities of both phases (liquid and vapor) are important here. The values calculated are the velocities at the choke plane. The moisture content of the fluid exiting the breach influences the damage potential of the jet. The quantity calculated here is the ratio of vapor mass flow rate to total mass flow rate at the choke plane.
ECCS SAFETY INJECTION FLOW: The rates of ECCS safety injection determine when the inventory of the RWST would be depleted, requiring switchover to ECCS recirculation through the emergency sump. The timing of switchover is important with regard to debris settling opportunities. Flow patterns in the water pool formed on the floor of containment would be influenced by injection rates. Injection rates determine accident progression as related to the rate at which the RCS is cooled down.
ECCS RECIRCULATION FLOW: The rate at which flow is recirculated through the emergency sump will determine the flow patterns, velocities, and turbulence levels in the containment pool. The potential for debris transport is governed by these traits.
CONTAINMENT SPRAY FLOW: Containment sprays have the potential to wash settled debris from containment structures and suspended debris from the containment atmosphere down to the containment pool. Whether the sprays are operating or not largely determines the time at which the RWST inventory is expended and the magnitude of the recirculation flow through the emergency sump. The flow patterns and turbulence levels in the containment pool may be affected by where and how the sprays drain. The potential for containment sprays to influence debris transport is thought to be considerable. As such, it is important to note the large variability in spray activation logic that exists from plant to plant, e.g., containment high-high pressure set points. Additionally, actions taken by the operators to shut containment sprays down would influence debris transport.
CONTAINMENT SPRAY TEMPERATURE: In some plants, recirculated spray water passes through heat exchangers. The heat removal would influence containment pressure and temperature trends. This phenomenon is of particular interest in ice-condenser containments. Therefore, special emphasis was put on modeling residual heat removal (RHR) heat exchangers and determining spray temperatures as close to reality as possible.
POOL DEPTH AND TEMPERATURE: The available NPSH at the recirculation pumps depends on the depth of the containment pool and its temperature. The velocities, flow patterns, and turbulence levels (and hence debris transport potential) in the pool depend on pool depth.
POOL pH: Basic or acidic tendencies in recirculating water may change the corrosion, dissolution, or precipitation characteristics of metal or degraded metal-based paints in containment. A specific concern is the possible precipitation of ZnOH formed from chemical interaction between zinc (in the zinc-based paints) and water at high temperature. The dissolution/precipitation of ZnOH in water is influenced by the degree of boration.
CONTAINMENT ATMOSPHERIC VELOCITY: The atmospheric velocities generated in the containment in response to an RCS breach determine to what degree generated debris initially disperses within the containment. These are the velocities developed as containment is subjected to the shock and pressurizing effects of the flashing break jet.
PAINT TEMPERATURE: Sustained elevated temperatures may degrade containment paints. An elaborate paint representation model was included in the MELCOR input model.

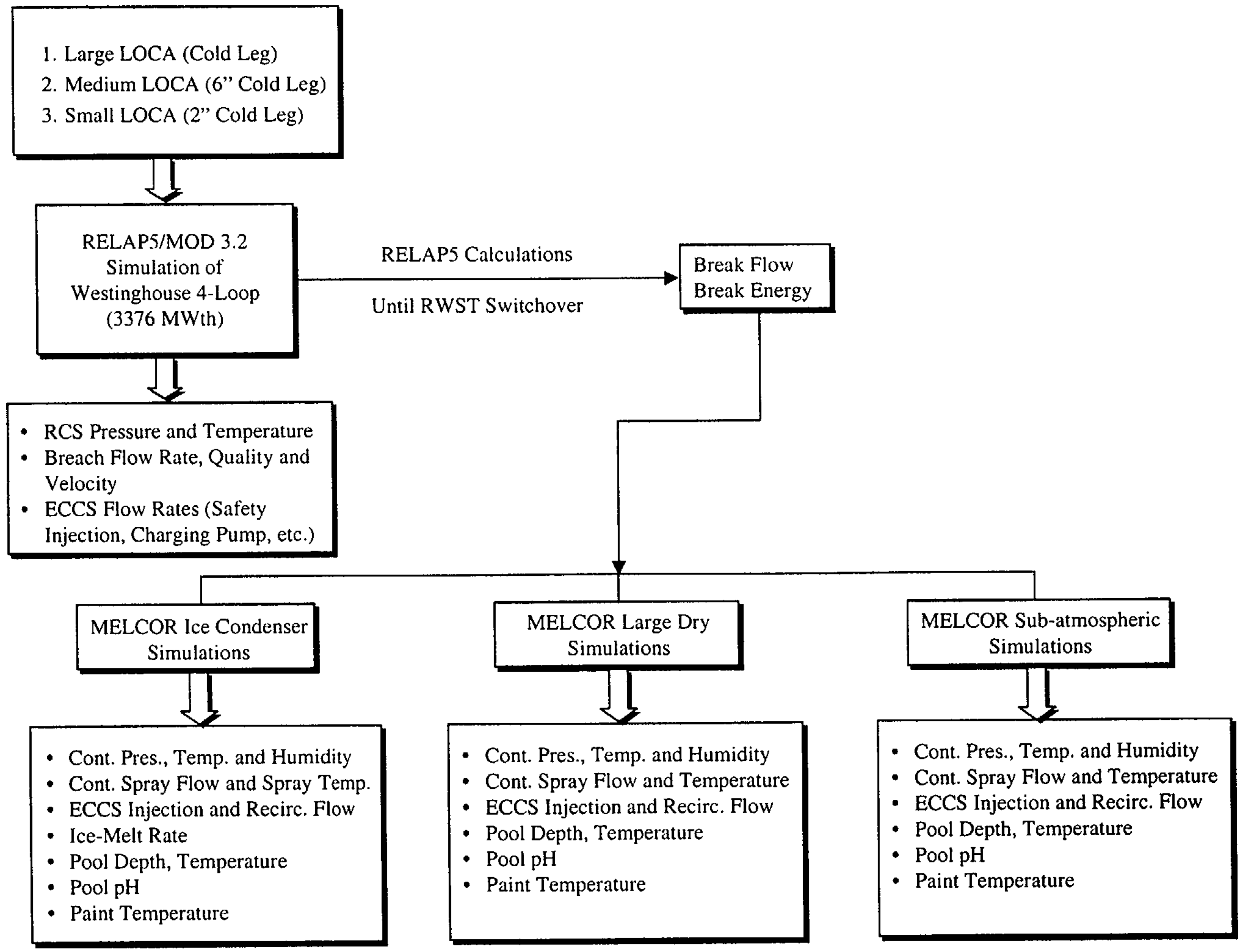

Fig. 2-1. Flow Chart of Analysis Process.

1. *Time at which blowdown commences and the duration over which blowdown occurs varies considerably with accident type.* In one extreme, the RCS blowdown following an LLOCA commences immediately and terminates within 30 s. The stagnation pressure at the break plane over that time period varies between 2000 and 300 psia. On the other extreme, blowdown following the SLOCA occurs over the first hour of the transient; even after 1 h, it is possible that the pressure vessel remains at pressures as high as 500 psi. Debris generation estimates must account for these differences, especially for those insulations for which generation is driven by erosion. It is possible that a small-break ZOI may be characterized by a larger L/D compared with large or medium breaks.[10]

2. *The magnitude of the ECCS recirculation flow through the emergency sump varies between events.* In the case of an SLOCA, the maximum ECCS flow through the sump during recirculation corresponds to the make-up flow for the high-presure spray injection (HPSI) and charging pump discharge into the RCS (at about 500 psi) and subsequently leaking into the containment through the breach. On the other hand, following a LLOCA or a MLOCA, the maximum ECCS flow approaches the design flow (which is approximately 11,000 gpm for the cases simulated). The implication is that the potential for debris transport would be higher following an LLOCA than for the SLOCA analyzed. The plant-specific estimates for ECCS recirculation flow for each case can be obtained as follows.

   - A generic value of 10,000 gpm (large break) could be used for most plants, or alternately, the plant response to NRC Generic Letter (GL) 97-04 [US NRC, 1997] may be used.

   - A generic value of 2500 gpm (small break) could be used for most plants. A survey of plant data suggests that actual ECCS flow following a SLOCA could vary between 1800 gpm and 4800 gpm, with a median value of 2500 gpm [LANL, 2001a].

3. *CS actuation is accident- and plant-specific.* In an accident where containment fan coolers sufficiently managed containment pressure and temperature to below the engineered safeguard feature (ESF) actuation set point, sprays would not actuate. If the sprays were not used or were used only sparingly, the length of time that ECCS injection could draw from the RWST would be largely increased. This also would minimize the potential for debris washdown by the cascading spray water. Note that for SLOCA events, sprays were not required for large dry containments whose actuation set points are higher than 10 psi, thereby limiting the maximum flow expected through the sump. Sprays were required for the ice condenser containment, resulting in sump flow rates nearly four times that required for the large dry plants. Sprays are also required for many large dry plants (including but not limited to sub-atmospheric containment) whose actuation set points are equal to or lower than 10 psi[11]. This is because of the following.

   - In several plants, the chilled water supply to the fan coolers is isolated following the LOCA, which reduces the efficiency of the fan coolers for removing containment heat. [The ultimate heat sink is the component cooling water (CCW), which may not be sufficiently sized to handle such heat loads.]

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[10]The ZOI is defined as the zone within which the break jet would have sufficient energy to generate debris of transportable size and form. L/D (read 'ell over dee') is a unitless measure of the size of the ZOI, where L is the maximum linear distance from the location of the break to the outer boundary of the ZOI and D is the diameter of the broken pipe.

[11]A SLOCA simulation was performed assuming fan coolers were not operational. Maximum containment pressure for this calculation was estimated to be approximately 18 psi, as opposed to 5 psi (See Table 2-7) for the case where fan coolers are assumed to operate [LANL, 2001b].

- Degradations in fan coolers may also be possible if LOCA debris reaches or deposits on the fan cooler heat exchangers.

- Fan coolers are not safety-class equipment in most PWRs. It is not clear that fan coolers can be relied on for pressure control for a variety of reasons ranging from the fact that their functionality is not tested for these conditions to the fact that the heat removal source for fan coolers may be isolated as a result of a hi-hi or hi containment pressure set point (differs from containment to containment).

The plant estimates for CS recirculation flow for each plant can be obtained as follows.

- A generic value of 6000 gpm can be used for most PWRs or alternatively one can use appropriate flow rates applicable to each plant. Individual plant flow is generally not significantly different, and thus will not influence the accident outcome.

2.2 Large Loss-of-Coolant Accident

The LLOCA simulated was a cold-leg, pump-discharge, double-ended guillotine break (DEGB). The RCS pressure and average temperature before the break were 2250 psia and 570°F. The cold-leg inside diameter was 27.5 in., corresponding to a cross-section area of 4.12 ft^2. The break was assumed to be instantaneous with a discharge coefficient of unity. A cold-leg break was chosen as the LLOCA event because design-basis accidents typically are cold-leg breaks. With respect to debris generation and transport, any differences between a cold-leg and hot-leg break likely would be small. This is not the case for core response, but with respect to emergency sump blockage, differences between large hot-leg and large cold-leg breaks are probably negligible. This assumption is supported by the results (not presented here) of a supplementary RELAP5 large-hot-leg-break calculation that compares closely with the results of the large-cold-leg-break calculation with respect to break flow characteristics.

The calculated results for the LLOCA events in large dry and ice condenser containments are provided in Tables 2-2 and 2-3, respectively.[12] These simulations were used to develop a generic description of LLOCA accident progression in a PWR, both in terms of the system's response and its implications on debris generation and transport. Table 2-4 provides a general chronology of events for a PWR LLOCA sequence. Figure 2-2 summarizes key findings to supplement the tabulated results, with further explanation as follows.

2.2.1 RCS Blowdown

In this report, the RCS blowdown refers to the event (or process) by which elevated energy in the RCS inventory is vented to containment as the RCS vents through the breach. Blowdown and the subsequent flashing[13] in containment causes rapid decay in the RCS pressure and rapid buildup of containment pressure. Either of these initiates reactor scram,[14] and with delay built-in, it is expected that reactor scram would occur within the first 2 s. It is during RCS blowdown that flow from the break occurs and the highest (and most destructive) energy is released. Therefore, debris generation by jet impingement would be greatest during this time. Also, debris could be displaced from the vicinity of the break as the flashing two-phase break jet expands into the containment. Large atmospheric velocities

[12]Large dry containment LLOCA results are representative of those expected for sub-atmospheric containments as well, with the exception that inside recirculation pump flow for the sub-atmospheric containment would have to be added.

[13]Flashing refers to the phenomenon by which the mainly liquid inventory of the RCS turns into a steam and liquid mixture as it is expelled into the containment atmosphere, which is at a significantly lower pressure.

[14]The accident progression in sequences in which scram does not occur is significantly different and will not be discussed in this document.

may develop in the containment (approaching 200 ft/s in the ice condenser containment and 300 ft/s in the large dry containment) as breach effluent quickly expands to all regions of the containment. In the vicinity of the breach, containment structures would be drenched by water flowing from the breach. Increase in containment pressure also causes immediate automatic actuation of containment sprays (for all plant types), condensing steam and washing structures throughout containment. Spray water drains over and down containment walls and equipment, carrying both insulation and particulate (e.g., dirt and dust) debris to a growing water pool on the containment floor. In most containments, NaOH liquid stored in the spray additive tank (SAT) will be added to the borated water to facilitate absorption of iodine that may be released to the containment. Therefore, a secondary CS effect is a potential increase in pool pH, which in turn, could play a role in particulate debris precipitation caused by the interaction of hot, borated, high-pH water with zinc and aluminum surfaces. The rates of these reactions are used in many FSARs to estimate the hydrogen source term and evaluate the potential for hydrogen accumulation in the containment.

Accurate characterizations of conditions that exist during the blowdown phase are important for estimating debris generation and, to some degree, debris transport. For LLOCA events, RCS blowdown occurs over a period of approximately 30 s, during which vessel pressure goes from 2250 psia to near atmospheric pressure. During this time, the reactor pressure vessel thermodynamic conditions undergo a rapid change. Initially, the break flow is subcooled at the break plane and flashes as it expands into the containment. Within 2 s, the vessel pressure drops below 2000 psi and the flow in the pipes and the vessel becomes saturated. Thereafter, the break flow quality is equal to or higher than 10%. On the other hand, the void fraction increases to approximately 1.0, clearly indicating that the water content would be dispersed in the vapor continuum in the form of small droplets. The corresponding flow velocity at the break plane reaches a maximum of about 930 ft/s. This clearly indicates that jets would reach supersonic conditions during their expansion upon exiting the break. Based on these simulations, the energetic blowdown terminates within 25-30 s as the vessel pressure decreases to near 150 psig. Although steam at high velocities continues to exit, the stagnation pressure is not sufficient to induce very high pressures at distances far from the break. Thus, it is reasonable to assume that debris generation following a LLOCA occurs within the first minute. (Note: Debris generation by non-jet-related phenomena may occur over a prolonged period of time as a result of high temperature and corrosion.) The RCS blowdown continues until the vessel pressure falls below the shut-off head for the accumulator tank,[15] the HPSI, and the LPSI. This causes increasingly large quantities of cooler, borated RWST water to quench the core and terminate blowdown.

2.2.2 ECCS Injection Phase

The injection phase refers to the period during which the RCS relies on safety injection, drawing on the RWST for decay heat removal. In the case of LLOCA, the injection phase immediately succeeds the initial RCS blowdown. During this phase, core reflood is accomplished and quasi-steady conditions are arrived at in the reactor, where decay heat is removed continually by injection flow. In ice condenser containments, the ice condenser compartment doors open and the recirculation fans move the containment atmosphere through the ice condensers. Opportunities would exist for debris to settle in the pool during this relatively quiescent time before ECCS recirculation. Containment pressure would largely decrease from its maximum value (reached in the blowdown phase). The injection phase is considered to be over when the RWST inventory is expended and switchover to sump recirculation is initiated.

Accurate characterization of conditions that exist during injection phase may be important for estimating the quantity of debris transported from the upper containment to the pool and for estimating the quantity of debris that may remain in suspension. Following the initial break, safety injection (SI) begins immediately because of the combined operation of the accumulators, the charging pump, the

[15]The accumulators are also known as safety injection tanks in some designs.

HPSI pumps, and the low-pressure safety injection (LPSI) (RHR) pumps. The SI flow approaches the design value (which is 11,500 gpm in the plant simulated) in about a minute and continues at that rate until switchover. Current simulations did not take credit for potential reduction in the injection flow (e.g., system-failure scenarios). Containment sprays continue to operate; spray water and water exiting the break will cause washdown of debris from the upper portions of the containment to the pool on the containment floor.

In conclusion, it has been determined that large quantities of water would be introduced into the containment within a few minutes following a LLOCA. As a result, the water pool depth on the containment floor increases steadily. In the case of a large dry containment, the peak pool height is reached at the end of the injection phase; in an ice-condenser containment, the peak value is reached several hours into the accident after all the ice has melted.

2.2.3 Recirculation Phase

After the RWST inventory is expended, the ECCS pumps would be realigned to take suction from the emergency sump in the containment floor. This would begin the ECCS recirculation phase, in which water would be pulled from the containment pool, passed through heat exchangers, and delivered to the RCS, where it would pick up decay heat from the reactor core, flow out the breach, and return to the containment pool. Pool depth would reach a steady state during the recirculation phase, and containment pressure and temperature would be gradually decreasing. It would be during this accident phase that the potential would exist for debris resulting from an RCS breach (or residing in containment beforehand) to continue to be transported to the containment emergency sump. Because of the suction from the sump, this pool debris may accumulate on the sump screens, restrict flow, and either reduce available NPSH or starve the ECCS recirculation pumps.

The primary observation regarding the RCS and containment conditions during the recirculation phase is that the sump flow rate reaches the design capacity of all the pumps (which in the plants analyzed is 17,500 gpm for the large dry and sub-atmospheric containments and 18,000 gpm for the ice condenser containment).

2.3 Medium Loss-of-Coolant Accident

The MLOCA simulated was a 6-in.-diam (0.1963-ft^2) circular hole in a cold leg downstream of the reactor coolant pump (RCP). The hole became full-sized instantaneously. It was situated on the side of the cold leg and centered halfway up. A discharge coefficient of unity was used, which made these simulations very conservative. The cold-leg location of the hole was chosen arbitrarily and is not expected to be a determining factor in the simulation results.

The calculated results for the MLOCA events in large dry and ice condenser containments are provided in Tables 2-5 and 2-6, respectively. Figure 2-3 presents the time scales associated with the occurrence of some of the events. The following sections highlight the differences between the MLOCA event and the LLOCA event described above.

2.3.1 RCS Blowdown

In the case of an MLOCA, RCS blowdown occurs over a prolonged period (3 min) compared with the that in an LLOCA. Blowdown starts at 0 s when the vessel is at 2250 psia and terminates as the RCS pressure and liquid subcooling decrease. Peak break flow for the MLOCA is at least a factor of 15 less than that observed for the LLOCA. In addition, the resulting vapor velocity in the containment peaks around 30 ft/s, as opposed to 200-300 ft/s for the LLOCA. These observations suggest less severe debris generation and transport caused by the LOCA jet itself. Another significant observation is that after

MLOCAs, the exit flow at the break plane remains subcooled throughout the blowdown (at least until the vessel pressure falls to a point where blowdown would have little effect on debris generation). This may affect the ZOI over which debris would be generated.

2.3.2 ECCS Injection Phase

The fundamental differences between an MLOCA and an LLOCA are as follows.

- ECCS injection begins before termination of the RCS blowdown. Initiation of injection occurs after 20-60 s, whereas the blowdown phase is not terminated until approximately 180 s.
- The LPSI does not inject significant quantities of water into the core in the short term. The LPSI (or RHR) pumps start injecting into the core at about 15 min.
- In the plants analyzed, spray actuation occurs shortly after ECCS injection begins (approximately 3 min, right around the termination of the RCS blowdown).

2.3.3 Recirculation phase

The recirculation phase accident characteristics for the MLOCA are similar to those described in Sec. 2.2.3 for the LLOCA. The sump recirculation flow rate for each plant analyzed was approximately half of that for the LLOCA simulation. No further observations are made for the MLOCA.

2.4 Small Loss-of-Coolant Accident

The SLOCA studied was a 2-in.-diam (0.0218-ft^2) circular hole in a cold leg downstream of the RCP.[16] The hole became full-sized instantaneously. It was situated on the side of the cold leg and centered halfway up. A conservative discharge coefficient of unity was defined. The cold-leg location of the hole was chosen arbitrarily and is not expected to be a determining factor in the simulation results. The 2-in. specification of this hole was made with the expectation that RCS pressure would stabilize above the accumulator pressure such that the accumulators would not inject.

The calculated results for the SLOCA events in large dry, ice condenser, and sub-atmospheric containments are provided in Tables 2-7 through 2-9, respectively. Figure 2-4 the presents time scales associated with the occurrence of some of the events.

2.4.1 RCS Blowdown

RCS blowdown in the case of an SLOCA occurs over a prolonged period (60 min). Blowdown starts at 0 s when the vessel is at 2000 psia and terminates mainly as the RCS pressure and liquid subcooling decrease. Peak break flow velocities for the SLOCAs are a factor of 30 less than those for the LLOCA and a factor of 2 less than those for the MLOCA. Containment atmosphere velocities are a factor of 30-60 less than those for the LLOCA and a factor of 2 less than those for the MLOCA. Another significant observation is that following SLOCAs, the exit flow at the break plane remains subcooled throughout the blowdown (at least until the vessel pressure falls to a point where blowdown would have little effect on debris generation). This may affect the ZOI over which debris would be generated.

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[16]The study also simulated a 1.75-in. break. The results were found to be very similar to the 2-in. break.

2.4.2 ECCS Injection Phase

The fundamental differences between a SLOCA and a LLOCA are as follows.

- The LPSI does not inject into the core at all; the HPSI and charging pumps are sufficient to make up for lost inventory.
- Actuation of containment sprays is highly plant specific and may not be needed at all. In the large dry containment plant analyzed (which has a CS actuation set point of 9.5 psig), spray operation is not required[17]. Spray actuation is seen after 30 min in the ice condenser simulation and after 15 min in the sub-atmospheric plant. Even then, the operator may terminate sprays during the SLOCA event to prolong RWST availability and rely on fan coolers (or the ice condenser) for decay heat removal from the containment. Note that washdown of debris from the upper containment to the floor pool may be limited to more localized areas (near the break) for plants in which containment sprays are not required.

2.4.3 Recirculation Phase

The recirculation phase accident characteristics for the SLOCA are similar to those described in Sec. 2.2.3 for the LLOCA. The primary difference is that the required flow rates for the SLOCA are significantly less than those for the LLOCA (as low as 2500 gpm for plants in which containment sprays do not actuate).

[17] Again, the results presented herein are for an accident scenario in which fan coolers operate. Other calculations suggest a peak containment pressure during a SLOCA in a large-dry containment could reach values nearing 18 psig if fan coolers fail to operate [LANL, 2001b].

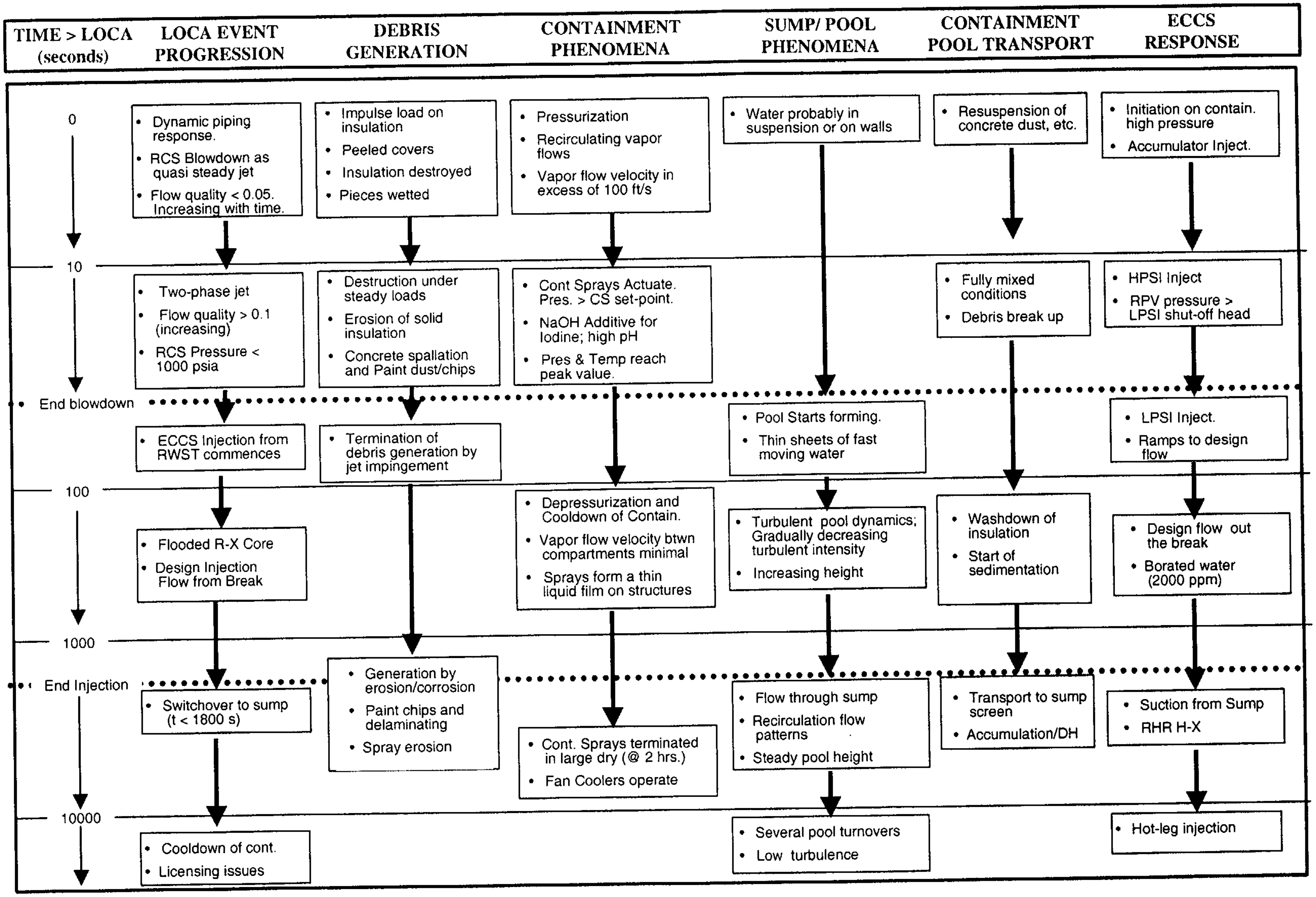

Fig. 2-2. PWR LLOCA Accident Progression in a Large Dry Containment.

Table 2-2. Debris Generation and Transport Parameters: LLOCA—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	**20 s**	**45 s**	**45 s**	**15 min**	**27 min**	**27 min**	**2 h**	**24 h**
RCS pressure at break (psia)	2250	393	55						
RCS temperature at break (°F)	531	291	250	250	173	144	144		
Break flow (lb/s)	7.97e4	1.28e4	4.89e3						
Break flow velocity (ft/s)	296	930	100						
Break flow quality	0	0.25	0.3	0.3	0				
Safety injection (gpm)				11500	11500	11500			
Recirculation flow (gpm)							17500	11800	11800
Spray flow (gpm)				0	5700	5700	5700	0	
Spray temperature (°F)					105	190	190		
Containment pressure (psig)	0	36	33	33	11.5	7	7	1.5	0
Containment temperature (°F)	110	305	250	250	190	163	163	115	95
Pool depth (ft)					2	3.5	3.5	3.5	3.5
Pool temperature (°F)					212	187	187	125	100
Pool pH									
Containment atmosphere velocity (ft/s)	282		7						
Containment relative humidity (%)	50	100	100	100	100	90	90	100	100
Paint temperature (°F)	100			215	240	220	220	145	112

Peak break flow: 7.97e4 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 36 psig at 20 s

Peak break flow velocity: 930 ft/s at 21 s
Quality at peak break flow velocity: 0.25
Peak containment atmosphere velocity: 282 ft/s at 0+ s

Table 2-3. Debris Generation and Transport Parameters: LLOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	20 s	45 s	45 s	10 min	17 min	17 min	2 h	24 h
RCS pressure at break (psia)	2250	393	55						
RCS temperature at break (°F)	531	291	250	250	200	160	160		
Break flow (lb/s)	7.97e4	1.28e4	4.89e3						
Break flow velocity (ft/s)	296	930	100						
Break flow quality	0	0.25	0.3	0.3	0				
Safety injection (gpm)				11500	11500	11500			
Recirculation flow (gpm)							18000	18000	18000
Spray flow (gpm)				6400	6400	6400	6400	6400	6400
Spray temperature (°F)				105	105	97	97	95	89
Containment pressure (psig)	0+	14	10.1	10.1	4.5	4.5	4.5	3	2
Containment temperature (°F)	100	168	160	160	103	105	105	98	100
Pool depth (ft)				4	8.5	10.75	10.75	10.8	10.1
Pool temperature (°F)				180	157	159	159	148	126
Pool pH									
Containment atmosphere velocity (ft/s)	184	18	1						
Containment relative humidity (%)	0	50	100	100	80	96	96	97	98
Paint temperature (°F)	100	106	112	112	113	112	112	90	90

Peak break flow: 7.97e4 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 14.4 psig at 15 s

Peak break flow velocity: 930 ft/s at 21 s
Quality at peak break flow velocity: 0.25
Peak containment atmosphere velocity: 184 ft/s at 0+ s

Table 2-4. PWR LLOCA Sequences

Time after LOCA (s)	Accum. (SI Tanks)	HPSI	LPSI	CS	Comments
0-1	Reactor scram. Initially high containment pressure. Followed by low pressure in the pressurizer. Debris generation commences caused by the initial pressure wave, followed by jet impingement. The blowdown flow rate is large. But mostly saturated water. Quality ≤0.05. Saturated jet-models are appropriate. SNL/ANSI Models suggest wider jets, but pressures decay rapidly with distance				
2		Initiation signal	Initiation signal	Initiation signal	Initiation signal from low pressurizer pressure or high containment pressure/temp
5	Accumulator injection begins	Pumps start to inject into vessel (bypass flow out)	Pumps start (RCS P > pump dead head)	Pump start and sprays on	In cold-leg break, ECCS bypass is caused by counter-current injection in the downcomer. Hot-leg does not have this problem.
10	The blowdown flow rate decreases steadily from ≈20,000 lb/s to 5000 lb/s. Cold-leg pressure falls considerably to about 1000 psia. At the same time, effluent quality increases from 0.1 to 0.5 (especially that from steam generator side of the break). Flow is vapor continuum with water droplets suspended in it. Saturated water or steam jet-models are appropriate. At these conditions, SNL/ANSI models show that jet expansion induces high pressures far from the break location.				
25		End of bypass; HPSI injection			
25-30	Break velocity reaches a maximum > 1000 ft/s. Quality in excess of 0.6. Steam flow at less than 500 lb/s. Highly energetic blowdown is probably complete. However, blowdown continues as residual steam continues to be vented.				
35	Accumulators empty		Vessel LPSI ramps to design flow.		
40	Blowdown is terminated, and therefore, debris generation is complete. Blowdown pressure at the nozzle less than 150 psi. Debris would be distributed throughout the containment. Pool is somewhat turbulent. Height < 1 ft.				
55-200	Reflood and quenching of the fuel rods ($T_{max} \sim$ 1036 °F). In cold-leg break, quenching occurs between 125 and 150 s. In the case of hot-leg break, quenching occurs between 45 and 60 s ($T_{max} \sim$ 950 °F).				
200-1200	Debris added to lower containment pool by spray washdown drainage and break washdown. The containment floor keeps filling. No directionality to the flow. Heavy debris may settle down.				
1200	RWST low level indication received by the operator. Operator prepares to turn on ECCS in sump recirculation mode. Actual switchover when the RWST low-low level signal is received.				
1500		Switch suction to sump	Switch suction to sump	Terminate or to sump	Many plants have containment fan coolers for long-term cooling.
1500-18000	Debris may be brought to the sump screen. Buildup of debris on the sump screen may cause excessive head loss. Containment sprays may be terminated in large dry containments at the 2-h mark.				
>36000		Switch to hot-leg recirculation.	Switch to hot-leg recirculation		

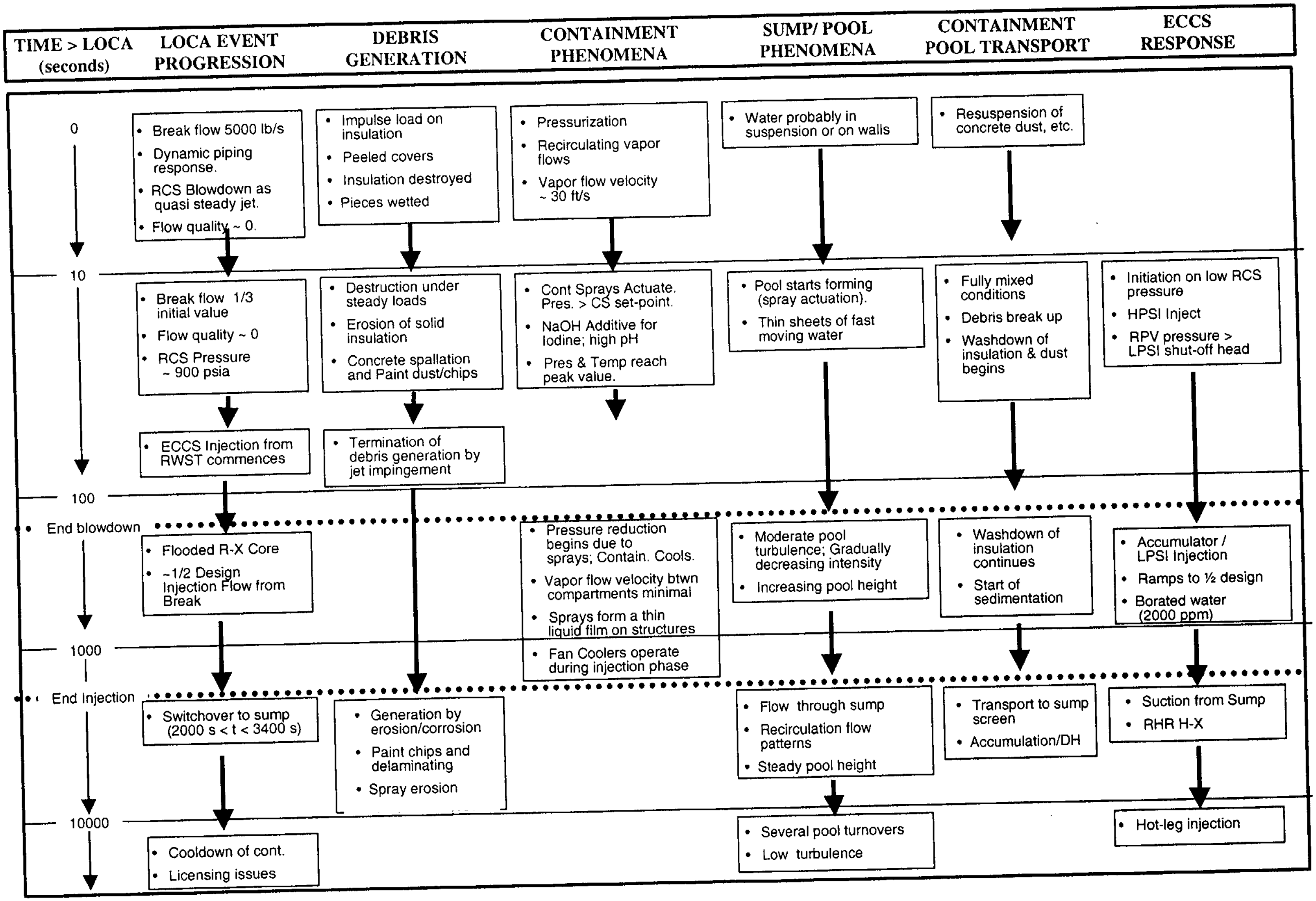

Fig. 2-3. PWR MLOCA Accident Progression in a Large Dry Containment.

Table 2-5. Debris Generation and Transport Parameters: MLOCA—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	30 s	180 s	20 s	15 min	57 min	57 min	2 h	24 h
RCS pressure at break (psia)	2250	900	508						
RCS temperature at break (°F)	537	521	392		330	274	274		
Break flow (lb/s)	4940	1670	1000						
Break flow velocity (ft/s)	510	190	108						
Break flow quality	0	0	0		0.03	0.03	0.03	0	
Safety injection (gpm)				885	2500	2500			
Recirculation flow (gpm)							8250	2550	2550
Spray flow (gpm)		0	5700		5700	5700	5700	0	
Spray temperature (°F)			105		105	150	150	150	
Containment pressure (psig)	0	6	9.5		5	3	3	4.2	1.5
Containment temperature (°F)	110	170	182		160	140	140	148	120
Pool depth (ft)					0.9	3.3	3.3	3.3	3.3
Pool temperature (°F)					170	145	145	147	125
Pool pH									
Containment atmosphere velocity (ft/s)	35	10	5						
Containment relative humidity (%)	50	100	100		98	98	98	98	100
Paint temperature (°F)	110		160		175	160	160	155	121

Peak break flow: 4940 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 10.2 psig at 2 min

Peak break flow velocity: 510 ft/s at 0+ s
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 35 ft/s at 0+ s

Table 2-6. Debris Generation and Transport Parameters: MLOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	30 s	180 s	20 s	15 min	34 min	34 min	2 h	24 h
RCS pressure at break (psia)	2250	900	508						
RCS temperature at break (°F)	537	521	392		330	300	300		
Break flow (lb/s)	4940	1670	1000						
Break flow velocity (ft/s)	510	190	108						
Break flow quality	0	0	0		0.03	0.03	0.03	0	
Safety injection (gpm)				885	2500	2500			
Recirculation flow (gpm)							9000	9000	9000
Spray flow (gpm)		0	6400		6400	6400	6400	6400	6400
Spray temperature (°F)			105		105	105	92.5	86.5	84
Containment pressure (psig)	0+	9.8	7.8		4	4	4	1.8	1.4
Containment temperature (°F)	100	145	151		110	110	110	87	90
Pool depth (ft)					4	7.9	7.9	8	9.6
Pool temperature (°F)					150	146	146	117	104
Pool pH									
Containment atmosphere velocity (ft/s)	30	2.5	1.25						
Containment relative humidity (%)	0	10	40		80	97	97	97	98
Paint temperature (°F)	100	101	125		130	125	125	95	90

Peak break flow: 4940 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 11 psig at 55 s

Peak break flow velocity: 510 ft/s at 0+ s
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 30 ft/s at 0+ s

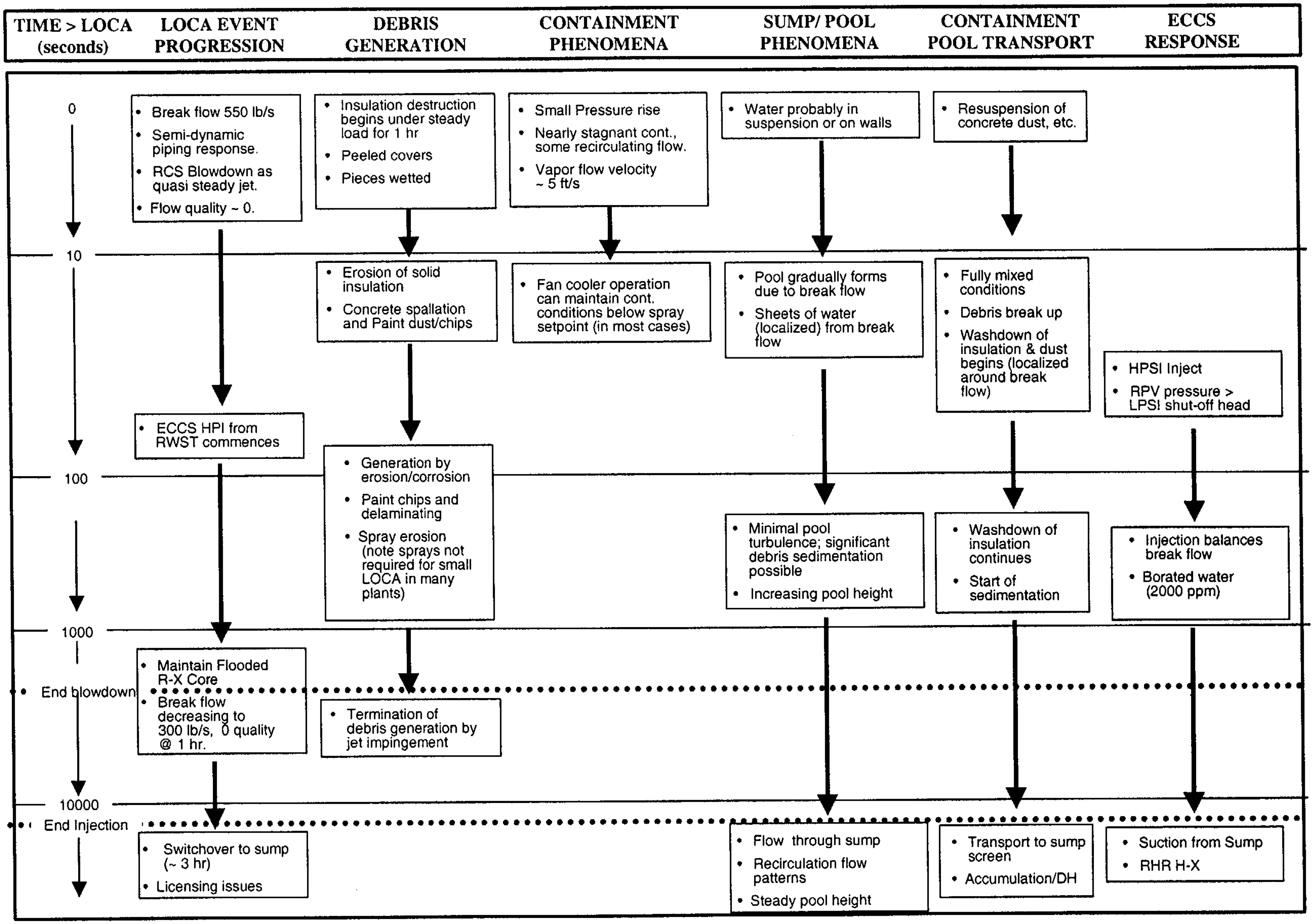

Fig. 2-4. PWR SLOCA Accident Progression in a Large Dry Containment.

Table 2-7. Debris Generation and Transport Parameters: SLOCA—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	30 min	1 h	60 s	2 h	3 h	3 h	12 h	24 h
RCS pressure at break (psia)	2250	605	512						
RCS temperature at break (°F)	538	354	371		270	236	236		
Break flow (lb/s)	550	343	300						
Break flow velocity (ft/s)	320	320	320						
Break flow quality	0	0	0						
Safety injection (gpm)				1500	2500	2500			
Recirculation flow (gpm)							2500	2500	2500
Spray flow (gpm)	Sprays not required								
Spray temperature (°F)									
Containment pressure (psig)	0	5	5		4	3	3	1	0.75
Containment temperature (°F)	110	160	160		150	140	140	115	110
Pool depth (ft)			0.8		1.5	2.25	2.25	3	3
Pool temperature (°F)			157		157	150	150	125	118
Pool pH									
Containment atmosphere velocity (ft/s)	9	4	4						
Containment relative humidity (%)	50	100	100		100	100	100	100	100
Paint temperature (°F)	100	160	160		157	153	153	127	117

Peak break flow: 550 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 6 psig at 38 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 9 ft/s at 20 s

Table 2-8. Debris Generation and Transport Parameters: SLOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	30 min	1 h	60 s	15 min	35 min	35 min	5 h	24 h
RCS pressure at break (psia)	2250	605	512						
RCS temperature at break (°F)	538	354	371		391	362	362		
Break flow (lb/s)	550	343	300						
Break flow velocity (ft/s)	320	320	320						
Break flow quality	0	0	0						
Safety injection (gpm)				1500	2500	2500			
Recirculation flow (gpm)							9000	9000	9000
Spray flow (gpm)		6400	6400	0	6400	6400	6400	6400	6400
Spray temperature (°F)		105	91		105	105	91	87.5	86
Containment pressure (psig)	0+	4.1	3.6	3.4	4.4	4.2	4.2	2.25	1.8
Containment temperature (°F)	100	111	96.5	94	112	110	110	92	95
Pool depth (ft)		5.5	6.75		2.5	6.5	6.5	9	8.9
Pool temperature (°F)		137	132		137	137	137	120	114
Pool pH									
Containment atmosphere velocity (ft/s)	2.9	0.7	0.7						
Containment relative humidity (%)	0	97	97	6	100	97	97	97	97
Paint temperature (°F)	100	110	104	100	106	110	110	92	96

Peak break flow: 550 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 4.4 psig at 15 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 2.9 ft/s at 23 s

Table 2-9. Debris Generation and Transport Parameters: SLOCA—Sub-Atmospheric Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase		
	0+	30 min	1 h	60 s	1 h	3 h	3 h	12 h	24 h
RCS pressure at break (psia)	2250	605	512						
RCS temperature at break (°F)	538	354	371		270	236	236		
Break flow (lb/s)	550	343	300						
Break flow velocity (ft/s)	320	320	320						
Break flow quality	0	0	0						
Safety injection (gpm)				1500	2500	2500			
Recirculation flow (gpm)							2500	2500	2500
Spray flow (gpm)					9000	9000	9000	9000	9000
Spray temperature (°F)					105	150	150	125	120
Containment pressure (psig)	0	5	5		4	3	3	1	0.75
Containment temperature (°F)	110	160	160		150	140	140	115	110
Pool depth (ft)			0.8		1.5	2.25	2.25	3	3
Pool temperature (°F)			157		157	150	150	125	118
Pool pH									
Containment atmosphere velocity (ft/s)	9	4	4						
Containment relative humidity (%)	50	100	100		100	100	100	100	100
Paint temperature (°F)	100	160	160		157	153	153	127	117

Peak break flow: 550 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 6 psig at 38 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 9 ft/s at 20 s

2.5 Other Plant Design Features That Influence Accident Progression

Other plant design features (beyond those previously discussed) may influence the debris-related accident progression. For example, in many plants, heat exchangers are installed directly in the core cooling recirculation flow paths to ensure that the water is cooled before it is returned to the core. However, in some plants, the core cooling recirculation systems do not have dedicated heat exchangers and instead make indirect use of heat exchangers from other systems (i.e., CS) to ensure that heat is removed from the reactor coolant. Examples of plants where core cooling makes indirect use of heat exchangers from CS includes the plants with sub-atmospheric containments and CE plants. For these types of plants, successful core cooling during recirculation will require (1) direct sump flow from the core cooling system and (2) sump recirculation cooling from the CS system.

For plants with sub-atmospheric containments, switchover for the set of "inside" recirculation spray pumps is performed quickly (approximately 2 min), whereas the switchover for ECCS pumps and CS pumps is considerably longer (on the order of 30 min or more depending on LOCA type). The relatively quick switchover of the inside recirculation spray pumps is accomplished to minimize containment pressure and temperature. The inside recirculation spray system is equipped with a heat exchanger, and it appears that its actuation is credited in estimating the $NPSH_{Margin}$ for the ECCS and CS system during the recirculation phase.

Recovery from a stuck-open PORV may be possible at many plants through operator actions to close the associated block valve. The need for sump recirculation could be avoided by this action.

The containment structures are sufficiently robust that failure of CS is not expected to cause containment failure from overpressure (~ 3 times design pressure).

3.0 TECHNICAL APPROACH

Subsection 3.1 provides a comprehensive overview of the technical approach used in these evaluations. The remainder of this section discusses specific assumptions important to the treatment of insulation debris generation, debris transport, and debris accumulation and head loss. The step-by-step process used in the parametric evaluations is described in Secs. 4 and 5.

3.1 Overview

The objective of this parametric study is to assess the vulnerability of the PWR population to potential blockage of the recirculation sump screen following a LOCA. Regardless of the break size, as discussed in Sec. 2, the LOCA accident sequence in any PWR involves (1) debris generation, (2) containment transport during depressurization, (3) debris washdown and degradation caused by containment sprays if they are actuated manually or automatically, (4) pool transport to the sump, and (5) debris-bed formation and head loss. Although a great deal has been learned about the individual processes through testing and simulations performed as part of the ongoing GSI-191 program, an integrated analysis of blockage potential requires plant-specific spatial information that is not part of the parametric assessment.[18] Therefore, the methodology developed here to assess vulnerability for each parametric case focuses first on the range of debris loadings needed for the plant to fail to meet the recirculation flow requirements and second on the range of debris volumes and compositions that can be generated. Assessment of the cumulative transport fraction required to fail the sump is considered last. This approach does not follow the chronological accident sequence, but, as shown in Fig. 3-1, it does introduce the highest quality information and the most refined models before more subjective arguments must be invoked.

Figure 3-2 provides a simplified description of the technical approach and the scope of evaluations performed. This approach consists of three major steps.

1. *Construct a representative parametric case for each PWR.* To the extent possible, these cases were constructed using actual plant information collected from sources described in Sec. 1.5. Table 3-1 provides a list of parameters used to construct each parametric case. Typically, information with high fidelity is available for the following parameters: (a) ECCS and CS flow rates following LLOCAs and MLOCAs, (b) $NPSH_{Margin}$ for each pumping system, (c) time to ECCS switchover following LLOCAs and MLOCAs, (d) expected water levels on the containment floor at the time of ECCS switchover, (e) containment-averaged fraction of insulation in each insulation type, and (f) recirculation-sump geometry and containment-layout information.[19] For these parameters, parametric variations addressed issues such as the comparison between a single operational ECCS train and design-basis performance. For some other parameters, information with high fidelity is not available. Primary examples of these parameters are the location of each insulation type in the containment[20] and the flow through the recirculation sump following an SLOCA. For these parameters, a variety of supporting analyses were performed to define a

[18]Even when detailed information is available for a single plant, variability in these parameters and uncertainty in the physical models creates a range of possible outcomes that must be interpreted by comparing the completeness of the available information and the confidence one has in the predictive capability of the methodology with the safety philosophy upon which decisions are based. These difficulties are further compounded for the industry-wide evaluations by the wide range of plant configurations that exist among operating PWRs.

[19]Most plant licensees provided such information in the form of engineering drawings, and the information was validated in many cases by comparing it with UFSAR descriptions.

[20]This information is available for two volunteer plants for which CAD drawings are available and, to some extent, information is available for 6 USI A-43 reference plants.

reasonable range over which they may vary. The "favorable" end of this range establishes values that tend to minimize the potential for sump-screen blockage. Conversely, the "unfavorable" end of this range provides values that enhance the potential for sump-screen blockage. Table 3-2 documents the favorable and unfavorable bounds for each parameter and describes the analytical tools used to define this range. The following sections provide further discussions of how some of the uncertainties in choosing these favorable and unfavorable parameter estimates are factored into the vulnerability assessment for each parametric case.

2. *Perform parametric case evaluations.* For each parametric case, calculations were used to estimate (a) the quantity of debris that would be necessary to cause sump-screen blockage of sufficient magnitude to render the ECCS and/or CS inoperable, (b) the quantity of each type of debris that might be generated for postulated breaks of different sizes, (c) the transport fractions applicable to each type of insulation and each break size, (d) the quantity of insulation that could be transported to the sump, and finally, (e) the head loss caused by debris accumulation. These case evaluations were used to calculate four parameters that formed the basis for decisions regarding the potential for sump failure. These parameters (or metrics) are described in Table 3-3.

3. *Judge the potential for blockage for each parametric case.* The potential for blockage is estimated for each case for each LOCA size using two general criteria.

   - To determine parametric cases that are **unlikely** to have a blockage problem, the analyses apply "unfavorable" estimates of parameters used in the evaluations. If the parametric case is proven to perform well even under these assumed unfavorable operating conditions, it is very likely that it would perform well following a real LOCA.
   - Conversely, when "favorable" assumptions are used in the analyses, parametric cases that fail are **very likely** to be susceptible to sump-screen blockage following a LOCA.

The favorable and unfavorable assumptions are itemized and discussed more fully in Table 3-2. Based on the criteria described above, some parametric cases were identified as **very likely** to experience blockage following a LOCA and some were identified as **unlikely** to experience a problem. Numerous parametric cases that lie between these extremes are further graded into two categories: **likely** to have a problem and **possible** to have a problem. Assignment to these categories is made when performance comparisons made under the favorable and unfavorable bounds do not indicate a clear decision. Additional features of the case such as the presence of curbs, the sump geometry, and the predominance of fiber or cal-sil insulation types must be considered to make the final judgment of vulnerability in these cases.

Table 3-1. List of Parameters Used to Construct Parametric Cases.

Parameter	Source of Information
Sump-Screen Area (wetted)	**LANL Analysis of GSI-191 Database**. Answers to Question 3e of GSI-191 survey provided the total screen area. LANL used plant drawings (provided for each plant) to estimate what fraction of this screen area would be submerged at the time of switchover.
$NPSH_{Margin}$	**NRC GL 97-04 database**. This value was not available for four plant units. A surrogate range was used for those plants.
Recirculation Flow Rates SLOCA (2-in.) Flow MLOCA/LLOCA Flow	**NRC GL 97-04 database.** Review of NUREG/CR-5640 for HPSI and charging pumps
Spray Activation Pressure	**LANL Survey of UFSARs for several plants.**
Containment Free Area (unobstructed flow paths near sump)	**GSI-191 Database**
Fan Cooler	**LANL Survey of UFSARs for several plants.**
Pool Levels At Switchover Maximum Height	**GSI-191 Database** **Question 1(a)** **Question 1(c)**
Sump Submergence	**LANL Analysis of GSI-191 Database.** LANL used plant drawings to determine if the sump would be submerged or not at the time of ECCS switchover.
Sump Location	**GSI-191 Database**
Sump-Screen Orientation	**GSI-191 Database**
Sump-Screen Approach Velocity	**LANL analyses** that used data from GSI-191 Database and NRC GL 97-04 database.
Sump-Screen Clearance	**GSI-191 Database**
Insulation Types	**GSI-191 Database**
Relative Fractions of Insulation Fibrous (Fiberglass and Kaowool) Cal-sil Reflective Metallic Insulation (RMI)	**GSI-191 Database**. Information for this field is not complete. Several plants provided no estimates. A surrogate range was developed by LANL based on qualitative descriptions provided by the licensees (such as RMI on RPV and steam generator and rest is fibrous insulation).

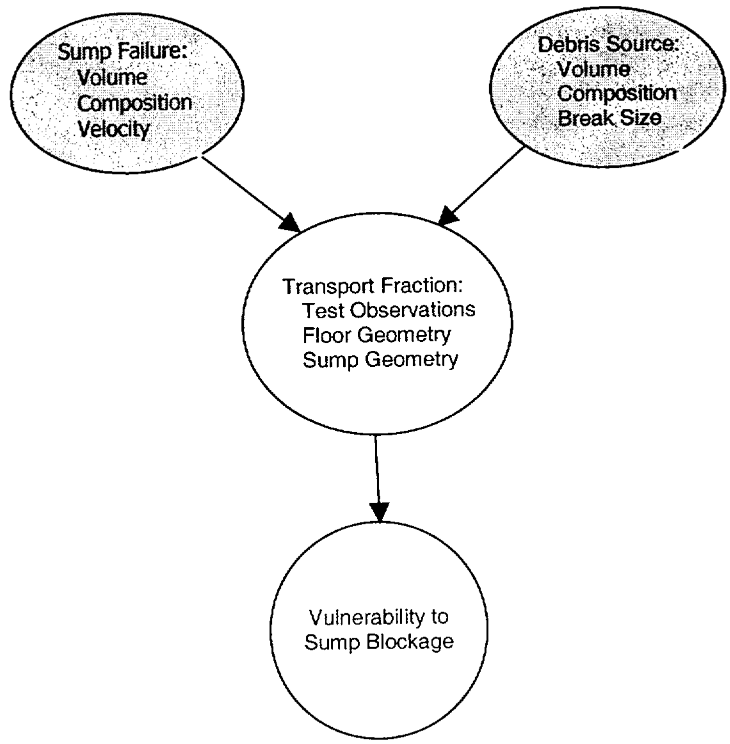

Fig. 3-1. Schematic of Parametric Methodology that Focuses First on Sump Failure, Second on Debris Generation, and Finally on Necessary Debris Transport.

Table 3-2. Summary of Analyses and "Favorable" and "Unfavorable" Modeling Assumptions Used in the Parametric Evaluations.

Parameter	Analyses Conducted	Modeling Assumptions[21]	
		Favorable Analysis	**Unfavorable Analysis**
Accident Scenario	• RELAP simulations of RCS • MELCOR simulations for dry, ice condenser, and sub-atmospheric containments	• Spray actuation on set point • Degraded fan-cooler • One operating train (LLOCA)	• Spray actuation on set point • No fan cooler • Design pump flows
ZOI Model	• CAD simulations for two GSI-191 volunteer plants • Detailed calculations for four USI A-43 plants • Simplified model for 63 plants	(No differences between "Favorable" and "Unfavorable") • BWROG URG data for ZOI (corrected for PWRs) • Homogenized mixture of insulations for SLOCA • Spherical ZOI	
Destruction Model	• No analyses. Approximate estimates based on URG data and other test data	• Incomplete destruction within ZOI. 1/3 into small fragments; 1/3 into larger fragments; remaining into torn blankets	• Use results from preliminary debris generation testing for cal-sil and fiberglass (50% into powder/small fragments)
Debris Transport	• GSI-191 test data applied similar to NUREG/CR-6369 • Detailed estimates for volunteer plants • Approximate estimates for non-volunteer plants	• 5% of ZOI debris volume deposits on sump when no sprays on for SLOCA • 10% of ZOI debris volume deposits on sump when sprays on for SLOCA or for LLOCA and MLOCA **Same for particulates**	10% and 25% were used for no-spray and spray sequences Also examined potential for transport of large pieces • By blowdown for exposed sumps • By floating up to the sump and sinking on the sump for horizontal sumps
Particulate (Paint Chips, Dirt, Dust, etc.)	• Oxidation calculations and models for zinc and aluminum • Approximate calculations for dust, dirt, and corrosion products (CPs) • SRS paint study	Relatively small quantities. Transport of about 10-20 lb • BWROG estimates • No paint contribution • No oxidation of zinc and aluminum contribution	Relatively large quantities • Dust/dirt estimates for PWR • SRS paint contribution • STUK and ANS model oxidation of zinc and aluminum contribution
Sump Flow	• RELAP results • Survey of HPSI and charging pump flow for each plant • GL 97-04 responses	• HPSI/charging + one train spray (if on) for SLOCA. • 1 residual train ECCS and spray for LLOCA/MLOCA	All ECCS and containment sprays (EOPs and GL 97-04)
Head Loss Model	• NUREG/CR-6224 model • Bump-up factors for miscellaneous debris • Cal-sil head-loss model (still underestimates head loss) • Validated for use	• Neglect RMI contribution • Treat cal-sil as just another particulate debris • Treat all fiber insulation as LDFG (per ft^3 LDFG results in lower head loss than Min-wool, Kaowool or some other fibrous insulation)	• RMI contribution • Treat cal-sil as just another particulate debris • Fiber represented by mineral wool or Tempmat when they are present

[21]Although the philosophy of "favorable" and "unfavorable" analyses was rigorously followed in assessment of debris transport and accumulation, it is less uniformly applied for other parts of the evaluations. In some cases (e.g., ZOI model), point estimates were used instead of a range of possibilities.

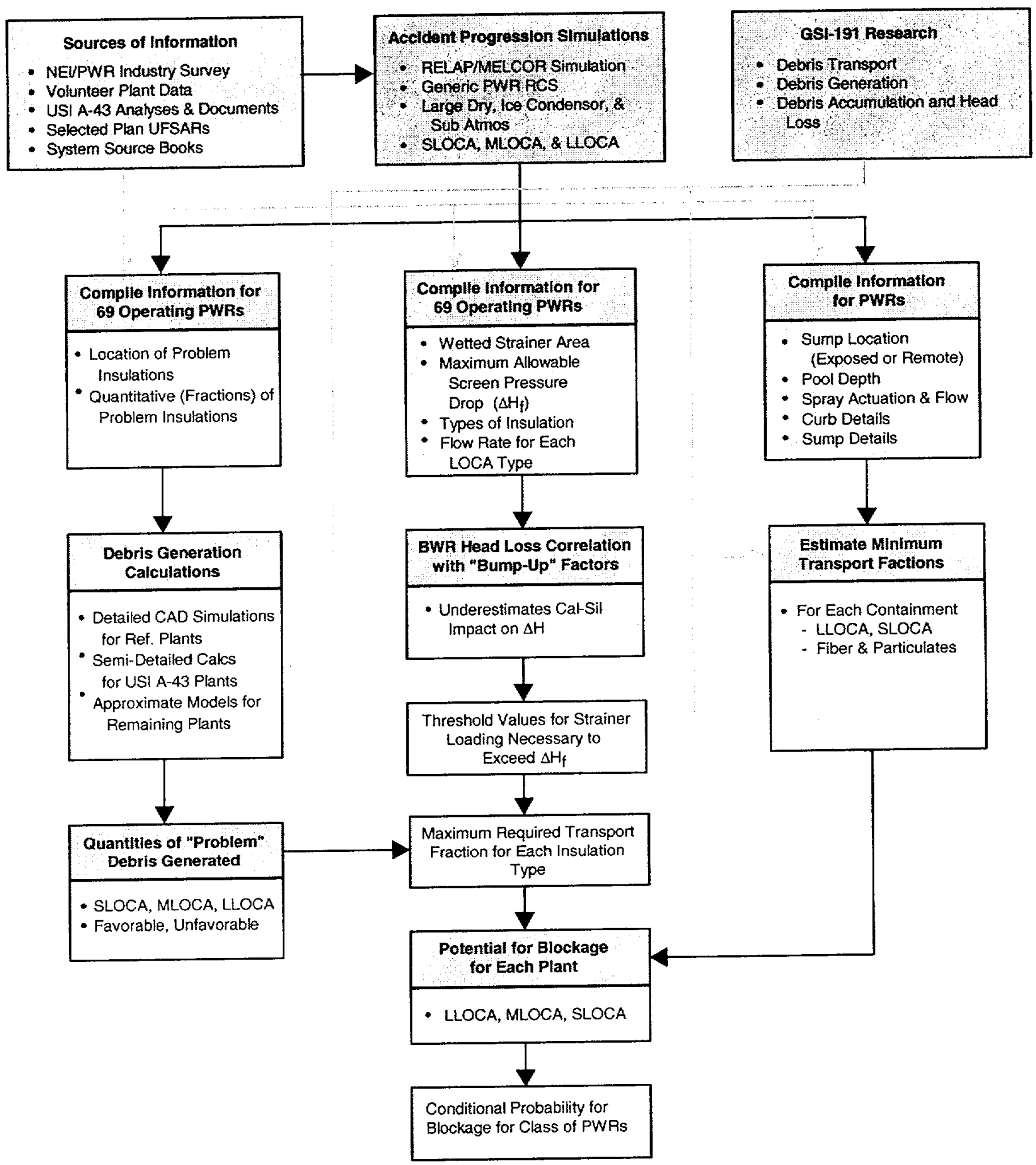

Fig. 3-2. Technical Methodology Used to Identify Plants Vulnerable to GSI-191 Related Safety Concerns.

Table 3-3. Description of Metrics Used in the Decision Process.

Failure-Threshold Debris Loading (FTDL). This metric represents the minimum sump screen debris loading necessary to induce head loss across the sump in excess of the failure criterion (e.g., $\Delta H_{screen} > NPSH_{Margin}$). Typically, data and models with high fidelity are available to estimate FTDL values, and thus, estimates of FTDL played a key role in determining the likely outcome of each parametric case. Figs. B-1 through B-69 present these values for each parametric case and each accident sequence. Section 3.4 describes how this metric was calculated.
Minimum Cumulative Transport Fraction. Defined as the ratio of FTDL to quantity of debris generated, this metric provides insights into the cumulative transport fraction required to reach the sump failure criterion. It is very instructive to calculate this ratio for each postulated accident condition because it forces one to consider the plausibility of the required transport processes before assigning a vulnerability to the parametric case. For example, a case that requires 2 ft^3 of fiber on the screen to induce failure that may generate as much as 200 ft^3 of fiber at the source requires a cumulative transport fraction of only 1%. Testing and simulation performed to date may either be viewed as (a) supporting a transport fraction of 10% under similar conditions or (b) failing to preclude this level of transport as a possibility. In either case, the plausibility of transport is much greater for this case than if the source can only generate 2.5 ft^3 of fiber. The later scenario would require an 80% transport fraction for failure, and current testing does not support a cumulative transport process of this efficiency except under very special circumstances. Important plant features (e.g., the presence of curbs, the sump geometry, and the predominance of fiber or cal-sil insulation types) were also considered on a case-by-case basis in addition to the failure-threshold transport fraction to make a final vulnerability assignment.
Range of Expected Debris. Testing and simulations performed as part of the ongoing GSI-191 program were used to obtain "favorable" and "unfavorable" estimates for debris loading on the sump screen. CFD-based simulations were performed for selected containment layouts, and engineering judgments were relied on to extend test data and analysis findings to each parametric case. Judgments regarding potential for blockage were reached by comparing this likely range of debris loadings with FTDL values. Figures B-1 through B-69 present these values for each parametric case and each accident sequence in the form of dashed box. Section 3.4 describes how this metric was calculated. Cases in which the range of expected debris exceeded FTDL values were assumed **very likely** to fail. Alternately, cases in which the range of expected debris was lower than FTDL values were assumed **unlikely** to fail. Intermediate cases were assigned **likely** and **possible** grades.
Range of Predicted Screen Head Loss. The favorable and unfavorable estimates for debris loadings were coupled with a head-loss model to obtain "favorable" and "unfavorable" estimates for head loss across the sump screen. Judgments regarding the potential for blockage were reached by comparing this likely range of head loss with the failure criterion. For example, a parametric case in which both favorable and unfavorable head-loss estimates far exceed the $NPSH_{Margin}$ is more likely to fail because failure in this case cannot be attributed to "conservative" assumptions used in the licensee estimates of $NPSH_{Margin}$[22].

[22]Typically licensee estimates for $NPSH_{Margin}$ are based on conservative assumptions regarding containment overpressure and coolant temperature. If ΔH_f predictions are only slightly higher than the $NPSH_{Margin}$, one could conclude that the failure is a reflection of "conservative" assumptions. This comparison provides insights on a case-by-case basis to address this uncertainty.

3.2 Insulation Debris Generation

Most, if not all, of the 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.

1. The spatial arrangement of piping systems and equipment that can serve both as targets and as locations of high-energy breaks

2. The spatial distribution of insulation types and thickness

3. The relative potential of breaks occurring in various sizes of pipes and piping locations such as walls and elbows

4. The unknown destruction response of each insulation type and of concrete and coatings to a two-phase depressurization jet

5. The unknown range and shape of a two-phase depressurization jet in the presence of obstacles such as concrete structures and adjacent piping

6. The exact location, severity, and directionality of a given LOCA event

Items 1 and 2 can be addressed with plant-specific spatial data and complete insulation inventories. The fidelity of estimates for items 3 and 4 can be addressed, in part, through exhaustive testing and analysis of in-service piping. However, many features of an accident scenario, such as items 5 and 6, will always retain a high degree of variability[23] that resists deterministic evaluation and requires bounding or stochastic analysis. Each of these complications is compounded in the present parametric analysis of recirculation-sump blockage potential by the wide variations in plant geometry, the variety of types and applications of various thermal insulations, and the incomplete knowledge of their spatial locations in any given plant. In particular, the best information currently available regarding insulation types in most plants is a rough estimate of volumetric proportion such as 80% RMI, 15% cal-sil, and 5% fiber.

To address the many complexities of debris generation, the CASINOVA computer model was developed in support of the ongoing GSI-191 program. This tool allows stochastic sampling of break locations and parametric investigation of issues such as the importance of jet direction, range, and shape on debris volumes. At the heart of this model are CAD data describing the relative spatial locations of piping systems, equipment, and insulation applications. Complete spatial data for two volunteer plants are available for comparison. Both volunteer plants have a Westinghouse four-loop RCS. The first is an ice condenser containment, and the second is a large dry containment. Given the spatial data in electronic form, damage zones can be mapped at any number of break locations, and the range of debris volumes can be estimated for each insulation type. Although simplistic, the CASINOVA simulation provides a wealth of information regarding the spatial correlation of piping systems, insulation types, and potential damage volumes.

Simulations of debris generation currently are performed assuming spherical ZOIs surrounding each break that completely destroy all insulation types out to a radius equal to 12 diameters (12D) of the broken pipe. These breaks are located uniformly along pipes of every size that can be considered high-energy lines (i.e., ≅ 500 psi or higher) capable of producing a jet when broken. In the present evaluations, the CASINOVA model simulated approximately 1350 break locations. Figure 3-3 shows the

[23]BWR experience suggests that this uncertainty may overwhelm any other uncertainties.

level of detail incorporated in the CASINOVA simulation of a volunteer plant. Insulation on large tanks and pipes is subdivided into panels as shown in the figure, and all insulated pipes are divided into discrete segments representing point insulation sources that can be enveloped by a damage zone. The large sphere in the lower right-hand corner of Fig. 3-3 identifies the ZOI surrounding a large pipe break.

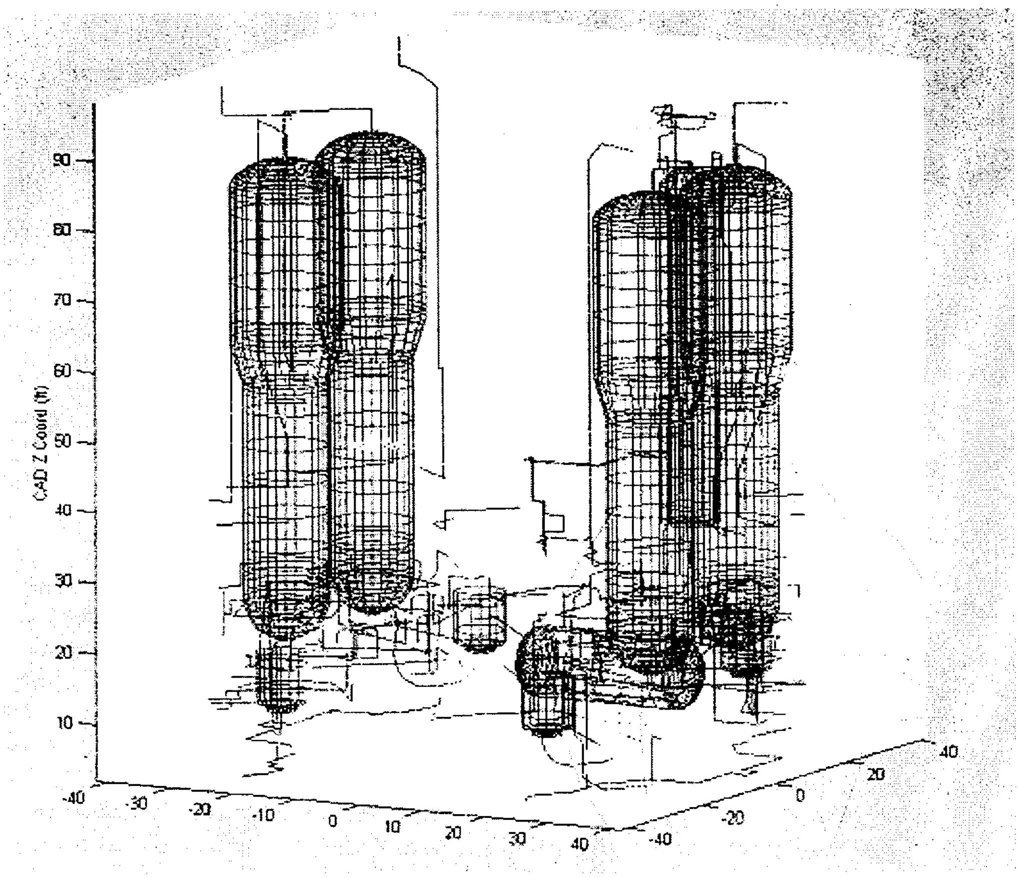

Fig. 3-3. Graphic of Volunteer Plant Piping and Equipment Data Imported to the CASINOVA Simulation Model.

The assumption of 12D damage zones for debris generation is based on engineering interpretations of high-pressure destruction testing performed (1) for the BWR Strainer Blockage Study [Zigler, 1995] using single-phase steam and air-jet surrogates and (2) in conjunction with the ongoing GSI-191 test program using 1400-psi, 310°C, two-phase water jets. Single-phase air jets were found to inflict significant damage to fibrous insulation types at a distance of 60D. Because of variability in the potential offset and separation of the broken pipe ends, LOCA jets traditionally have been assumed capable of damage to all insulation within a sphere of equivalent radius. Recent GSI-191 tests using two-phase water jets have exhibited damage to cal-sil and fiber insulation greater than previously measured in terms of both damage distances and fraction of finer fragments generated. This testing indicates that use of 12D spheres is a reasonable approximation for fibrous and cal-sil insulation debris generation.

Because complete, plant-specific information is not available, several important assumptions must be made for the present parametric analyses to apply high-fidelity volunteer-plant data in a generic way.

1. The lengths, sizes and complexity of piping and equipment present in the volunteer plants are representative of all PWR designs. This assumption extends to the relative proportion of piping sizes.
2. The thickness of an insulation application is proportional to the piping size, or the equipment circumference and is roughly the same regardless of the insulation type.
3. 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.
4. Where volumetric fractions of several insulation types have been provided, they can be assumed distributed in those proportions homogeneously throughout the containment.

The applicability of the first and third assumptions can be addressed only by compiling more plant-specific models of spatial data. If CAD models of a plant already exist, it is relatively easy to import these data to the CASINOVA simulation. The validity of the second assumption was confirmed by comparing the thicknesses of various types of insulation applied to pipes of comparable size in different plants.

The fourth assumption (regarding homogeneity of insulation types) is thought to be the most limiting condition of the present parametric analysis. Careful inspection of detailed insulation layout data available for six USI A-43 plants and two GSI-191 volunteer plants confirms that this assumption is not accurate for most regions of their containment. 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 (This finding is also consistent with the GSI-191 database [NEI, 1997]). 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 could actually 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 plants. Because large breaks already generate and transport large quantities of debris, this issue is not likely to affect the assessment of the potential for sump failure for LLOCAs.

The limitations of assuming homogeneous insulation types were mitigated in the following way. First, distributions of possible debris volumes were constructed for the volunteer plants by examining all possible breaks in pipes of three size ranges. Pipes between 2 and 4 in. in diameter represent small breaks.[24] Pipes between 4 and 6 in. in diameter represent medium breaks. All pipes greater than 6 in. in diameter represent large breaks. Figure 3-4 shows the frequency distribution (histogram) of insulation-debris volumes that can be generated in volunteer plant 1 from large-pipe breaks if all insulation types suffer equal damage to a spherical radius of 12D. Figure 3-5 presents the same data in a cumulative format. For example, 50% (fraction of 0.5) of all breaks will generate 250 ft^3 of debris or less for large-break LOCAs.

Second, the 95th percentile was selected as a representative debris volume for each of the three break sizes, and finally, the homogenized composition factors were applied to estimate the volume of debris for each insulation type. Use of the 95th percentile as an upper estimate avoids the extreme conservatism of reporting the debris volume of the single worst break, but it compensates for potential

[24]The choice of 2 in. to 4 in. was made based on the volunteer plant definition of an SLOCA. These results are equally applicable to a postulated 2-in.-equivalent break in a larger pipe. It should be noted that when 2-in.-equivalent breaks are postulated in the hot leg and cold leg (e.g., 2-in. circular hole in the hot leg), they generate significantly larger amounts of debris.

spatial correlations that cannot be assessed in the parametric study. Table 3-4 summarizes the statistics of the debris-generation simulations. Although debris-volume estimates derived from only two volunteer-plants are used for all cases, they are the best surrogates available for the parametric analysis of industry-wide vulnerability to sump blockage.

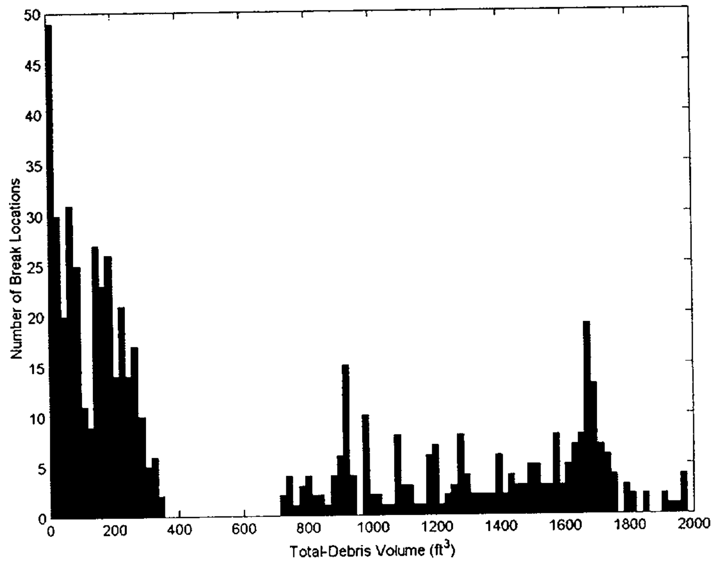

Fig. 3-4. Frequency Distribution of Possible Breaks from Large-Pipe Breaks in Volunteer Plant 1.

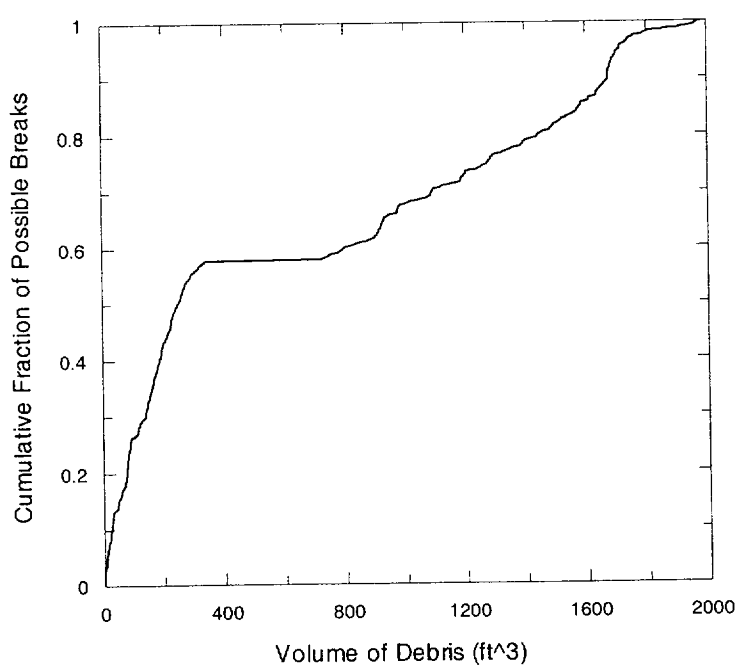

Fig. 3-5. Cumulative Distribution of Debris Volumes for LLOCA Occurring in Volunteer Plant 1.

Table 3-4. Summary of Debris-Generation Simulations for Three Break Sizes.

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

Table 3-5 cites other estimates of LOCA debris volumes that have been reported in the literature for several PWR power plants [Kolbe, 1982]. The total debris volumes summed over all insulation types agree well with the CASINOVA value of 1700 ft^3 for the 95^{th} percentile of volumes that can be generated from large breaks in volunteer plant 1. This table provides confirmation that LOCAs can damage a significant fraction of the insulation present in the containment, and it offers a quality assurance check that the CASINOVA simulation is properly calculating volumes for all other break sizes. For reference, there is approximately 7200 ft^3 of insulation in the containment of volunteer plant 1 distributed by volume as 21% fiber, 46% particulate, and 33% RMI.

Table 3-5. Comparison Debris Volumes for Limiting Breaks in Several PWRs [Kolbe, 1982].

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**

3.3 Debris Transport

Table 3-6 lists the "favorable" and "unfavorable" transport fractions used in the present study. Note that these values are based on consideration of generation, washdown, and pool transport of "transportable" forms of fibrous debris only. Neither the "favorable" nor the "unfavorable" values listed in the table considered the potential for transport of large pieces[25] or the potential for increased transport in containments that have specific features that might enhance transport (e.g., a horizontal sump screen with no curb and an exposed sump location). In keeping with the philosophy of comparing required transport with the FTDL, it is felt that a case capable of failing when applying the "favorable" transport fraction is very likely to fail. On the other hand, cases that did not fail when assessed using "unfavorable" estimates may still fail if one were to include other mechanisms of transport (e.g., exposed sump transport).

Table 3-6. "Favorable" and "Unfavorable" Estimates for Debris Transport Fraction.

Transport Conditions	Favorable Estimate	Unfavorable Estimate
SLOCA with Sprays Inactive	5%	10%
SLOCA with Sprays Active All MLOCAs and LLOCAs	10%	25%

The underlying assumptions that form the basis for these transport fractions are as follows.

- Based on BWROG and GSI-191 debris generation experimental data, it is assumed that **not** all the insulation contained in the ZOI would be generated into "transportable" form. It is assumed that approximately 33% of the insulation would be generated into smaller "transportable" forms.[26] The other 67% is assumed to be generated in the form of partially torn blankets or large pieces that would sink to bottom of the pool. A part of this debris would erode when subjected to falling break water flow. Current analyses assumed that about 50% of the debris might be generated in the transportable form.

- The generated insulation fragments would be transported and distributed throughout the containment by the jets. Only a fraction of this debris would be deposited directly into the pool. The rest of the insulation would not be added to the pool if CS was not activated. The fraction added to the pool would be higher for the SLOCA and MLOCA because vapor flow velocities in the containment are expected to be low.

- Only a fraction of the debris added to the pool formed on the containment floor would be transported to the sump screen. Several experiments have been carried out to establish a defensible minimum value that can be used in the parametric evaluations [LANL, 2001c; LANL, 2001d]. Findings from these experiments were used in the transport fraction estimates.

[25]As noted below, large pieces stay afloat for up to 30 min following a LOCA. The density of a dry blanket is only 2.3 lb/ft^3. These pieces could be easily transported toward the sump and deposit on the sump screen.

[26]Ongoing debris generation experiments suggest that up to 50% of the debris may be in transportable form. This finding applies to both cal-sil and fiberglass insulation. Thus, 33% presents a reasonable estimate considering that not all insulation is arranged as in the configurations tested.

Early considerations of containment pool debris transport focused on the sliding and tumbling properties of debris pieces along the floor, and an extensive test program was pursued to measure the threshold velocities required for motion of various debris sizes. A draft report is available that describes this series of separate-effects tests [Maji, 2000]. In summary, the following was found.

1. Flocks of loosely attached fiberglass debris could remain suspended and move to the sump screen at flume-averaged velocities as low as 0.05 ft/s. These flocks (referred to as Size Class 1 and 2 in NUREG/CR-6224 [Zigler, 1995]) can be maintained in suspension for hours with small amounts of turbulence.

2. Fiberglass insulation fragments (sizes between 1/2 and 1 in.) that have settled to the floor will begin to tumble and slide with a depth-averaged flow of approximately 0.12 ft/s. These fragments can also remain in suspension for prolonged periods of time. Furthermore, these fragments can easily degrade into finer fragments when subjected to turbulent mixing flows.

3. RMI shreds are much less mobile and can be de-emphasized as a transport concern except for horizontal sump screens with no curbing that are located near to or are exposed to the break.

4. Cal-sil in fragmented form easily dissolves in hot water and transports as a suspended particulate up to physical diameters approaching 1/2 in. As confirmed by recent testing and shown in Fig. 3-5, the combination of cal-sil and minimal amounts of fiber form a very effective filter capable of inducing significant head losses across a sump screen. Also, cal-sil fragments by themselves can accumulate on the sump screen, even without the presence of fiberglass. Such deposition coupled with hot water induces very large pressure drops.

5. As-manufactured fiberglass blankets and RMI cassettes initially float on water and take between 15 and 30 min to sink. Therefore, their transport could not be ruled out for exposed sumps, especially for sumps with horizontal sump screens.

A series of tests was designed and specifically carried out in the three-dimensional (3-D) tank facility to obtain further data on debris transportability. Some of the important conclusions, as used in this study, are as follows.

1. Although floor-level transport is still an important consideration for determining maximum possible transport fractions, tests show significant transport of individual fibers and small clusters of fibers. These materials can be easily washed down by sprays (or small films of draining water). This testing can be viewed as (a) supporting a transport fraction of 10% under conditions expected to exist in the containment following a LOCA (including an SLOCA) or (b) failing to preclude this level of transport as a possibility. This material tends to deposit uniformly over a vertical or horizontal screen in very thin layers, and continued collection of this material has been observed to continue at a gradually decreasing rate for as long as 5 h.[27]

2. Real fractions of transport could be very large depending on spray actuation, sump flow and location, and orientation of the sump. Transport fractions in excess of 0.75 were measured for fibrous shreds when they were subjected to flow conditions representative of conditions expected to exist in the containment following an LLOCA.

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[27] Decreasing collection rates for most tests suggest that a finite amount of initial source material is being slowly filtered from a finite pool of water, but other tests that combine threshold floor velocities with splashing water that penetrates to the pool bottom suggest that migration and turbulent degradation can be an important long-term source of finely divided fibers.

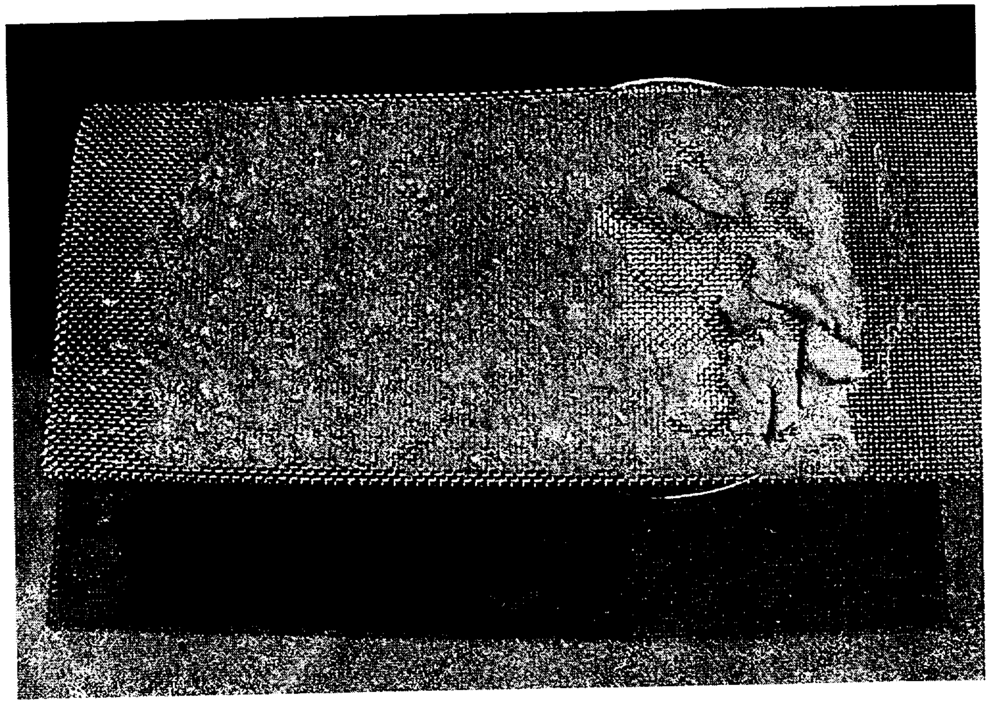

Fig. 3-6. Screen of 1/8-in. Mesh Opening Obstructed by Cal-Sil (Small Yellow Lumps) and Fiberglass (Uniform Translucent Mat). Close Inspection Reveals Very Small to Microscopic Cal-Sil Granules Imbedded in a Complex Fiber Mat. The Broken Bed to the Right of the Photo Was Damaged During Screen Removal. Nominal Fiber Thickness is 1/10-in.

3.4 Debris Accumulation and Buildup

Ongoing GSI-191 tests have shown that debris accumulation and buildup on a sump screen depends strongly on the orientation of the sump screen (i.e., vertical, horizontal, or slanted), approach velocity, and debris type. For debris type and sizes of present interest (i.e., small fragments of cal-sil and fiberglass), GSI-191 developed an extensive database for vertical screens and a limited database for horizontal screens. These experiments are being continued to gather additional data. The important experimental findings (to date) are as follows.

1. Fine debris tends to build up uniformly on vertical or horizontal screens. This trend is shown in Figs. 3-6 and 3-7. In both cases, small volumes of fine fibrous (nominal thickness of 1/10-in.) and cal-sil insulation were introduced into the flume and allowed to accumulate naturally on the screen.

2. Heavier debris builds up preferentially from bottom to top on vertical screens and uniformly in the case of horizontal sumps. Although curbs have an effect on debris accumulation, their effect is minimal when approach velocities are high (0.25 ft/s).

3. Very small approach velocities (<0.05 ft/s) are sufficient to keep a piece of fiberglass debris attached to a vertical sump screen. Buildup of thicker (1 to 2 in.) fiber beds would be necessary to induce the high head losses necessary to overwhelm the $NPSH_{Margin}$. However, fibrous debris readily detaches from the screen when flow through the screen is terminated.

4. Fibrous debris buildup in the presence of cal-sil is very similar to buildup in its absence (see Fig. 3-6). However, debris beds made up of cal-sil and fiber behave differently. Very small quantities of fibrous debris may induce very large pressure drops if cal-sil is present. In fact, a very thin bed could induce large pressure drops. For example, the bed shown in Fig. 3-6 caused a head loss in excess of 1 ft-water (and still increasing when the experiment was terminated[28]). However, upon termination of flow, the debris remained intact on the screen instead of crumbling as noted in the case of pure fiber beds.

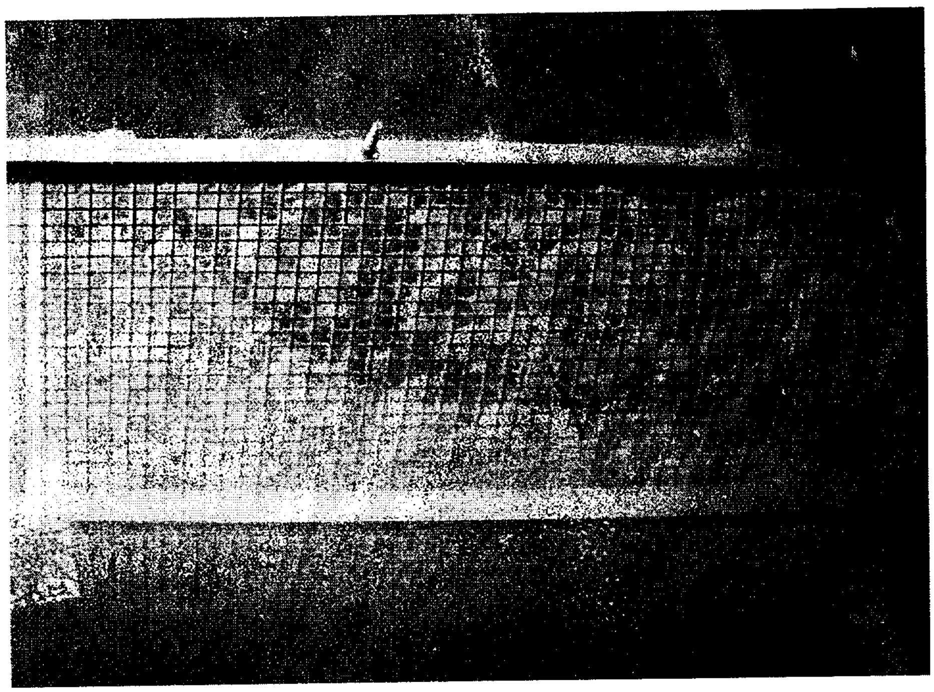

Fig. 3-7. Thin Fiber Bed Beginning to Build on a Vertical Screen of 1/4-in. Mesh Opening.

Based on these findings, it was concluded that the fibrous and particulate debris of present interest would accumulate uniformly on the screen. However, two questions remained.

1. Would such fine fragments be capable of bridging relatively larger (¼-in.) screen mesh openings?
2. Would a 1/8-in.-thick[29] bed be able to filter debris and induce head loss?

Experiments were conducted to address these issues, and the findings are as follows.

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

[29]Previous testing [Zigler, 1995] has shown that fiber beds spanning a regular mesh are vulnerable to localized collapse under very high pressures, so some minimum thickness will be needed to maintain mechanical integrity while supporting the imbedded particulate. NUREG/CR-6224 stated that fiber beds can survive approximately 50 ft of water per inch of thickness; so to withstand a nominal $NPSH_{Margin}$ of 6 ft, our analyses assumed that 1/8-in.-thick fiber beds would be necessary. This finding is based on test data obtained for 1/8-in.-mesh-opening BWR strainers. Confirmation of this finding for ¼-in. screens was necessary.

1. Fiber beds as thin as 1/8 in. can filter significant quantities of cal-sil and induce high head losses. However, significant head loss can occur for much thinner layers, especially when combined with cal-sil (see Fig. 3-6). The assumption that a full 1/8-in.-thick fiber bed is required for failure is certainly a favorable assumption for plants with a small $NPSH_{Margin}$ or with partially submerged screens where thin beds do not have to support an extreme head loss to reach the sump failure criterion. This assumption can be used to estimate FTDL for fibrous debris.

2. Figure 3-7 shows the initial growth of a fiber bed on a 1/4-in.-mesh screen. Note how individual fibers are able to stretch across the corners of the mesh and gradually reduce the effective opening. At this point of bed development, the solid patches of fiber represent the larger flocks of debris that were suspended in the water flow. After several minutes, the fiber mat becomes contiguous, causes significant head loss, and is virtually indistinguishable from similar beds formed on 1/8-in.-mesh screens.

3.5 Head-Loss Modeling and Assumptions

Detailed head-loss calculations were performed for each parametric case. The primary objective of these calculations was to define all combinations of particulate and fiber that can fail the required sump-performance conditions. Of special interest are (a) the minimum volume of fiber in combination with particulate debris needed to fail the sump and (b) the minimum volume of fiber needed to fail the sump in the absence of particulates. A secondary objective was to estimate the range of expected screen head loss for each parametric case.

To meet this objective, head-loss calculations were performed for a very large number of fiber volumes and particulate masses combined uniformly on each wetted sump-screen area. In some cases, the wetted area was estimated from the pool depth, the screen height, and the reported screen area. Head-loss correlations that predict the differential pressure drop per unit thickness of the debris bed were adopted from previous studies performed in support of the BWR strainer-blockage study [Zigler, 1995]. These correlations predict pressure drop as a function of the water-flow velocity and the debris-bed characteristics for a uniform bed with no significant edge effects. Thus, a head-loss estimate can be made for any combination of particulate and fiber debris. As explained above, both favorable and unfavorable values were defined for each parameter. For example, if a case required both Kaowool and Nukon as the fibrous component of a mixed debris bed, the head-loss characteristics of Kaowool were adopted for the unfavorable calculation (larger pressure drop per unit thickness) and the head-loss characteristics of Nukon were adopted for the favorable calculation (smaller pressure drop per unit thickness).

The strainer head losses associated with a debris bed composed of both fibrous insulation and particulate debris depends on the type of particulate within the bed, as well as on the type of fibrous debris. Several types of particulate debris would likely be available within PWR containments for transport to the sump screen. First, the destruction of certain types of insulation and fire barrier materials, such as cal-sil, would likely result in substantial quantities of particulate debris. Other types of particulate debris include: resident dust and dirt, concrete dust from erosion in the break jet, failed containment coatings, and Zn and Al precipitation byproducts. The characteristics affecting head-loss performance are unique for each type of particulate and are not well known for most types.

Comparisons of the "bump-up" factors associated with each particulate type validated assumptions made in the parametric study for the treatment of particulate debris[30]. Bump-up factors are defined as

[30] Note that "bump-up" factors were not used in the head loss calculations. This discussion is provided only to illustrate the relative contribution to head loss when different types of particulate are introduced to a fibrous debris bed.

the ratio of the head loss with particulate in the fiber bed to the head loss without particulate for the same flow conditions. Bump-up factors were determined from the URG gravity head-loss tests [BWROG, 1998] by dividing the head loss associated with a given quantity of particulate and fiber by the head loss for a similar test without particulate. Note that (1) these tests were all conducted in one test facility using the same test procedures so that the only substantial difference was the type of particulate, (2) all tests that were compared had a particulate-to-fiber mass ratio of approximately 1, and (3) the thickness of the fiber debris bed was approximately 2 in. Bump-up factors determined in this manner for several particulate types are compared in Fig. 3-8.

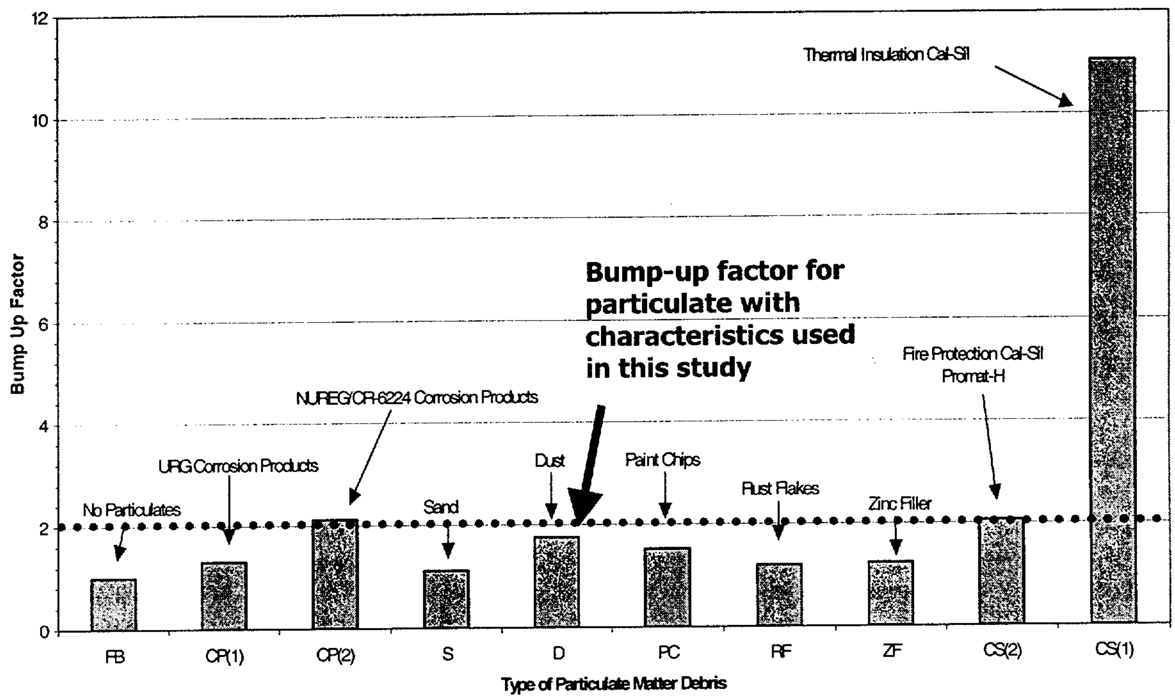


Fig. 3-8. Comparison of Particulate Bump-Up Factors.

The types of particulate examined in the gravity head-loss tests included corrosion products, sand, concrete dust, paint chips, rust flakes, zinc filler, and two types of cal-sil. Figure 3-8 shows that most types of particulates tested caused similar magnitudes of head loss; i.e., the bump-up factors ranged from 1 to 2. Note that the factors for the corrosion product tests documented in NUREG/CR-6224 are comparable to the factors for corrosion products determined from the gravity head-loss tests. The notable exception was particulate formed from the thermal insulation cal-sil. Its bump-up factor was approximately 11. Furthermore, cal-sil bump-up factors determined from other test data suggest that the factors could reach as high as 50 for thin debris beds.

High cal-sil bump-up factors mean that cal-sil insulation debris will produce much higher head losses than comparable quantities of other types of particulate. However in this parametric study, cal-sil and all other microporous insulation debris were treated as a generic particulate. This means that the effect of cal-sil insulation debris in all head-loss calculations was underestimated in favor of reduced sump-blockage potential. This very favorable assumption was partly compensated for in the final vulnerability assignment by shifting cases with large amounts of cal-sil and designations of **possible** up one grade to

likely[31]. Comprehensive head-loss testing of typical PWR insulation types currently is being planned as an important part of the continuing GSI-191 PWR Sump Blockage Study. This testing is critical for the quantification and public dissemination of information that characterizes the behavior of these insulations when combined in a debris bed.

Pressure drop across a mixed debris bed is a function of the water velocity through the screen, the composition of the debris, and the thickness of the bed. Head losses were computed for each parametric case over a wide range of fiber volumes and particulate masses present in the bed to generate a head-loss response surface similar to that shown in Fig. 3-9. This figure shows the favorable range of head loss (vertical axis) that is characteristic of Nukon fiber beds on the sump screen of parametric case 17 (discussed in Section 4). Each combination of debris creates a unique pressure drop that may be less than or greater than the failure condition ΔH_f, which can be represented for this plant by a horizontal plane slicing through the surface at a height of 1.1 ft of water. Figure 3-10 presents a close-up view of the same response surface that has been limited to an upper range equal to ΔH_f. All debris beds that fall in the region defined by the upper plateau create unacceptable head loss; debris combinations that lie in the corner "notch" can still meet the required flow condition. Note that the three vertices of the acceptable performance region are defined by the debris combinations of (a) minimum fiber volume (0.59 ft^3) with zero particulate, (b) minimum fiber volume with minimum particulate loading required to meet the failure threshold (2.1 lb), and (c) zero particulate and the minimum fiber loading required to meet the failure threshold (3.24 ft^3).

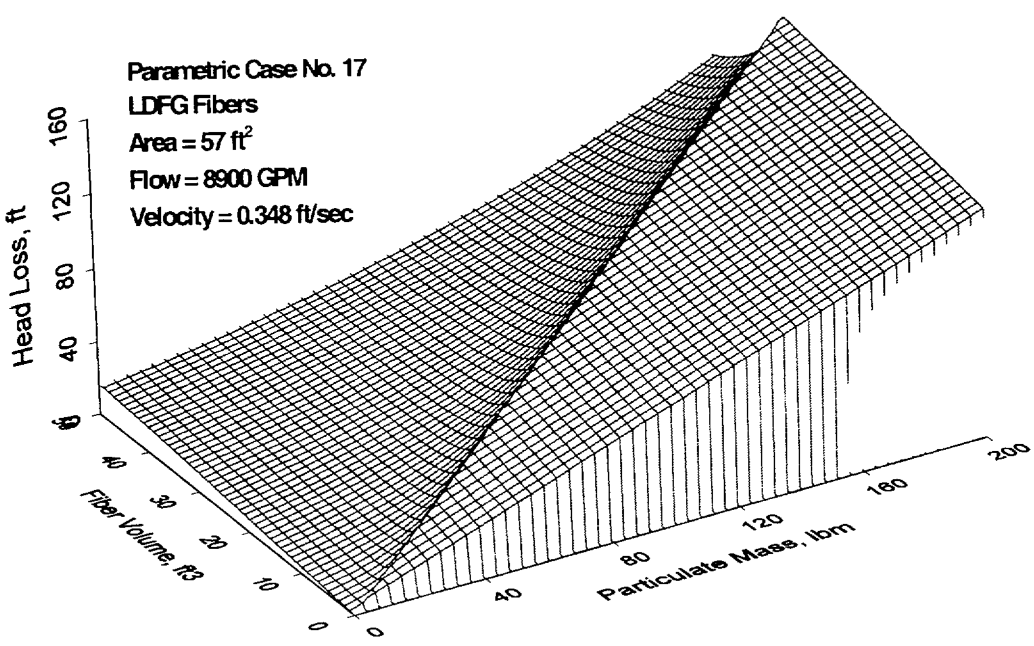


Fig. 3-9. Head-Loss Response Surface for Parametric Case 17.

[31] Similar adjustments were made for other qualitative grades (e.g., likely to very likely) as well. See Section 5 for further details.

Any combination of debris that lies on the contour of the failure condition will be referred to as an FTDL. This collection of points forms the failure-threshold function that is shown in Fig. 3-11 for SLOCA conditions in Case 17 for both favorable and unfavorable debris head-loss characteristics. Debris combinations that lie to the right of the curves will induce unacceptable head losses; combinations to the left will meet the ΔH_f performance criterion. The vertical line shared by both the favorable and unfavorable conditions simply emphasizes that any particulate mass above the threshold value corresponding to the minimum assumed fiber volume will cause excessive head loss. The box formed of dashed lines near the upper center of the figure delineates the approximate range of particulate and fiber loadings that might be expected to form on the screen. These ranges account for the generation and transport fractions in the manner described in Secs 3.2 and 3.3. For this case, all expected debris loadings lie in the failure region, and blockage is rated as **likely**, but for many of the parametric cases, the failure-threshold conditions intersect the range of expected. This implies that blockage is **possible**, and that plant features must be examined to identify any additional concerns.

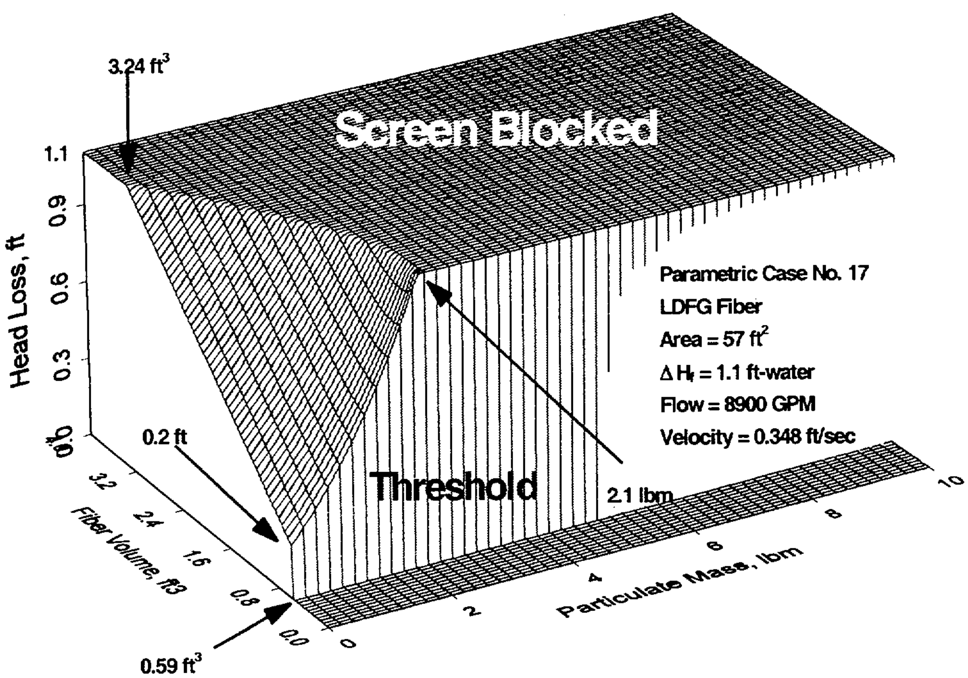


Fig. 3-10. Close-Up View of Head Loss Response Surface for Parametric Case 17.

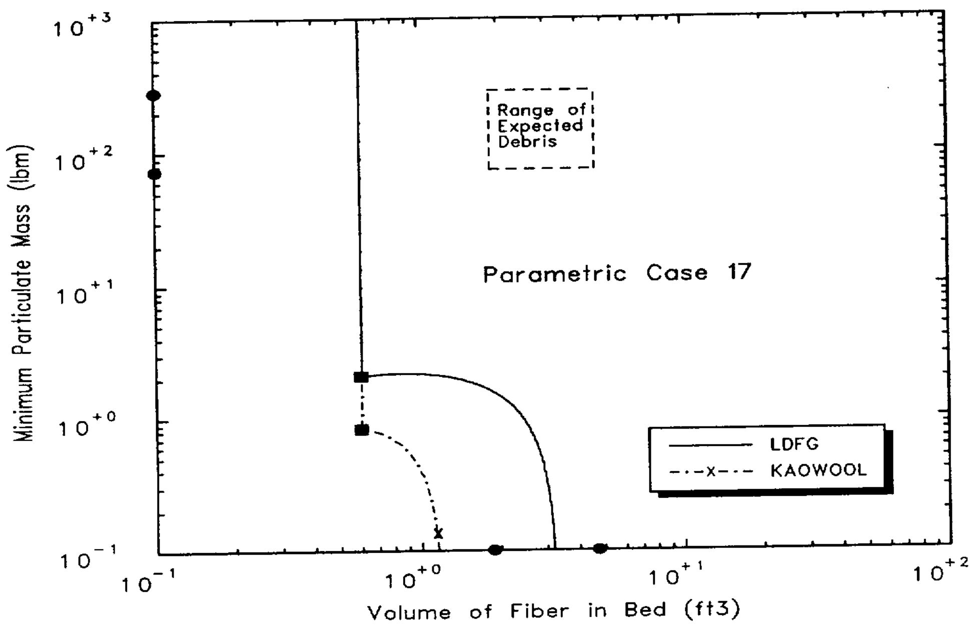


Fig. 3-11. Failure-Threshold Functions for Case 17 under SLOCA Conditions and Both Favorable (LDFG) and Unfavorable (Kaowool) Head-Loss Characteristics

Appendix B includes figures similar to Fig. 3-11 for all 69 parametric cases under both favorable and unfavorable head-loss assumptions for four flow conditions corresponding to SLOCA, MLOCA, LLOCA. Recall that the wetted screen area and the volumetric flow requirements together determine the face-averaged flow velocity of water approaching the screen. Summaries of these calculations and explanations of trends observed across the industry are presented in Sec. 5.0.

4.0 SAMPLE PARAMETRIC CALCULATION

Parametric calculations were performed for 69 cases to examine the potential for blockage of the sump screens by LOCA-generated debris. The parametric calculation approach and assumptions were discussed in Sec. 3. The results and limitations of these calculations are presented for all parametric calculations in Sec. 5. In this section, the calculation for one parametric case is presented to more completely illustrate the calculational approach. Parametric Case 17 was randomly chosen for demonstration purposes. Although Parametric Case 17 was chosen to closely represent a PWR unit (based on the unit's response to the Industry Survey and the unit's response to NRC GL 97-04 [US NRC, 1997]), it is possible that several differences exist between the data used in this analysis and the actual plant data. Therefore, these results, by themselves, should not be used to judge the susceptibility of a particular plant unit.

4.1 Description of the Parametric Case

The parameters used for the Case 17 calculation are listed in Table 4-1. As shown, the characteristics of this parametric case include both a relatively small sump-screen area and relatively large quantities of fibrous and cal-sil insulations; each is an indicator of likely screen blockage in the event of LOCA-generated debris. The following ECCS features characterize this parametric case.

- The safety injection (HPSI) pumps have an $NPSH_{Margin}$ of 13 ft-water; this value is significantly higher than that for RHR pumps or the CS pump in the recirculation mode (1.1 ft-water).[32] This is typical of most (but not all) operating PWRs. The $NPSH_{Margin}$ estimate assumes containment overpressurization.

- The plant has one of the smallest containments (10^6 ft^3 of free volume) and a CS actuation set point of 5.9 psig. Once again, several such PWR containments exist, and in all these cases, MELCOR calculations suggest that CS actuation is most likely even after a 2-in. line break.[33] Assuming that the CS pumps would actuate following a LOCA, the minimum recirculation flow (HPSI+CS flow) is approximately 8900 gpm, and maximum flow can reach 15,100 gpm. These values compare reasonably well with most of the operating PWRs in recirculation mode.

- The plant RCS is insulated with fiberglass, Kaowool, and jacketed cal-sil. The insulation on the other piping is not known and likely consists of fiberglass. Once again, this is typical of most operating plants. That is, inventories of insulations on non-RCS piping are not well accounted for in the survey.

- The screen hole size is 0.178 in.; which is larger than the median industry value but compares well with several plants.

[32]The plant IPE states that HPSI (three out of three pumps operating) is enough to make up for break flow following an LLOCA or SLOCA during recirculation mode. However, CS or RHR pumps would be necessary for decay heat removal.

[33]Sensitivity analyses examined the following possibilities for this case where a signal would isolate the chilled water supply to the fan coolers: aligning CCW for heat removal (an operator action not part of EOPs) and degraded fan-cooler performance caused by a fine layer of debris buildup.

Table 4-1. Plant Parameters Used in the Sample "Parametric-Case" Calculation.

Plant Parameter	Value
Sump-Screen Area	57 ft^2
NPSH Margin	1.1 ft-water CS and RHR 13 ft-water for HPSI
ECCS Pump Flow Rates (sprays on) SLOCA ECCS Flow (assuming CS) All ECCS Flow	8,900 gpm 15,100 gpm
Sprays Activation Pressure	5 psig CS actuation likely for 2-in. line because containment volume is 10^6 ft^3 (relatively small)
Containment Free Area	Net area 6740 ft^2 Narrowest channel close to the strainer is 9 ft wide. Assuming that the6 ft water height in this channel flow area in the close proximity is about 60 ft^2; results in about 0.4 ft/s.
Fan Cooler	Not safety class.
Pool Levels At Switchover Maximum Height	5.4 ft (@20 min) 6.78 ft (@24 min)
Sump Submergence	Completely submerged both at switchover and later. Base plant uses "cylindrical" basket strainers arranged vertically on the floor.
Sump Location	Remote
Sump-Screen Orientation	Vertical with respect to approaching flow
Sump-Screen Approach Velocity	SLOCA ECCS = 0.35 ft/s, All ECCS = 0.59 ft/s
Sump-Screen Clearance	0.178 in.
Insulation Types	Fiberglass blankets Kaowool blankets Jacketed cal-sil
Relative Fractions of Insulation Fibrous (fiberglass and Kaowool) Cal-Sil	74.6% 25.4%

4.2 Minimum Debris Necessary to Induce Sump Failure

The failure threshold debris loading was obtained using the following steps.

Step #1. Define failure criterion.
Step #2. Define types of debris that might accumulate on the sump screen. This should include both fibrous and non-fibrous debris.
Step #3. Determine threshold debris loadings by inversing head-loss correlation (see Sec. 5.2 for further discussion).

Sump Failure Criterion

Because the sump screen would be completely submerged during the recirculation phase of ECCS core cooling, neither the screen area nor ΔH_f was limited by pool height, as was the case for several of the parametric cases. The sump failure criterion in this case is determined as follows for each system.

- *Containment Spray: ΔH across sump > 1.1 ft-water*
- *RHR: ΔH across sump > 1.1 ft-water*
- *HPSI: ΔH across sump screen > 13 ft-water*

The RHR heat exchangers are usually aligned with the LPSI system, which also acts as the RHR system during normal shutdown. When used as part of ECCS, the LPSI (RHR) system provides the necessary injection during the injection phase, but upon receiving a switchover signal, the RHR system is isolated and core make up is provided by HPSI only. Although, the operator can and may realign RHR to also provide reactor vessel makeup, it is not part of the licensing basis $NPSH_{Margin}$ estimates. The licensing basis estimates [US NRC, 1997] assume that only HPSI would be providing makeup water at a flow rate of approximately 1500 gpm (three pumps on two trains) and the CS system will provide for decay heat removal. At least one of the CS pumps must operate at full capacity to maintain sump water below the temperature used to estimate $NPSH_{Margin}$ for these pumps. Note also that the plant on which this parametric case is based takes limited credit for containment overpressure and/or sump water subcooling. These values were derived from containment modeling analyses.

Debris Sources and Types Used in Head Loss Estimation

This parametric case assumes that the piping is insulated by either fibrous or cal-sil insulation. The fibrous insulation was one of two types, either fiberglass or Kaowool; therefore, the fibrous debris formed on the screen could consist of either one of these types or a mixture of the two types. For this calculation, the fiberglass was represented by LDFG properties (typical of Nukon and Thermal Wrap). Because Kaowool is known to cause significantly larger head losses than LDFG, assuming Kaowool represented a less favorable assumption than assuming LDFG. Cal-sil was considered only as a particulate filtered by the fibrous debris bed. This was a favorable assumption because ongoing GSI-191 experiments have shown that cal-sil can itself accumulate on screens with clearances exceeding 1/8 in. and cause much more severe head losses than predicted by simply treating it as a particulate.

In addition to LOCA-generated insulation debris, other types of debris could accumulate. This debris could include dirt, dust, concrete dust, paint chips and particulate, corrosion products, and miscellaneous materials left inside the containment, such as duct tape and plastic tags. The LOCA jet would likely generate some of this debris, such as paint chips or concrete dust. For the parametric study, a generic composition of particulate with the approximate characteristics of dirt was assumed. The mass of miscellaneous particulate in containment was assumed to range from 100 to 500 lb. Applying the transport fraction leads to a range of particulate in the screen debris of 10 to 125 lb.

In summary, the head-loss analysis assumed the following.

- A fibrous layer would form on the strainer surface through accumulation of fibrous debris that is generated by LOCA jets and transported thereafter by recirculating water. "Favorable" analyses assumed that these fibers would consist of LDFG fibers, whereas Kaowool fibers were used in the "unfavorable" analyses.
- Head loss could be caused by fibers themselves and by filtration of particulate debris by the fiber bed. These particulates would include substantial quantities of cal-sil and miscellaneous particulates. The head loss is estimated assuming that all particulates are made of "dirt", which is a favorable assumption because BWROG studies have clearly shown that cal-sil results in very high head losses compared with dirt, dust, or any other particulate material (See Sec. 3 for discussion).

Threshold Quantities

The minimum mass of particulate needed for a specified fiber volume to reach the sump failure criterion (ΔH_f) was determined for various LOCAs in Figs. 4-1 through 4-4. Figures 4-1 through 4-3 present these threshold values for the CS system. Figure 4-4 presents these values for a SLOCA and blockage of the HPSI system. In all these figures, the minimum particulate mass is shown for both LDFG and Kaowool fibers. The following conclusions can be drawn from these figures.

- The inflection points of these figures (also denoted by square points) show that the screen in parametric case 17 could be blocked effectively with as little as 0.59 ft^3 of LDFG insulation debris.[34] This quantity of fibrous debris coupled with 2.1 lb of particulate debris is sufficient to reach the sump failure criterion (ΔH_f) for CS following a SLOCA. Even lower quantities of fiberglass and particulates would block the CS following a LLOCA. On the other hand, a larger quantity of particulate debris would be necessary to block the HPSI system. Specifically, a combination of 0.59 ft^3 of fiber and 21 lb of particulate debris will cause the sump failure criterion (ΔH_f) to be exceeded for the HPSI system.

- These figures also show that 3.24 ft^3 of LDFG debris and no particulate would be sufficient to reach the sump failure criterion (ΔH_f) for CS following a SLOCA.

- Note that in each case, the quantity of Kaowool necessary to reach the sump failure criterion (ΔH_f) is less than that calculated for LDFG.

In all these figures, a dashed square indicates the quantity of debris expected to reach the sump. The following section describes how these estimates were obtained for parametric case 17.

[34]With less fiber than this minimum, the fiber would not effectively filter the particulate from the flow stream.

4.3 Likely Quantity of Debris Expected to Accumulate on the Sump

The quantity of debris that likely will accumulate on the sump screen was estimated following the steps below.

1. Estimate the quantity of debris generated by the LOCA. This estimate should include insulation and non-insulation debris (e.g., concrete dust).

2. Estimate the quantity of debris that would be transported to the close proximity of the sump screen. This estimate is obtained by multiplying the quantity generated by the transport fraction.

Quantity of Insulation Debris Generated

A simple model was used to estimate the quantity of debris generated. This model (a) assumes that postulated SLOCA, MLOCA, and LLOCA[35] events would generate approximately 25 ft^3, 40 ft^3, and 1700 ft^3 of insulation, respectively, and (b) proportions that volume according to the containment-averaged fractions of different insulations present in the containment. For parametric case 17, where 74.6% was fibrous and 25.4% was cal-sil, the volumes of debris generated are shown in Table 4-2.

The basis for these assumptions and the associated uncertainties is discussed in Sec. 3.

Quantity of Non-Insulation Debris Generated

The only debris sources (other than insulation) considered in the present calculation are "miscellaneous particulates." A "generic value" of 100 to 500 lb was used in these calculations, where "favorable" estimates are based on a particulate mass of 100 lb and "unfavorable" estimates are based on 500 lb. These miscellaneous particulate estimates are to account for the following potential debris sources.

- *Dust and Dirt.* The BWROG URG suggests a "generic" value of 150 lb for this category. Given that PWRs have larger surface areas, quantities in excess of 150 lb are possible. See Sec. 3 for dust-loading estimates.

- *Precipitants.* All PWR containments have large exposed aluminum and zinc surfaces. Hot, high-pH borated water reacts with such surfaces and generates hydrogen and particulates with a median size of 10 microns.

- *Paint Dust.* Jet interactions with the paint could produce large volumes of paint dust as demonstrated by Heissdampfreaktor (HDR) tests. BWROG URG proposed a generic estimate of 85 lb.

- *Fire Barrier Materials.* Pabco rigid panel (approximately 200 ft^3) is used as the fire barrier material. Whether this material is susceptible to debris generation is not known. If it is comparable to Marinite, ongoing debris generation tests indicate that very little debris would be generated (unless the material is subjected to high radiation aging for long time, in which some debris generation is likely).

[35]The LLOCA contribution for case 17 also was estimated assuming reported debris to be on RCS piping. This special case resulted in 300 ft^3. This special case was run because Plant 17 reported only fibrous and cal-sil debris inventory in the containment. The rest is not included in the plant survey. This does not change the outcome.

- *Filter Materials and Other Miscellaneous Fibers.* The filters used are fiberglass, high-efficiency particulate air (HEPA) filters, and charcoal filters. None of these are located inside the missile shield; all are located in the annulus region. Potential for generation is probably minimal.

- *Failed Paint Coatings.* Approximately 200,000 ft^2 of steel and concrete surfaces are coated in the plant that formed the basis for parametric case 17. Use of the SRS results suggests that up to 25 ft^3 of paint debris may be generated by "failure" of a 1- to 2-mil-thick top layer during a LOCA.

Table 4-2. Estimates for Parametric Case 17 Insulation Debris Generation.

Break Size	Debris Generated (ft^3)		Miscellaneous Debris (lb)	
	Fibrous	Cal-Sil	Favorable	Unfavorable
SLOCA	18.7	6.4	100	500
MLOCA	29.8	10.2	100	500
LLOCA	1270	432	100	500

Debris Transport Fraction

The transport of LOCA-generated debris from the point of generation to the sump screen is also a very difficult and complex problem. For the parametric study, a simple approach was used to gain insights into the relative effect of debris transport on the potential for PWR sump screen blockage. Reasonable transport fractions were assumed to determine the quantities of insulation debris on the screen. The transport fractions are shown in Table 4-3 for conditions considered favorable and unfavorable to debris transport. These transport fractions are supported by the following characteristics for Parametric Case 17.

- Velocity in the annulus as compared with the transport velocities of the debris of interest
- Sump location with respect to spray drainage

Numerous experiments confirm these transport fractions.

Table 4-3. Estimates for Parametric Case 17 Debris Transport Fractions.

Transport Conditions	Favorable Estimate	Unfavorable Estimate
SLOCA with Sprays Inactive	5%	10%
SLOCA with Sprays Active All MLOCAs and LLOCAs	10%	25%

Debris Accumulation and Head Loss

The debris-generation quantities in Table 4-2 and the transport fractions in Table 4-3 determined the ranges of masses of debris expected to accumulate on the screen following a LOCA. These quantities are shown in Table 4-4. Note that cal-sil is listed in mass units to reflect that it was treated as a particulate (the density of cal-sil is nominally about 100 lb/ft^3).

The debris was assumed to be uniformly mixed and evenly spread across the screen. This assumption is supported by the following characteristics for parametric case 17.

- At a flow rate of 8,900 gpm, the screen approach velocity is 0.35 ft/s.
- At such high approach velocities, both cal-sil and fibrous insulation are found (experimentally) to form uniform beds. Beds as low as 0.1 in. tended to be uniform. Such uniform beds were built on screens with clearances of up to 1/4 in. (see the discussions in Sec. 3).

Table 4-4. Estimates for Parametric Case 17 Insulation Debris Accumulated on Screen.

Break Size	Range of Debris Accumulated	
	Favorable	Unfavorable
SLOCA	Fiber: 1.9 ft^3 Cal-Sil: 64 lb Misc.: 10 lb	Fiber: 4.7 ft^3 Cal-Sil: 159 lb Misc.: 125 lb
MLOCA	Fiber: 3.0 ft^3 Cal-Sil: 102 lb Misc.: 10 lb	Fiber: 7.5 ft^3 Cal-Sil: 254 lb Misc.: 125 lb
LLOCA	Fiber: 127 ft^3 Cal-Sil: 4320 lb Misc.: 10 lb	Fiber: 317 ft^3 Cal-Sil: 10800 lb Misc.: 125 lb

4.4 Sump Loss Potential

The values shown in Table 4-4 are plotted as the dashed box in Figs. 4-1 through 4-4. As demonstrated in these three figures, the boxes of expected debris ranges were far in excess of the minimum particulate masses needed to block the screen. It was judged **very likely** that the screens in parametric case 17 will be blocked by debris following a LOCA. This judgment also considers the effects of uncertainties, such as the unknown accident progression for a SLOCA and variability in the actual amount of debris generated.

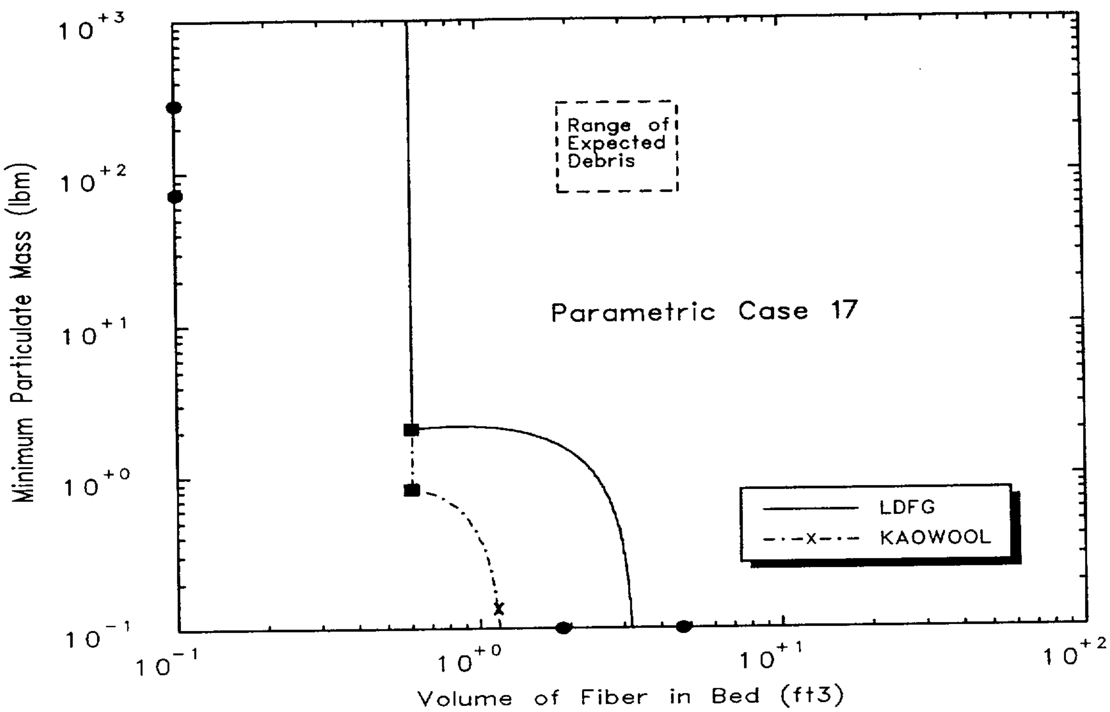


Fig. 4-1. Minimum Debris Loading Necessary for CS Failure Following an SLOCA.

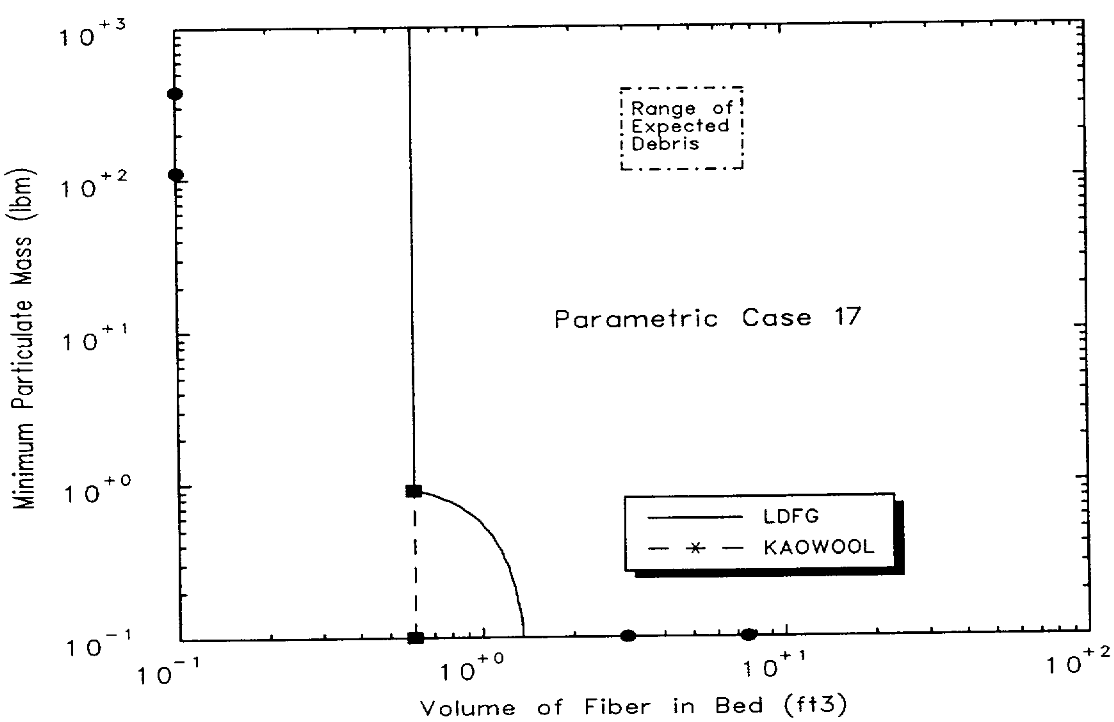


Fig. 4-2. Minimum Debris Loading Necessary for CS Failure following an MLOCA.

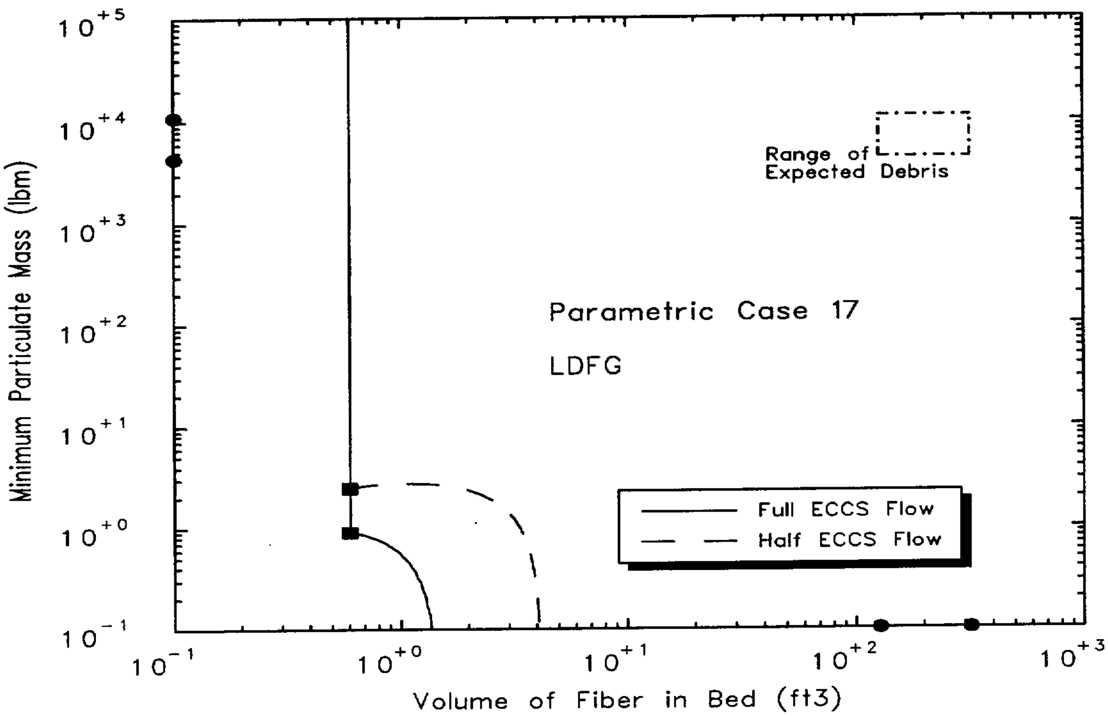


Fig. 4-3. Minimum Debris Loading Necessary for CS Failure following an LLOCA.

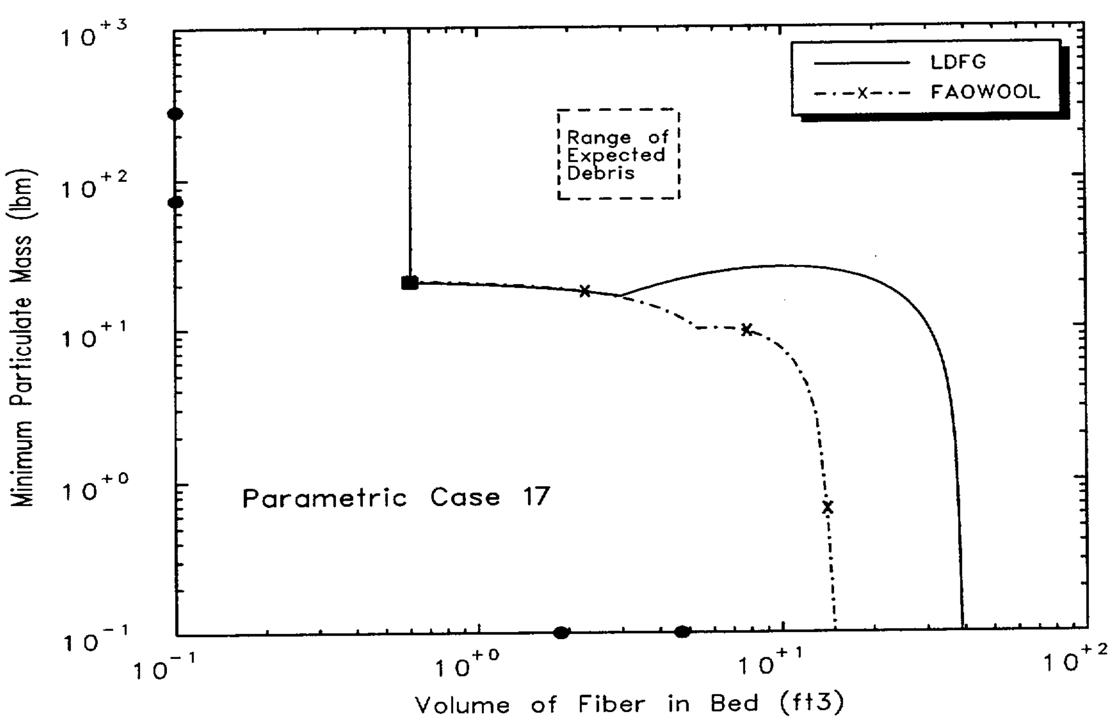


Fig. 4-4. Minimum Debris Loading Necessary for an SLOCA with HPSI Failure.

For parametric case 17, the fraction of the ZOI debris volume subsequently transported to the sump screen that would result in screen blockage was determined to be minimal. These minimum transport fractions are shown in Fig. 4-5 for each of the systems and break scenarios studied. Transport of less than 4% of the ZOI fibrous debris following a SLOCA may result in a FDTL on the sump screen. Because more debris would be generated following a MLOCA or LLOCA, the transport fractions for these events that result in the failure-threshold debris loading were even lower. The largest particulate transport fraction of 3.2% was for the HPSI system. It was higher than the corresponding SLOCA transport fraction of 0.3% for the CS system because the 13 ft-water ΔH_f for the HPSI was much higher than the 1.1 ft-water ΔH_f for the CS. In other words, it would take substantially more particulate mass to overcome the higher ΔH_f. However, even for the HPSI, the transport fractions needed to reach the ΔH_f were all relatively small.

Yet another way to look at the severity of the potential problem in parametric case 17 was to calculate the predicted head losses for both the estimated favorable and unfavorable debris screen loadings. These debris quantities are shown in Figs. 4-2, 4-3, and 4-4 for an SLOCA, MLOCA, and LLOCA, respectively. Specifically, the lower left corners of the dashed boxes represent the favorable conditions and the upper right corners represent the unfavorable conditions. These head losses are shown in Fig. 4-6. It is easily shown that these head losses all greatly exceeded the ΔH_f. In fact, most of these calculated head losses exceeded the recognized validity range of the head-loss correlation, but it must be concluded that the screen would very likely be blocked by all of these debris loadings.

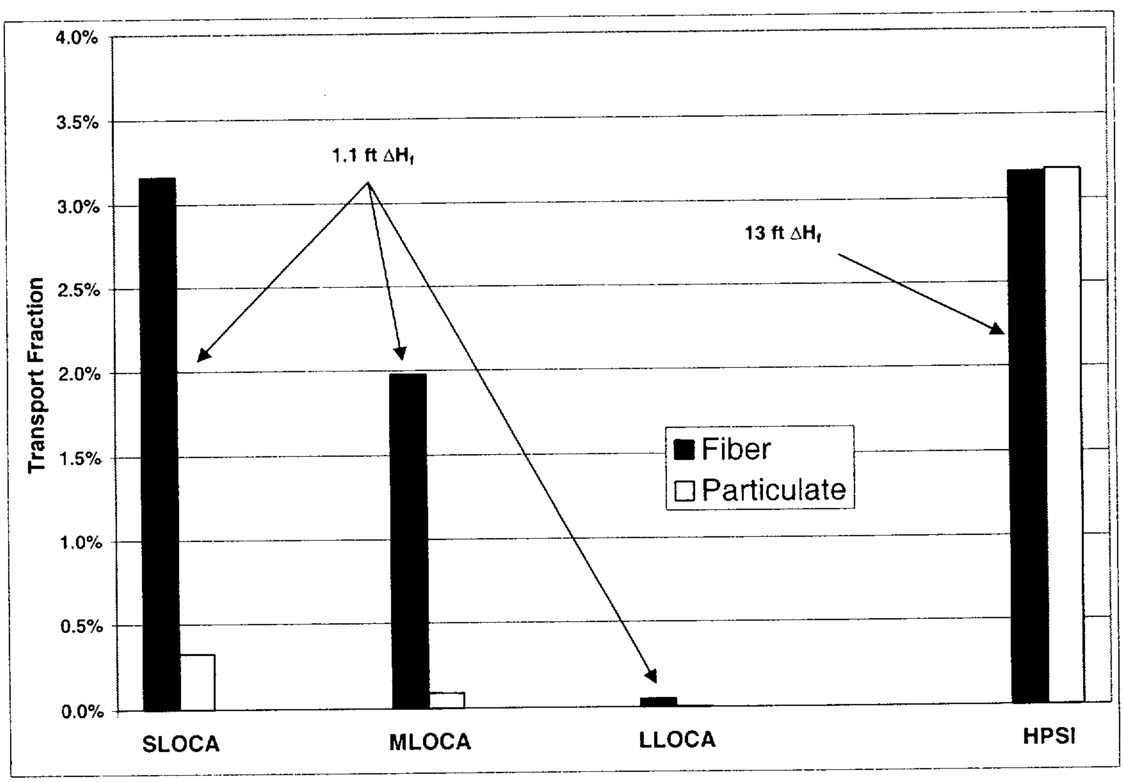


Fig. 4-5. Minimum Transport Fraction for Fiber and Particulate Debris.

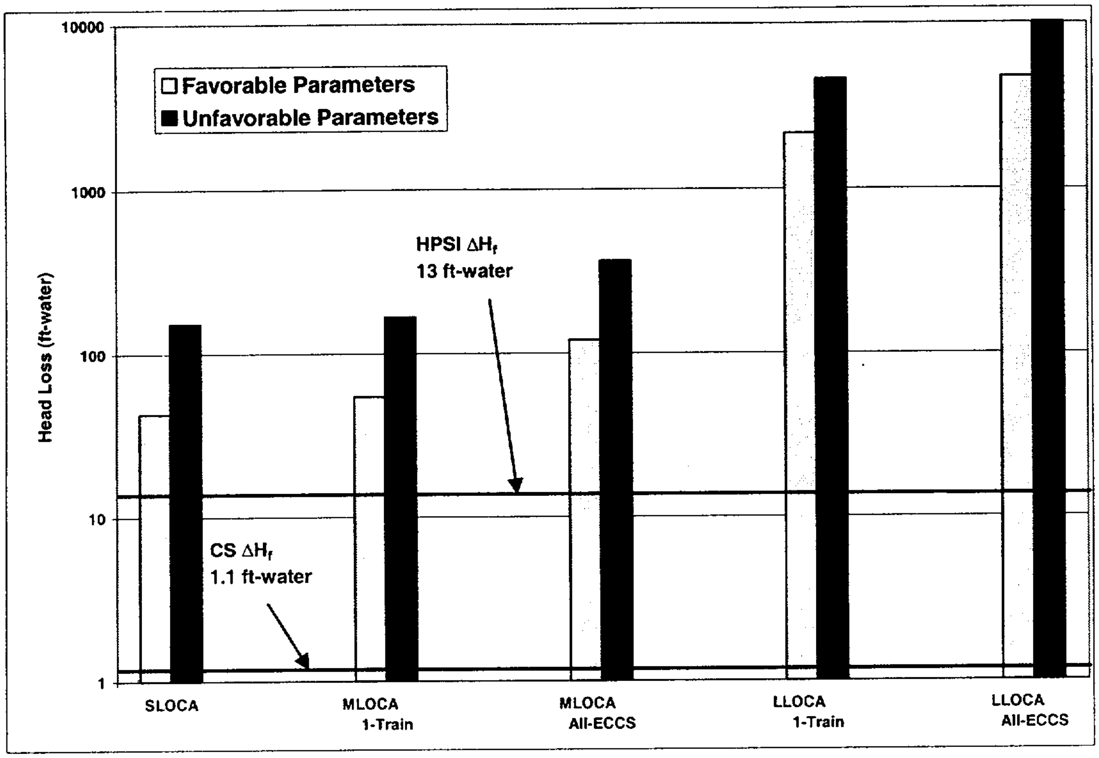


Fig. 4-6. Likely Pressure Drop across the Screen Caused by Debris Accumulation.

5.0 RESULTS OF THE PARAMETRIC CALCULATIONS

As explained in Sec. 1, each operating power plant was represented by a parametric case study using the best available information. In brief, each case was examined following the step-by-step procedure discussed in Sec. 4 to assess their individual vulnerability to sump blockage. Final determinations of the blockage potential for each case were expressed with a qualitative grade of **unlikely, possible, likely,** and **very likely**. The results of the parametric evaluations are presented and explained in this section. The input data that formed the bases for these evaluations are presented in Appendix A, and specific results for each parametric case are provided in Appendix B.

5.1 Description of the Parametric Case Set

As previously noted, central to each parametric case study is the best available physical description of an actual PWR. Within resource constraints, every attempt was made to base these parametric cases on the 69 operating PWRs, as described below.

- To the extent feasible, actual plant information was collected from available sources such as licensee responses to NRC GL 97-04 [US NRC, 1997], the GSI-191 Industry Survey [NEI, 1997], and plant UFSARs.

- Where sufficient information from these sources could not be obtained or the information included in those sources was incomplete, one of two options was undertaken. In the preferred option, sources such as NRC website data, the report "Overview and Comparison of US Commercial Nuclear Power Plants" [US NRC, 1990], or NUREGs developed as part of the USI A-43 study[36] [Serkiz, 1985; Wysocki, 1982; Wysocki, 1983; Kolbe, 1982; Weigand, 1982] were used to compile data that could be confirmed with either NRC or plant information sources.[37] Alternatively, data from units of similar type and vintage were adopted as surrogates for plant-specific descriptions.

Table 5-1 provides values for many of the important parameters that define each parametric case; a more detailed set of tables is included in Appendix A. The following general conclusions can be drawn regarding the accuracy and fidelity of the data presented in this table.

- Typically, information with high fidelity was available for the following parameters: (a) ECCS and CS flow rates following large- and medium-break LOCAs, (b) $NPSH_{Margin}$ for each pumping system, (c) time to ECCS switchover following large and medium LOCAs, (d) expected water levels on the containment floor at the time of ECCS switchover, (e) containment-averaged volumetric fraction of insulation in each insulation type, and (f) recirculation-sump geometry and containment-layout information. For these factors, parametric variations addressed issues such as the comparison between a single operational ECCS train and nominal full-flow plant performance.

- Information describing the accident progression following an SLOCA was not readily available in any of the official plant documents. Of particular interest was the status of CS following a SLOCA and the net flow through the recirculation sump. This gap in understanding of the SLOCA accident progression is a reflection of two facts: (a) the SLOCA (and MLOCA for that matter) has

[36]NUREGs from the USI A-43 study provided very valuable data. However, insulation information from these sources appears to be outdated because many plants continue to replace insulation with other types as needed.
[37]Insulation vendors confirmed the insulation data in some cases.

not been part of DBA or licensing-basis safety evaluations and (b) considerable variability exists between licensees in their ECCS and CS responses to SLOCAs. To overcome this gap, a series of RCS and containment simulations was carried out with the objective of determining the range of "favorable" and "unfavorable" conditions that could exist in the containment following a postulated SLOCA.

- Insulation information was available to the required detail for only two GSI-191 volunteer plants and six USI A-43 plants [Serkiz, 1985]. For the rest of the plants, available insulation information included (a) the types of insulation present on the RCS piping and (b) either the quantities of each type present in containment or the volumetric fraction of the total insulation belonging to each type. This information is not sufficient to perform precise debris-generation estimates because the locations of each insulation type in containment are not known. In fact, some of the plant estimates for even the volumetric fraction are tenuous. This is a reflection of the fact that licensees have not tracked rigorously the type(s), location(s), or quantities of different insulations in the containment[38]. Because only rough estimates of insulation composition were available, this generic assessment places more emphasis on estimating failure-threshold debris loadings than on estimating the quantities of debris generated and transported. Although the latter estimates also were used in determining the relative likelihood of plant blockage, they are just two of the many factors that were examined parametrically.

Despite some of these limitations, the case studies do serve their central purpose of providing a set of parametric samples that closely represent US PWRs. Therefore, the parametric analyses provide a reasonable representation of the magnitude of the sump-blockage problem, and the results can be used to gain valuable and defensible insights into the safety significance of this issue to the industry.

[38] This situation is very similar to the BWR experience at the onset of BWR study.

Table 5-1. Important Parameters that Define Parametric Case Studies.

Case	Reported Sump Screen Area	Reported NPSH Margin	Full ECCS Flow	Cont. Spray Act. Set-point	Switchover Pool Height	Maximum Pool Height	Height of Sump Screen	Sump Submergence	Sump Location	Open Cont. Floor Area	Sump Screen Hole Size	Fibrous Insulation	Reflective Metallic Insulation	Micro (Cal Sil) Insulation	Other Insulations
Units	ft²	ft-water	GPM	psig	ft	ft	ft	-	-	ft²	inch	%	%	%	%
1	42.4	10.02	7600	30	5.3	5.5	6	Partial	exposed	NR	0.125	yes	yes	yes	0
2	260	5	18424	18.2	2.24	4.7	6.25	Partial	remote	7400	0.115	13.4	85.7	0.9	0
3	210	3.8	19740	8.5	4.5	11	4.5	Fully	remote	13000	0.09	20.0	80.0	0	0
4	135	1.7	18416	2.9	5.5	14	NR	NR	NR	7000	0.204	50	50	<1	<<1
5	51.31	8.2	10000	NR	2.93	4.75	1	Fully	int. exp.	7500	0.25	yes	yes	yes	0
6	66	9	15600	2.9	NR	NR	5.25	Fully	int. exp.	NR	0.250	21	33	46	0
7	12.67	4.3	14200	20	0.82	6.1	1.5	At Max	NR	11682	0.152	0	100	0	0
8	135	1.7	18416	2.9	5.5	14	NR	NR	NR	7000	0.204	50	50	<1	<<1
9	11.64	2.6	14200	21.5	3.5	9.41	0	Fully	remote	15077	0.12	100.0	0	0	0
10	104	1.9	16000	14	1.92	7.5	3.5	At Max	int. exp.	10823	0.3	yes	yes	yes	yes
11	229	3	10498	4.75	5.25	5.25	3.5	Fully	exposed	10300	0.224	80.0	0	20.0	0
12	93.2	NR	7600	NR	5.33	6.89	below	Fully	NR	8497	0.25	yes	yes	0	0
13	214.4	NR	10000	30	1.74	5.89	below	Fully	remote	10415	0.125	9.0	91.0	0	0
14	204	0.96	10720	30	6	9.18	4.75	Fully	exposed	7700	0.132	17.4	67.5	15.2	0
15	368	0.54	14200	18	3.84	4.14	2.2	Fully	NR	11948	0.097	100	0	0	0
16	229	3	10498	4.75	5.25	5.25	3.5	Fully	exposed	10300	0.224	80.0	0	20.0	0
17	57	1.1	15100	5	5.4	6.78	3.5	Fully	remote	6740	0.1783	74.6	0	25.4	0
18	28.4	9.26	15600	2.81	2.5	13.2	3	At Max	exposed	4530	0.25	0	100	0	0
19	36.1	3.3	10300	22	2.1	4.1	below	Fully	int. exp.	NR	0.125	36.0	10.0	39.3	14.7
20	11.64	2.6	14200	21.5	3.5	9.41	0	Fully	remote	15077	0.12	100.0	0	0	0
21	225	7.35	16000	3	5.43	11.45	5	Fully	remote	NR	0.078	85	15	0	0
22	85.4	4.2	10498	25	1.5	5.5	0	Fully	NR	NR	0.221	yes	yes	yes	0
23	260	5	18424	18.2	2.24	4.7	6.25	Partial	remote	7400	0.115	13.4	85.7	0.9	0
24	12.67	4.3	14200	20	0.82	6.1	1.5	At Max	NR	11682	0.152	0	100	0	0
25	414	3.5	17400	9.5	3.6	NR	3	Fully	remote	NR	0.25	yes	yes	0	0
26	93	1.5	10720	10	4.27	4.27	below	Fully	exposed	8700	0.12	20.0	75.0	5.0	0
27	392	0.9	19920	27	2.12	4.41	8.667	Partial	remote	NR	0.125	yes	yes	0	yes
28	134	1.1	17500	25.3	3.67	5.5	3.75	At Max	remote	6273	0.125	55.0	30.0	15.0	0
29	12.67	4.3	14200	20	0.82	6.1	1.5	At Max	NR	11682	0.152	0	100	0	0
30	127.93	3.6	11836	22	2.73	5.42	5	At Max	int. exp.	3775	0.125	1	50	48	1
31	12.67	4.3	14200	20	0.82	6.1	1.5	At Max	NR	11682	0.152	0	100	0	0
32	168	0.7	12100	13.05	0.9	6.1	6.25	Partial	exposed	10464	0.1197	65.0	30.0	5.0	0
33	692	0.9	10008	27	1.9	4.5	7	Partial	NR	12300	0.25	yes	yes	yes	NR
34	51	13	7600	23	3.25	8.5	2.75	Fully	int. exp.	4690	NR	3.7	96.3	0	0
35	62.75	8.2	10000	NR	2.93	4.75	1	Fully	int. exp.	7500	0.25	yes	yes	yes	0
36	86.4	1.3	11000	30	4	7	below	Fully	remote	10714	0.25	50.0	30.0	0	20.0
37	158	0.83	10000	10.3	0.7	4.7	5	Partial	exposed	10545	0.75	35.0	60.0	5.0	0
38	210	3.8	19740	8.5	4.5	11	4.5	Fully	remote	13000	0.09	20.0	80.0	0	0
39	318	NR	12114	10	3	7.3	3	Fully	int. exp.	9500	0.125	40.0	60.0	0	0
40	201	0.9	15960	8	5.8	9.9	5	Fully	remote	9843	0.094	10	75	15	0
41	330	5.25	15600	3	7	21	6	Fully	NR	1710	0.12	60.0	40.0	0	0
42	134	3.9	17500	25.3	3.67	5.5	3.75	At Max	remote	6273	0.125	55.0	30.0	15.0	0
43	127.93	3.6	11836	22	2.73	5.42	5	At Max	int. exp.	3775	0.125	1	50	48	1
44	37.5	1.3	17610	27	3.5	9.5	2.5	Fully	int. exp.	9460	0.12	0.5	80.0	0.0	19.5
45	70	0	9625	3.7	3.5	6.83	0	Fully	NR	7497	0.132	yes	yes	yes	0
46	571	1.07	15330	NR	2.13	2.25	0	Fully	int. exp.	NR	0.25	87.0	10.0	3.0	0
47	48	0.97	13314	24	1.75	3.5	0	Fully	int. exp.	13265	0.25	31.9	8.9	42.2	17.0
48	168	0.7	12100	13.05	0.9	6.1	6.25	Partial	exposed	10464	0.1197	65.0	30.0	5.0	0
49	187.2	1.7	15600	3	8.52	14.42	8	Fully	exposed	4033	0.25	0	95.0	0	5.0
50	330	5.25	15600	3	7	21	6	Fully	NR	1710	0.12	20.0	80.0	0	0
51	150	0.62	17050	8.6	7	11.5	7	Fully	remote	7700	0.1875	9.3	31.7	59.0	0
52	210	3.8	19740	8.5	4.5	11	4.5	Fully	remote	13000	0.09	20.0	80.0	0	0
53	66	9	15600	2.9	NR	NR	5.25	Fully	int. exp.	NR	0.250	21	33	46	0
54	42.4	10.02	7600	30	5.3	5.5	6	Partial	exposed	NR	0.125	yes	yes	yes	0
55	115.4	1.01	10480	9.48	4.59	7.6	0	Fully	exposed	9310	0.09375	yes	yes	yes	0
56	37.5	1.3	17610	27	3.5	9.5	2.5	Fully	int. exp.	9460	0.12	0.5	80.0	0.0	19.5
57	39.62	17	9200	23	3.5	8	5.083	At Max	int. exp.	4930	1	1	61	38	0
58	NR	15.1	15900	8	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
59	158	0.83	10000	10.3	0.7	4.7	5	Partial	exposed	10545	0.75	35.0	60.0	5.0	0
60	108	5.6	5600	28	2.78	5.4	below	Fully	exposed	6000	0.1875	44.5	6.4	12.7	36.4
61	51	13	7600	23	3.25	8.5	2.75	Fully	int. exp.	4690	NR	3.7	96.3	0	0
62	104	1.9	16000	14	1.92	7.5	3.5	At Max	int. exp.	10823	0.3	yes	yes	yes	yes
63	93	1.5	10720	10	4.27	4.27	below	Fully	exposed	8700	0.12	20.0	75.0	5.0	0
64	28.4	9.26	15600	2.81	2.5	13.2	3	At Max	exposed	4530	0.25	0	100	0	0
65	93	1.5	10720	10	4.27	4.27	below	Fully	exposed	8700	0.12	20.0	75.0	5.0	0
66	224	0.6	15800	8	5.8	9.9	5	Fully	remote	11318	NR	0	80	20	0
67	414	3.5	17400	9.5	3.6	NR	3	Fully	remote	NR	0.25	yes	yes	0	0
68	370	2.1	15300	NR	0.5	2.75	0	Fully	int. exp.	NR	0.25	15.0	60.0	25.0	0
69	125	2.4	11000	23	2	6.7	2	Fully	NR	8832	0.25	2.0	98.0	0	0

5.2 Failure-Threshold Debris Loadings

For each parametric case, the quantity of debris that would be necessary to cause sump-screen blockage of a magnitude sufficient to affect the performance of the ECCS and/or CS pumps was calculated following the steps described below. The results from each of these steps are discussed in the following subsections.

1. Define the failure criterion, ΔH_f, in terms of pressure loss across the screen. This failure criterion was based either on $NPSH_{Margin}$ or on pool depth as described in Sec. 1.

2. Compile a list of insulations that may be potentially present on the sump screen and identify the appropriate head-loss correlations for each type when they are present on the screen individually and in combination with other debris.

3. Estimate the debris quantities required to induce failure by iteratively solving debris-bed head-loss correlations taken from NUREG/CR-6224. In other words, the amount of debris needed on the screen was determined by solving the head-loss correlations with the failure criterion, ΔH_f, assumed as the pressure drop. This step defined all combinations of fiber and particulate that could result in an assumed failure of the sump as a result of excessive pressure drop across *each* screen defined in the parametric case studies. Results from these comprehensive calculations are presented graphically in Appendix B.

5.2.1 Definition of Sump Failure Criteria

The GSI-191 Industry Survey [NEI, 1997] queried each plant licensee for information about (see Fig. 5-1)

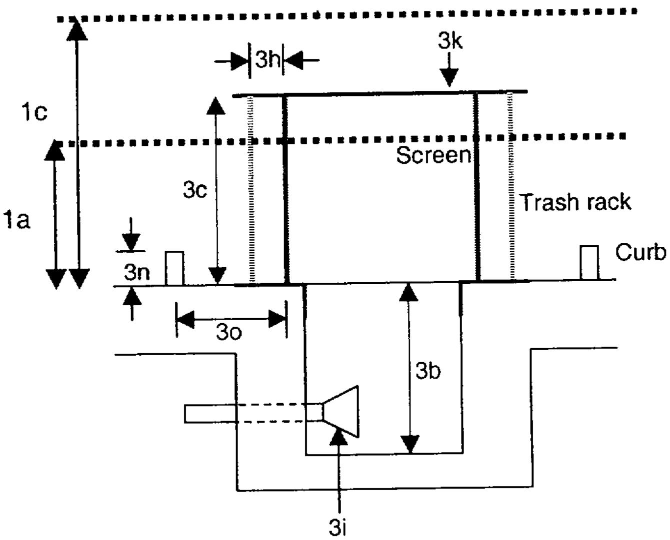
1. the height of water on the containment floor at the time of switchover following a postulated LOCA (Question 1a in survey) and
2. the height of the top of the sump screen measured from the containment floor (Question 3c in survey).

The responses were compared to identify those sumps that are expected to be fully submerged for the duration of the recirculation phase (i.e., Response 3c < Response 1a) and those that are expected to be only partially submerged (i.e., Response 3c > Response 1a). See Fig. 1-1 for schematics of submerged and partially submerged sumps.

Submerged Sumps

For completely submerged sumps, failure of the ECCS or CS was assumed to occur when sump-screen head loss exceeded the $NPSH_{Margin}$ for that pump. While applying this general criterion, some simplifications were made to address several interdependencies between various pumping systems.

- Some reactors depend on HPSI systems for core decay-heat removal during an SLOCA (e.g., a 2-in. break) and on the CS system for heat rejection from the sump. In these reactors, the HPSI pumps typically have a higher $NPSH_{Margin}$ (~10 ft) than the CS pumps (1 to 5 ft). Because the margins are so different for these systems, it is not clear what failure criterion should be used. As a first-order approximation, core damage could be assumed when the HPSI-pump $NPSH_{Margin}$ is lost. However, this approximation may not be accurate because loss of the CS system could permit the sump-water temperature to exceed the maximum temperature assumed in the HPSI-pump $NPSH_{Margin}$ calculation. The present study assumed that sump failure occurs when head loss across the screen exceeds the $NPSH_{Margin}$ of *either* of these systems. This assumption is only important for an SLOCA in some large containments, and it has little or no effect on the outcome of the MLOCA and LLOCA sequences.



Question #	Information
3a	No. of cont. sumps
3b	Sump depth
3c	Height above floor
3d	Whether it has screen
3e	Screen area
3f	Screen hole size
3g	Trash rack status
3h	Dist. between trash rack and screen
3I	Trash rack area
3j	Trash rack hole size
3k	Solid plate
3l	Vortex suppressor
3m	Debris curb
3n	Debris curb height
3o	Dist. between debris curb and screen
1a	Height of water pool on containment floor at time of switchover
1c	Maximum height of water pool on the containment floor

Fig. 5-1. Illustration of Sump Parameters Queried in the GSI-191 Industry Survey.

- In the case of sub-atmospheric containments, inside recirculation pumps switch on within minutes after an LLOCA or MLOCA. During this time, the containment pool is very turbulent and debris is expected to be in suspension. As a result, these pumps may fail from debris blockage long before ECCS switchover occurs. Again, it is not clear what head-loss criterion should be used to determine success or failure. Sensitivity analyses suggest that this is not a major issue because both the inside recirculation pumps and the LPSI/CS pumps have approximately the same $NPSH_{Margin}$. The present study assumed sump failure when screen head losses exceeded the LPSI $NPSH_{Margin}$.

- Parametric analyses for all break sizes used NPSH margins estimated by the licensees for LLOCA flow conditions, and their calculations credit sources of water that would not be available for a MLOCA or SLOCA. Examples of these sources include water from accumulators and from the RCS inventory. As a result, the NPSH margins available following an SLOCA and MLOCA may actually be lower than the favorable values adopted here. However, it is likely that other conservatisms in the licensee estimates (e.g., no containment overpressure credit) partially compensate for these differences.

Partially Submerged Sumps

In the case of partially submerged sumps, failure was assumed if the screen head loss exceeded either (a) the $NPSH_{Margin}$ defined as discussed above or (b) 1/2 the pool height reported in response to Question 1(a) of the Industry Survey. A set of the parametric cases with screens that are only partially submerged at ECCS switchover and whose failure criteria are limited by the pool depth rather than by the $NPSH_{Margin}$ is shown in Fig. 5-2. Each case is described by a group of three vertical bars. The first bar shows the limiting $NPSH_{Margin}$ reported in the survey; the second bar shows the failure criterion, ΔH_f, that would be assumed for the parametric case if the pool were at maximum depth; and the third bar shows the failure criterion that would be assumed for the pool depth at ECCS switchover. Failure criteria for *all* parametric calculations were defined based on the pool depth at switchover (third bar for these cases) because any significant debris transport will occur during recirculation at this depth and because maximum pool depths may only be reached much later in the accident sequence. It is clear from Fig. 5-2 that a partially submerged sump is much more vulnerable to failure by blockage than if the same screen is fully submerged.

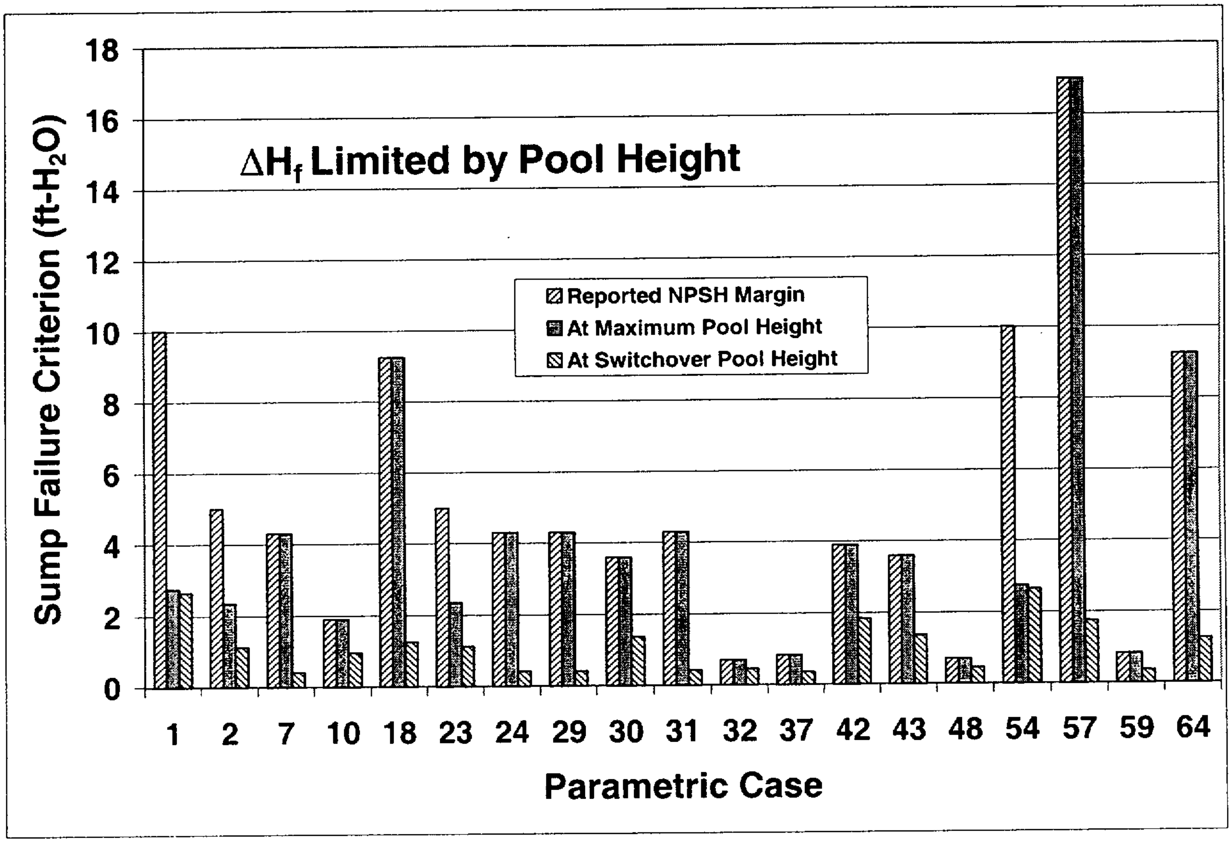


Figure 5-2. Effect of Partial Sump-Screen Submergence on Sump Failure Criterion.

Full or partial screen submergence also affects the area available for debris deposition, and it determines the water velocity through the screen for a constant volumetric flow rate. The screen area covered by the pool will be referred to as the "wetted" screen area. Larger wetted areas reduce the concern for blockage because (1) the screen-surface water velocities are lower, which reduces both debris transport and debris-bed head loss and (2) larger screens can accommodate more debris for the same thickness of bed. Wetted areas for all parametric cases with screens partially submerged at ECCS switchover are shown in Fig. 5-3. Again, each case is described by a group of three bars as defined for Fig. 5-2. Note that 13 of 25 cases transition from partially submerged to fully submerged as the pool fills to maximum depth (bars 2 and 3 equal) and that several plants reported screen areas that will never be covered by water (bar 1 > bar 2).

Wetted screen area and the assumed sump failure criterion, ΔH_f, are both important metrics used to determine the potential for debris blockage. Typically, both lower wetted area and lower available head increase the concern. Figure 5-4 plots the values assumed for these parameters in each case study. Note that many of the points represent multiple cases with nearly equivalent sump conditions.

This figure demonstrates that numerous parametric cases have combinations of low ΔH_f *and* small screen area and that most cases have failure conditions of less than 6 ft-water and screen areas less than 200 ft^2.

5.2.2 Types of Debris Expected to Reach the Sump

Information regarding the types of debris present in containment was used in the head-loss model to estimate FTDLs for each case. Table 5-1 provides the proportions of each insulation type that were assumed to be present in the containment. As explained in Sec. 3, any debris generated and transported to the screen was assumed to have the same proportional composition. This implies that the insulation is distributed homogeneously throughout the containment when, in fact, important spatial dependencies have been observed in the detailed volunteer-plant data. A generic debris type referred to here as "particulate" augments the reported insulation list. This type is used to represent particulate debris that is expected to be either present in the containment at the time of a LOCA or generated during the course of the LOCA progression. Reasonable particulate loadings on the sump screen range from 10 to 125 lbm.

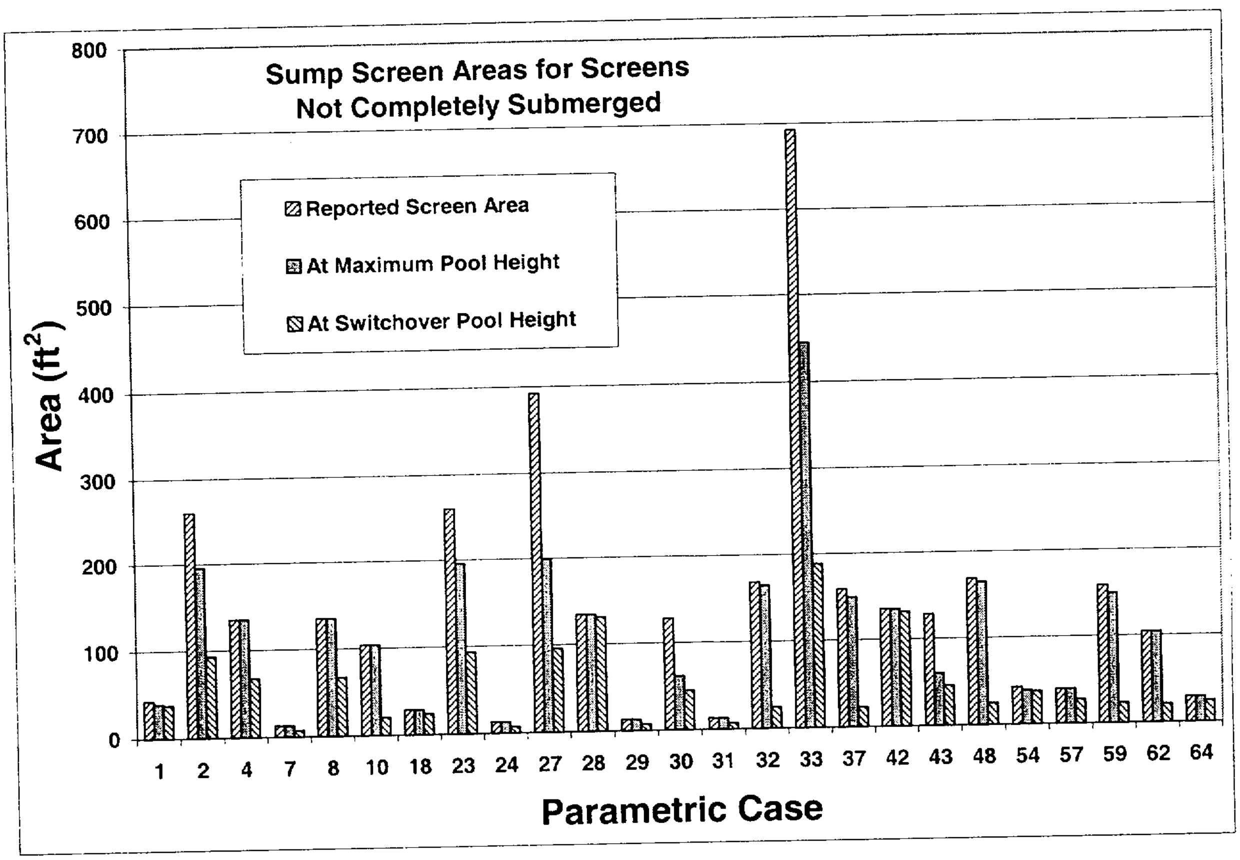


Fig. 5-3. Impact of Pool Submergence on Sump Screen Area.

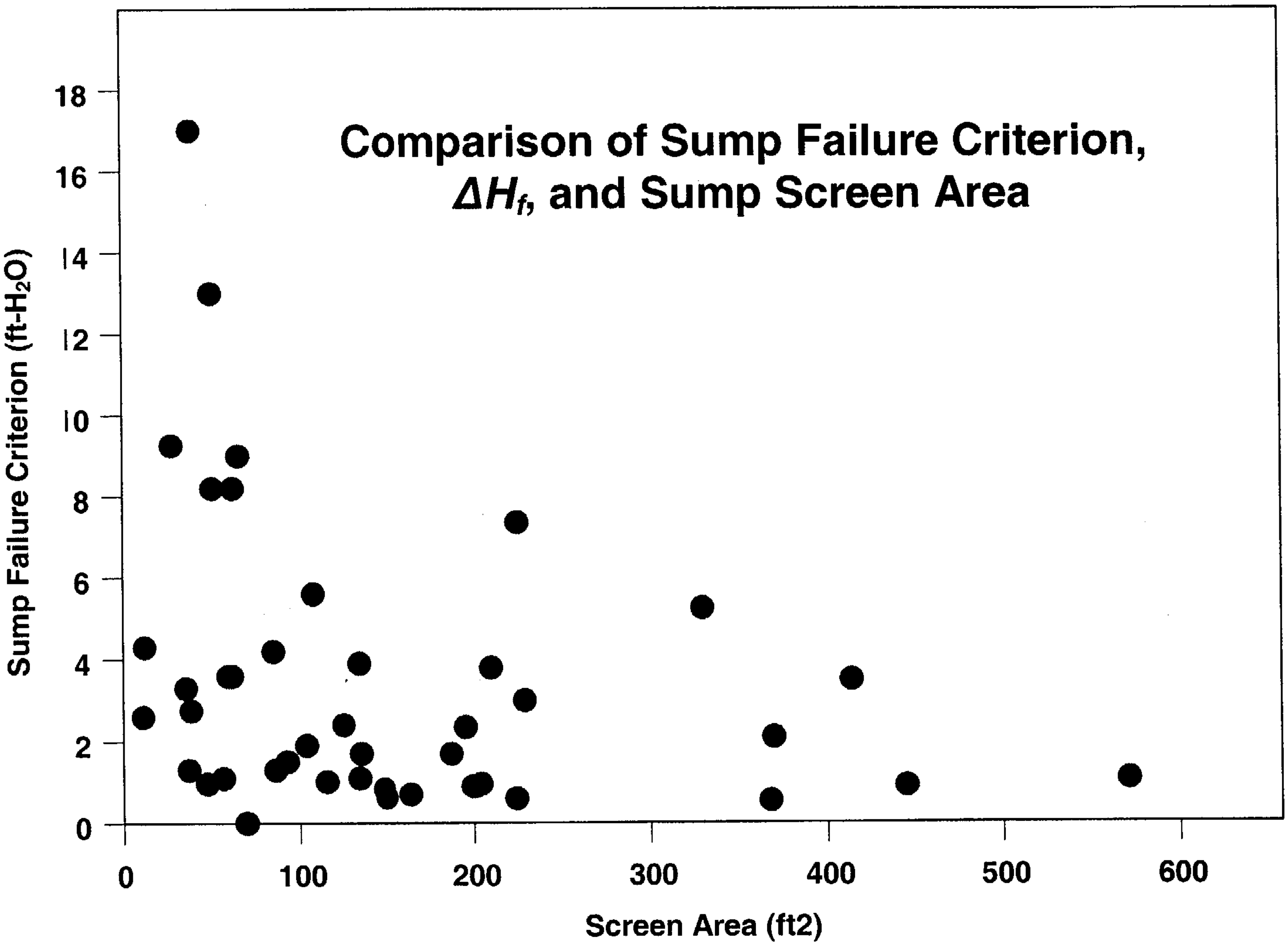


Fig. 5-4. Comparison of Sump Failure Criteria and Sump Screen Areas for All Parametric Cases.

5.2.3 Failure-Threshold RMI Debris Loading

For each parametric case, the threshold stainless-steel[39] RMI quantity needed on the screen to induce sump failure is shown in Fig. 5-5 for both an SLOCA (dark bars in back) and an LLOCA (light bars in front). Also plotted on the figure are the estimated volumes (from Table 3-3) of insulation that may be damaged by the corresponding ZOI (assuming an insulation composition of 100% RMI) and the quantities of foil expected to be separated from the cassettes.[40] Note that the amount of RMI debris needed to block the sump is always greater for an SLOCA than for an LLOCA because the recirculation flow velocities are lower, and thus, the debris bed must be thicker to cause the same head loss. Case number 45 is unique because it has such a low $NPSH_{Margin}$ that very small amounts of debris will fail the sump (bar not shown in figure).

For an LLOCA, failure-threshold RMI debris volumes range between 1 ft^3 and 3 x 10^4 ft^3. Considering that the maximum quantity of RMI-foil shreds generated in a LLOCA ZOI would be approximately 560 ft^3, blockage by RMI debris is unlikely for most parametric cases unless the transport fraction to the sump exceeds about 0.18 (100 ft^3/560 ft^3). Several additional arguments eliminate many of the remaining cases.

(1) Few have large proportions of RMI insulation in containment.
(2) The ZOI may be smaller for some RMI types than the 12D zone assumed here, so the volume of RMI debris may be overestimated.
(3) Bulk flow velocities in excess of 0.4 ft/s would be necessary to transport RMI debris on the floor, making RMI one of the least transportable debris types expected in containment.
(4) Screen approach velocities in excess of 1 ft/s are required for upward movement of debris near a curb [Maji, 2000].

For an SLOCA, the above arguments are even more severe, and only a very small subset of the parametric cases needs to be examined for potential RMI blockage. This subset may include cases 45, 32, 37, 48, and 59.

Realistically, plant susceptibility to RMI debris is unlikely to be an industry-wide concern and is probably only valid for a small subset of the parametric cases that have (a) large volumes of RMI insulation, (b) exposed sump locations with horizontal screens at or below floor level, and (c) no curbing surrounding the sump.

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[39] The GSI-191 survey suggests that PWRs exclusively used stainless-steel RMI on the primary piping. A few plants used aluminum RMI on the reactor vessel, but that is not a major source of debris in the present evaluations. Therefore, the analyses and conclusions stated here should not be extrapolated to all types of RMI.

[40] Debris generation testing has shown that approximately 33% of damaged cassettes are reduced to shredded foil [BWRORG, 1998].

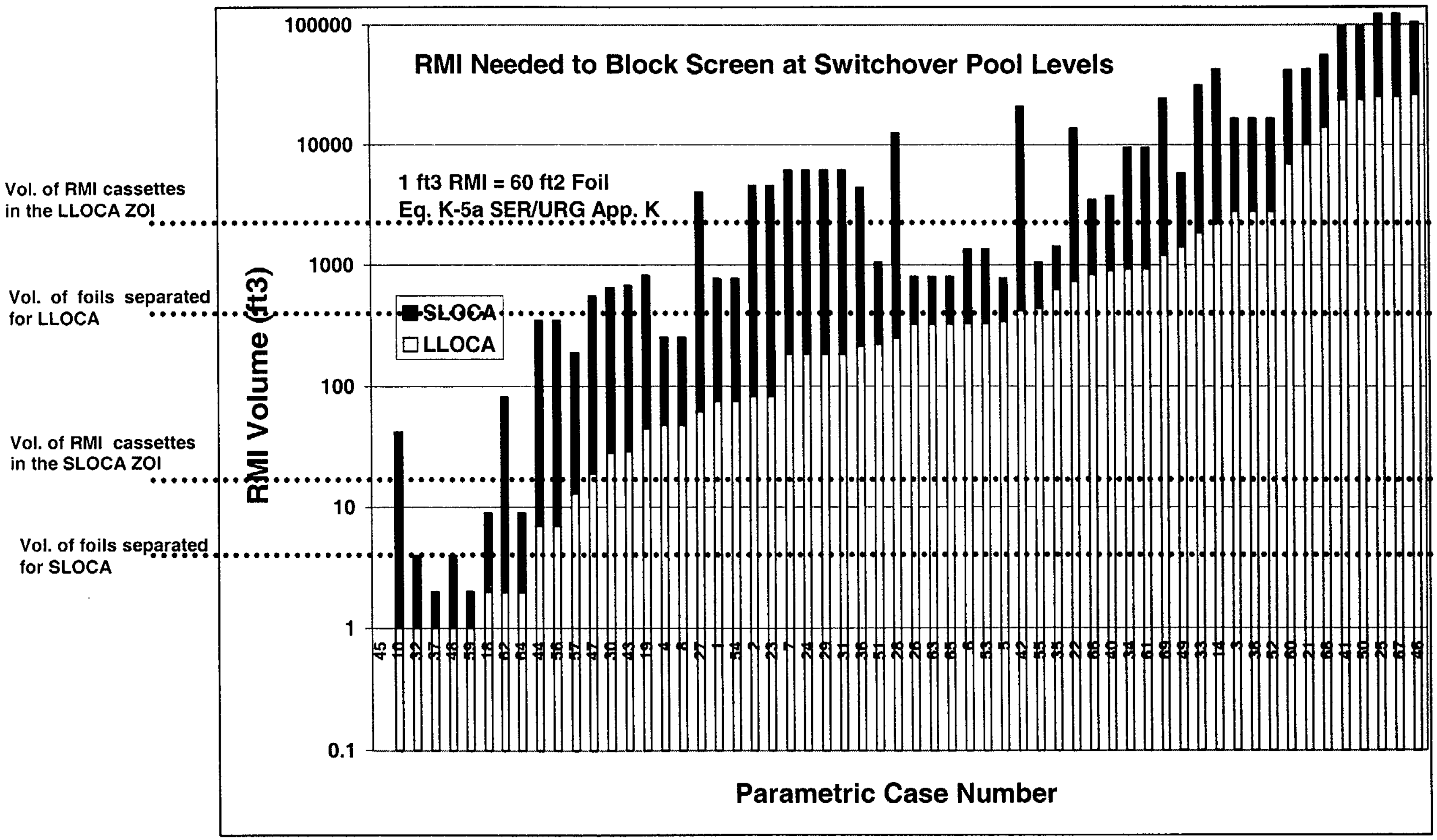

Fig. 5-5. Failure-Threshold RMI Debris Loading for Each Parametric Case.

5.2.4 Threshold Quantities for Fiber and Particulate Accumulation

For each parametric case, the threshold fiber and particulate quantities necessary to induce blockage were calculated. Appendix B presents these results graphically, and this section provides a summary of the findings.

Testing and calculations confirm that blockage can occur in one of two ways.

1. The first and most likely means for blockage involves formation of a thin fibrous bed on the screen, which then filters incoming particulates. Tests performed as part of the BWROG study demonstrated that beds with a nominal thickness of 1/8 in. could filter significant fractions of debris approaching the strainer and induce large differential pressure drops.[41] The filtration of particulates by thin layers of fiber (the "thin-bed effect") is the most limiting mechanism for sump blockage for many plants, especially following an SLOCA because (a) relatively small quantities of fibers are necessary to build a 1/8-in.-thick debris layer on the screen surface, (b) large quantities of particulate debris are already present in containment in the form of resident dirt and dust, and (c) significant quantities of particulate debris can be generated as a result of a LOCA.

2. The second mechanism for blockage involves formation of a thick-cake fiber layer on the surface with minimal particulates present. Tests performed as part of the BWROG study demonstrated that substantial head losses can be induced by pure fiber beds. Pure fiber beds are not realistic for a PWR LOCA accident scenario given the resident dust and the potential to damage particulate insulation types, but they are included in this discussion to demonstrate that blockage concerns are not driven solely by the presence of particulates.

Recent preliminary tests suggest that a screen clearance of 1/8 in. also can be obstructed by cal-sil granules alone without the presence of a fiber mat for enhanced filtration. Further testing is required to determine the sump conditions under which this blockage mechanism may be a concern, so it was not considered in the parametric analyses. Thus, if the minimum fiber needed for a 1/8-in. bed is not present, the sump was assumed to function adequately with any mass of particulate loading.

Figure 5-6 provides estimates for the volume of fibrous debris needed to build a 1/8-in.-thick contiguous debris bed on the wetted screen surface. For most parametric cases, this is the minimum quantity of fiber that would be necessary to cause sump failure if it were combined with a sufficient mass of particulate. Cases with large, partially submerged screen areas can accommodate more fiber as the water level rises (dark bars in background). Note that at switchover pool levels, over half of the cases can tolerate less than 1 ft^3 of fiber debris if sufficient particulate is present in the pool. Figure 5-7 presents the associated particulate masses necessary to cause sump failure in combination with the minimum fiber volume. Note that the first nine cases can fail on the minimum fiber loading alone without any contribution from particulates, and over half of the cases can fail with less than 50 lb of particulate on the minimum fiber bed, even for SLOCA flow conditions.

Figures 5-8 and 5-9 present, respectively, the cumulative distributions of the same data that are presented in Figs. 5-6 and 5-7. The cumulative distribution of minimum fiber volume (Fig. 5-8) simply shows the total number of parametric cases with minimum fiber volumes less than or equal to any value of interest. The cumulative distribution of failure-threshold particulate mass is similar except that ranges

[41]The ongoing GSI-191 study performed several tests to confirm the validity of this assumption for PWRs where some sump screens are oriented vertically and in some cases the screen clearance is as large as ¼ in. Section 3 discusses the experimental findings, which essentially are (a) uniform and contiguous LDFG debris layers can form at nominal thicknesses as low as 1/10 in., (b) these beds can filter significant quantities of cal-sil and other particulate debris, and (c) filtration can cause large pressure drops across an obstructed screen.

are provided to illustrate the number of cases that would fail at a given particulate loading under both favorable and unfavorable head-loss conditions.

From these two cumulative plots, the following conclusions can be drawn.

1. The minimum amount of fibrous debris necessary to cause sump failure varies from 0.25 ft^3 to 6 ft^3. This range is a direct reflection of variability in sump-screen areas across the PWR population. As shown in Fig. 5-8, transport and accumulation of approximately 1/2 ft^3 of fibrous material would be sufficient to raise blockage concerns for approximately 20 parametric cases; this number reaches 40 when the fiber volume is increased to 1 ft^3. As discussed in later sections, these are very small volumes compared with the quantity of debris that might be generated following a LOCA.

2. The failure-threshold particulate debris mass ranged from 2 lb to 175 lb for a LLOCA and from 5 lb to 300 lb for an SLOCA. For each break size, the ranges are a strong function of the variability in screen areas, and the difference between the two break sizes is caused primarily by the different recirculation water demands of the two accident scenarios. As shown in Fig. 5-9, a particulate loading of approximately 10 to 20 lb is adequate to meet the sump failure criteria for about 30 of the parametric cases, even following an SLOCA.

In summary, calculations of head loss for mixed debris beds on the sump screens of each parametric case indicate that the potential for blockage by a combination of fibrous and particulate debris is high. Because of the very small quantities of debris required in many cases to exceed the sump failure criteria, careful consideration of the potential fiber and particulate debris sources is needed.[42]

[42]In this context, it should be recognized that several of the BWR precursor events in the U.S. involved miscellaneous fiber sources such as air-handling-unit (AHU) filters.

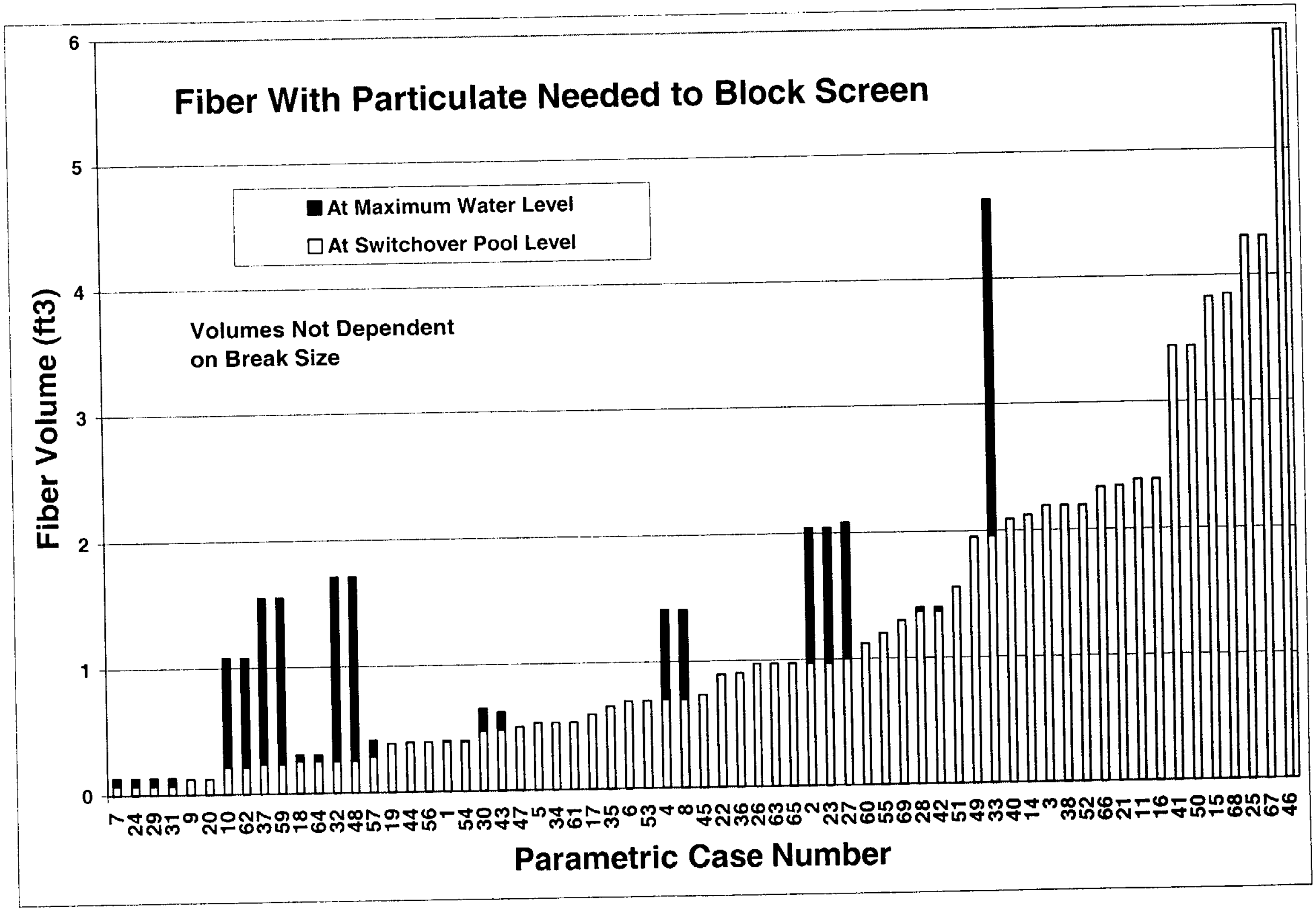

Fig. 5-6. Failure-Threshold Fiber Debris Loading for Each Parametric Case.

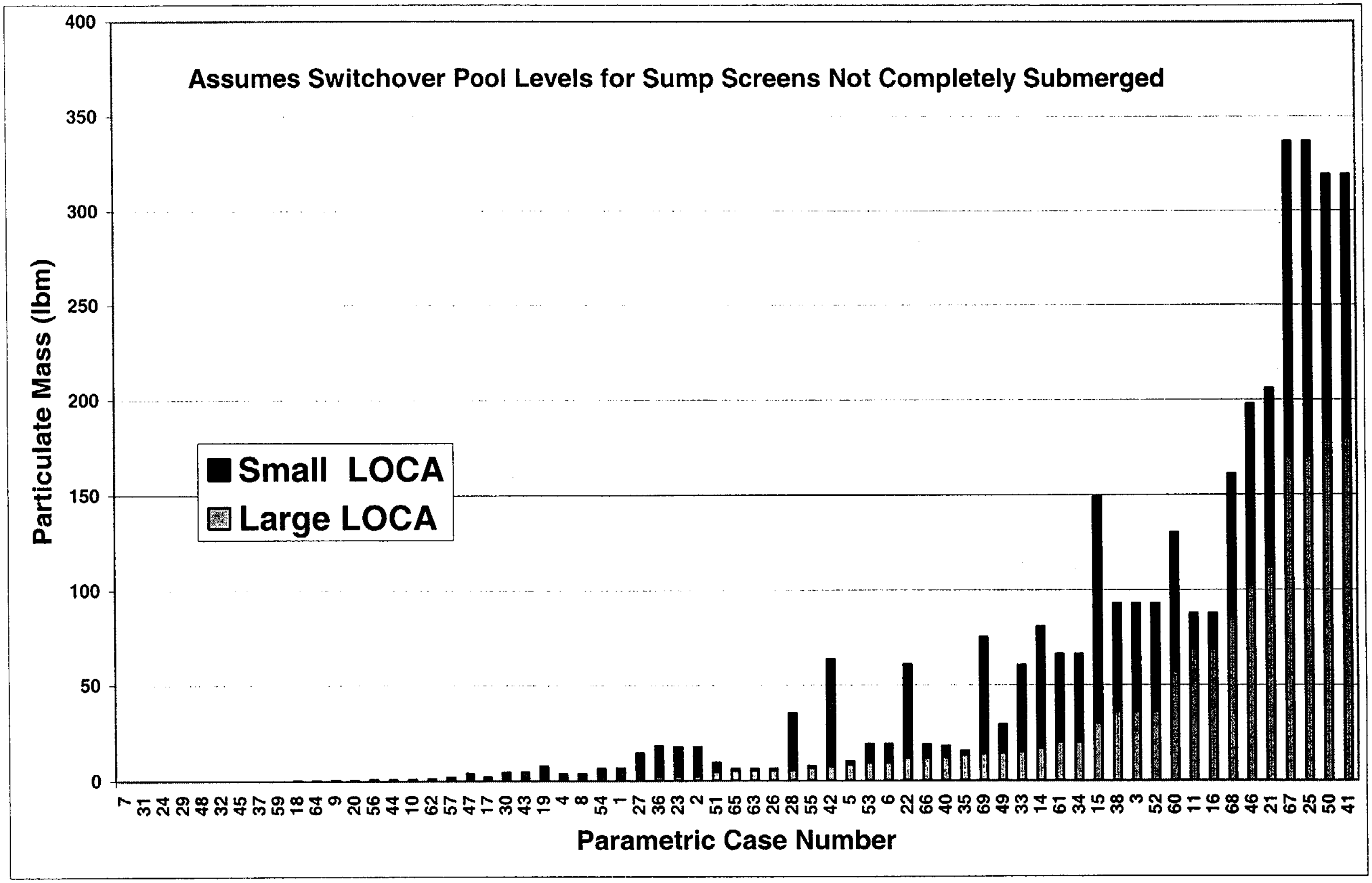

Fig. 5-7. Failure-Threshold Particulate Debris Loading for Each Parametric Case.

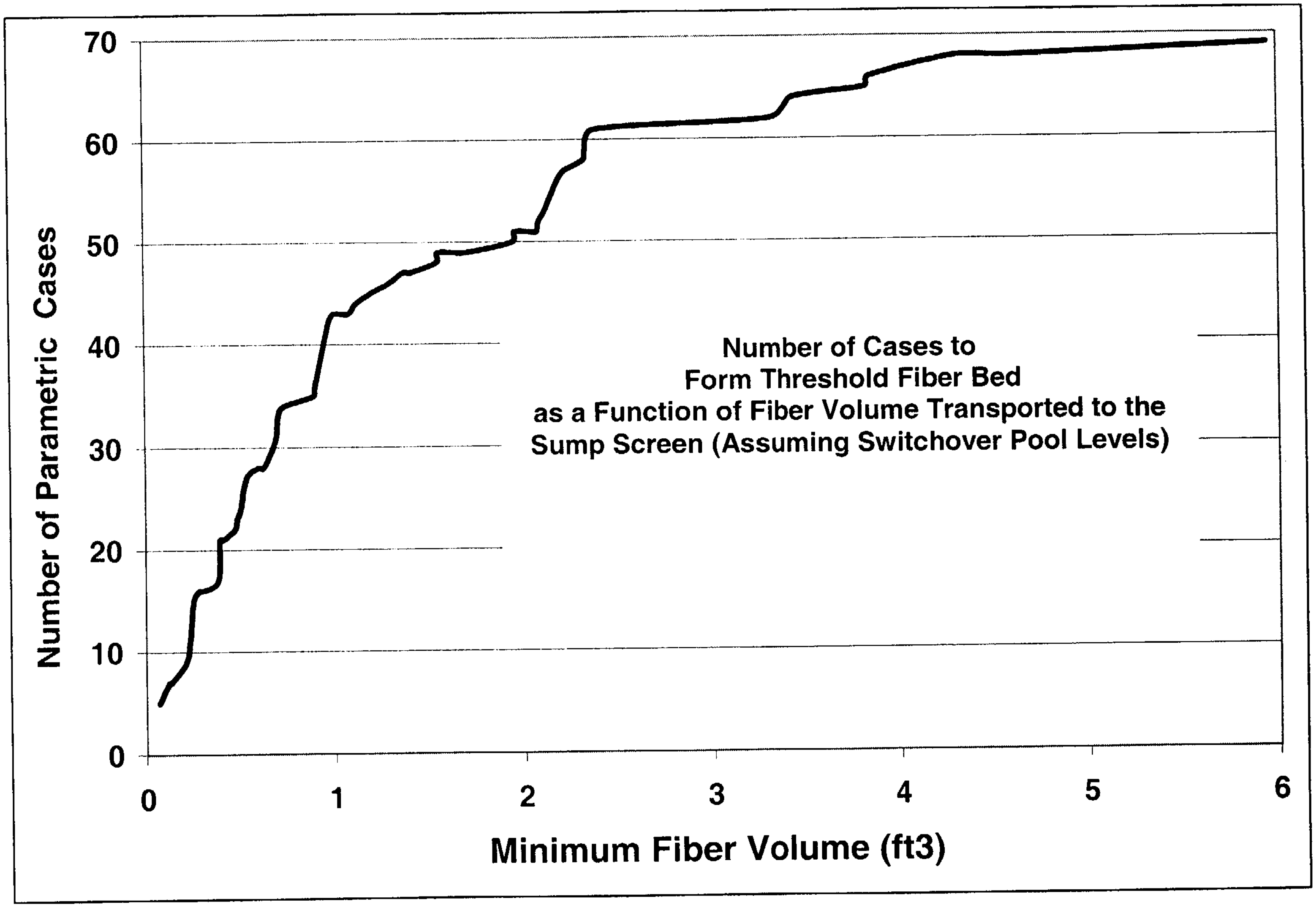

Fig. 5-8. Cumulative Distribution of Failure-Threshold Fiber Volume.

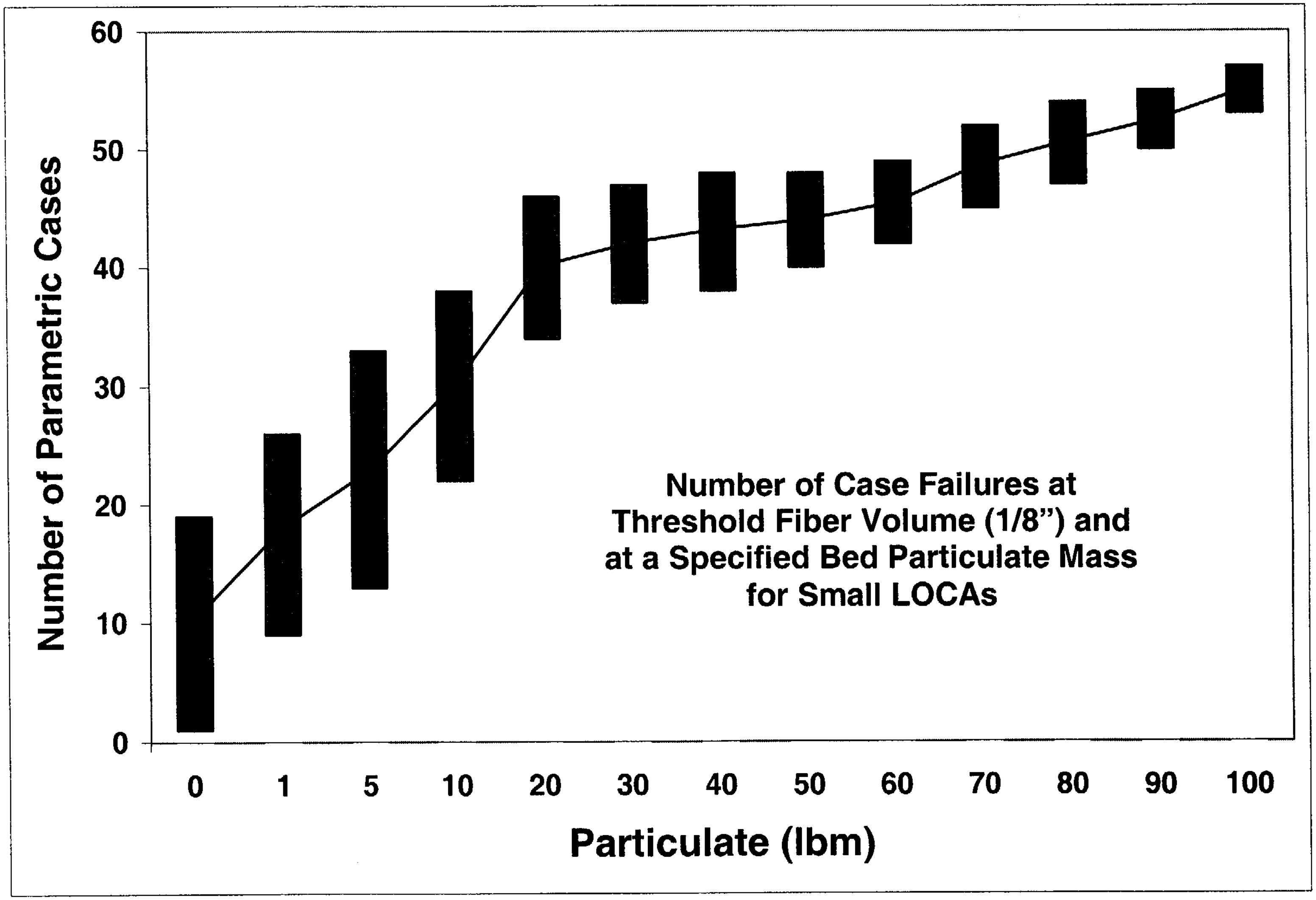

Fig. 5-9. Cumulative Distribution of Failure-Threshold Particulate Mass Corresponding to an SLOCA.

5.3 Quantity of Debris Expected to Accumulate at the Sump

Sources of Debris and Estimates for Volumes

Table 5-2 presents "generic" estimates for the quantity of insulation contained in the ZOI for each of the postulated break sizes. It should be noted that these values are not "bounding" estimates,[43] but rather are 95th percentile values as shown in Table 3-2. Section 3 provides further calculational bases for these estimates. In addition to debris generated by a break jet, there may be a significant inventory of dust and dirt in containment that represents an additional source of particulate debris. Table 5-2 includes a range of reasonable estimates of this inventory that are based on considerations of total surface area and dust-layer thickness.

Table 5-2. "Generic" Estimates of Insulation and Noninsulation Debris Volumes.

Break Size	Insulation Debris ZOI Inventory (ft^3)	Miscellaneous Particulate Debris in Containment (lbm)	
		Favorable	Unfavorable
SLOCA	25	100	500
MLOCA	40	100	500
LLOCA	1700	100	500

The next and final step in estimating the insulation debris source term is to proportion the ZOI volumes given in Table 5-2 according to the insulation fractions. Containment-averaged insulation fractions were provided by the licensees as part of the GSI-191 survey (Questions 5c and 5d). The following uncertainties exist in the debris generation estimates.

1. The ZOI estimates are based on interpretations of very preliminary debris generation test data obtained for cal-sil and preformed fiberglass blankets.

2. Case studies for the GSI-191 plants have shown that a majority of SLOCAs generate debris volumes substantially lower than the 25 ft^3 assumed above; however, the higher value was chosen to compensate for the fact that proportioning the ZOI volume by the insulation fractions tends to underestimate the quantity of fibrous or cal-sil debris generated because these insulation types are typically located on smaller pipes. Thus, the local proportion of fiber near a small break may be much higher than the containment-averaged proportion. This is not a major issue for the LLOCA or MLOCA, where sufficiently large quantities of debris are generated by most breaks and the ZOIs are, in general, large enough to envelop a large portion of the insulation in containment.

3. The only debris source other than insulation that was credited in the present calculation was "miscellaneous particulates." A "generic range" of 100 lb to 500 lb was used with a "favorable" estimate of 100 lb and an "unfavorable" estimate of 500 lb. DBA models for zinc and aluminum oxidation and paint dust inventories from the SRS study indicate a potential for the generation of significantly higher quantities of particulate.

[43]Limiting debris volumes were estimated as 28 ft^3, 50 ft^3, and 1900 ft^3 for the SLOCA, MLCOA, and LLOCA, respectively.

Minimum Transport Fraction

Another metric that is very useful to judge the relative potential for sump blockage is the minimum transport fraction required for failure. This figure of merit is a measure of the smallest fraction of debris present in the ZOI that would have to be transported to the sump screen before the FTDL is attained. This parameter is defined as

Min Transport Fraction = Threshold Debris Volume / Generated Debris Volume.

Figures 5-10 through 5-15 present the estimated minimum transport fractions for fibrous and particulate debris corresponding to LLOCA and SLOCA breaks. Figures 5-10 and 5-11 present SLOCA failure-threshold transport fractions for each parametric case for fiber and particulate, respectively. Figure 5-12 presents the minimum LLOCA particulate transport fraction for each case, but minimum fiber transport fractions for LLOCA were not illustrated because they were lower than 10% for all parametric cases. Figures 13 through 15 present the corresponding information in a cumulative format so that it is convenient to read the number of plants affected by transport fractions up to any value of interest. For example, Fig. 5-13 shows that sumps would fail in a SLOCA for 15 of the 60 parametric cases that contain fibrous insulation if the fiber transport fraction reaches 0.1 (10%). Further examination of these figures suggests the following conclusions.

- Very small fractions of the fiber debris generated (i.e., ZOI insulation volume) coupled with very small fractions of resident particulates would be necessary to cause blockage following a LLOCA. As shown in the cumulative distribution plots, 10% transport is sufficient to block the sump screens of virtually all the parametric cases in which fibrous insulation is present.

- Minimum sump-failure transport fractions for an SLOCA are higher than those for an LLOCA and in some cases reach nearly 100%. This is a reflection of the fact that SLOCAs have small ZOIs and lower recirculation flow rates. (Another issue is that HPSI systems generally tended to have larger $NPSH_{Margins}$).

Debris Transport:

Assessments over all parametric cases of the minimum transport fraction required to induce sump failure facilitate a comparison between the transport fractions of concern (minimum required for failure) and the transport fractions that are plausible under various accident scenarios. For example, if all parametric cases required that 90% of the generated debris be transported to the screen before failure occurred, then the industry-wide vulnerability would be very low because very few transport mechanisms are that efficient and the FTDLs would never be reached. However, a significant number of parametric cases were found to be vulnerable to transport fractions below 10%. Variability in the accident scenarios (particularly for SLOCAs) and limitations in the ability to predict detailed debris transport phenomena make it impossible to prove that transport fractions of 10% cannot occur. Recent transport testing has demonstrated that transport fractions of up to 25% are possible for some configurations of sump location, debris location and flow rates. Therefore, the favorable and unfavorable fractions defined in Table 5-3 were selected as reasonable values to use in this study. Section 3 discussed the fidelity of these estimated transport fractions in greater detail.

Table 5-3. Transport Fractions Used in the Parametric Study.

Transport Conditions	Favorable Transport Conditions	Unfavorable Transport Conditions
SLOCA with sprays inactive	5%	10%
SLOCA with sprays active All MLOCAs and LLOCAs where sprays would automatically activate	10%	25%

Debris Accumulation

The debris generation quantities and the transport fractions in Table 5-3 determine the ranges of debris masses expected to accumulate on the screen following a LOCA. These quantities are shown in Tables 5-4 and 5-5 for fiber and particulate debris, respectively. Note that cal-sil is listed in mass units to indicate that it was treated as a particulate. (The density of cal-sil is nominally about 100 lb/ft^3). Parametric case-specific plots in Appendix B compare the ranges of debris that might accumulate on the screen with the ranges necessary to cause sump failure.

Head Loss

All debris reaching the sump was assumed to be uniformly mixed and evenly spread across the screen. This assumption was validated for several different approach velocities and screen orientations as described in Sec. 3.

Head loss estimates were based on the research and experience associated with the resolution of the BWR strainer blockage issue. For fibrous debris beds, the NUREG/CR-6224 correlation was used. This correlation has been verified for (a) fibrous debris of different types (e.g., Nukon, ThermalWrap, or Kaowool) and (b) miscellaneous particulates (e.g., sludge). This correlation has not been validated for application with cal-sil debris or for use with some other types of miscellaneous debris. As shown in Sec. 3, this approach considerably underpredicts the effect of cal-sil by as much as an order of magnitude.

Table 5-6 presents the head-loss estimates obtained under favorable assumptions and unfavorable assumptions for the SLOCA, MLOCA, and LLOCA for all parametric cases.

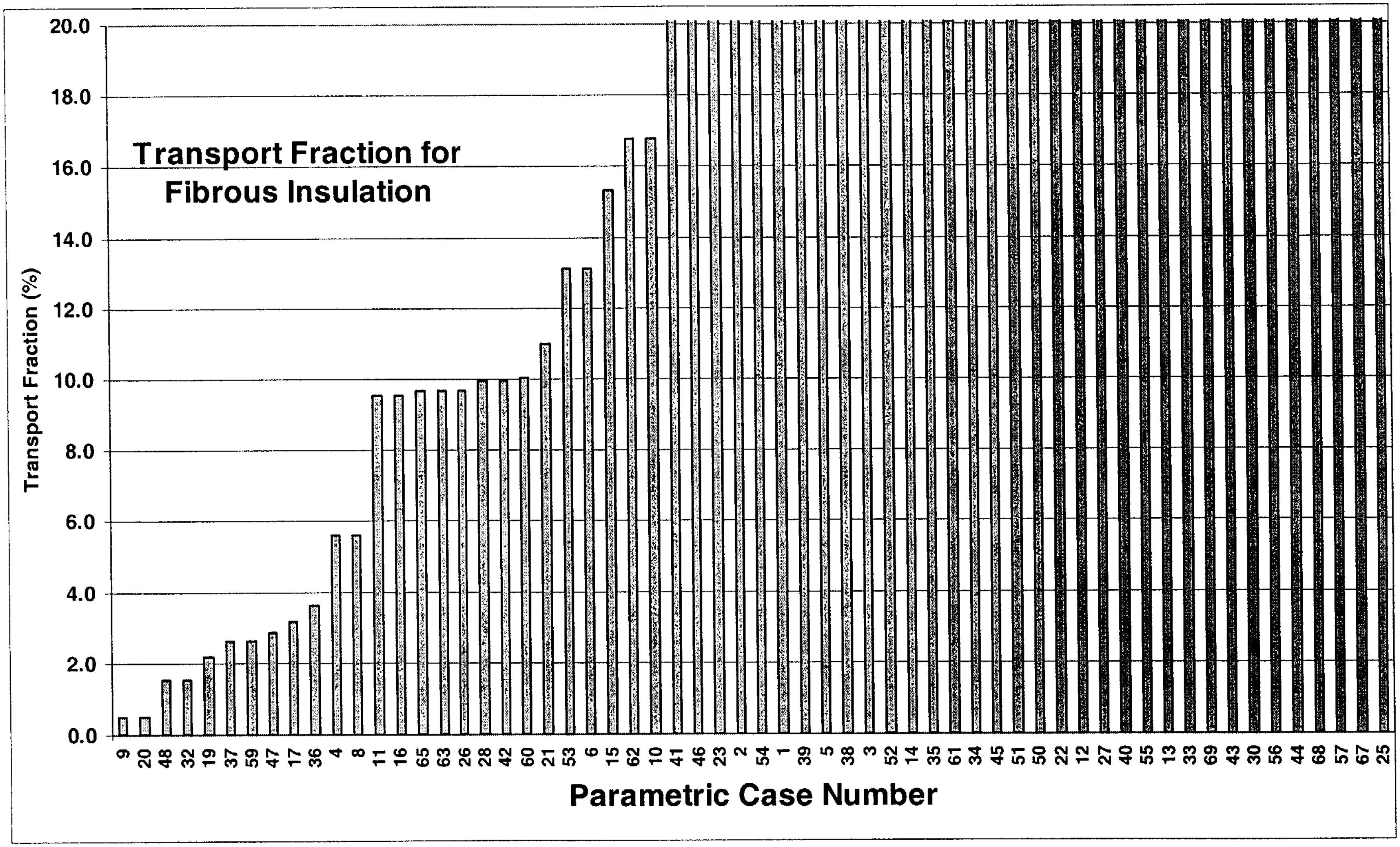

Fig. 5-10. Transport Fraction for Minimum Fibrous Insulation Volume for SLOCA.

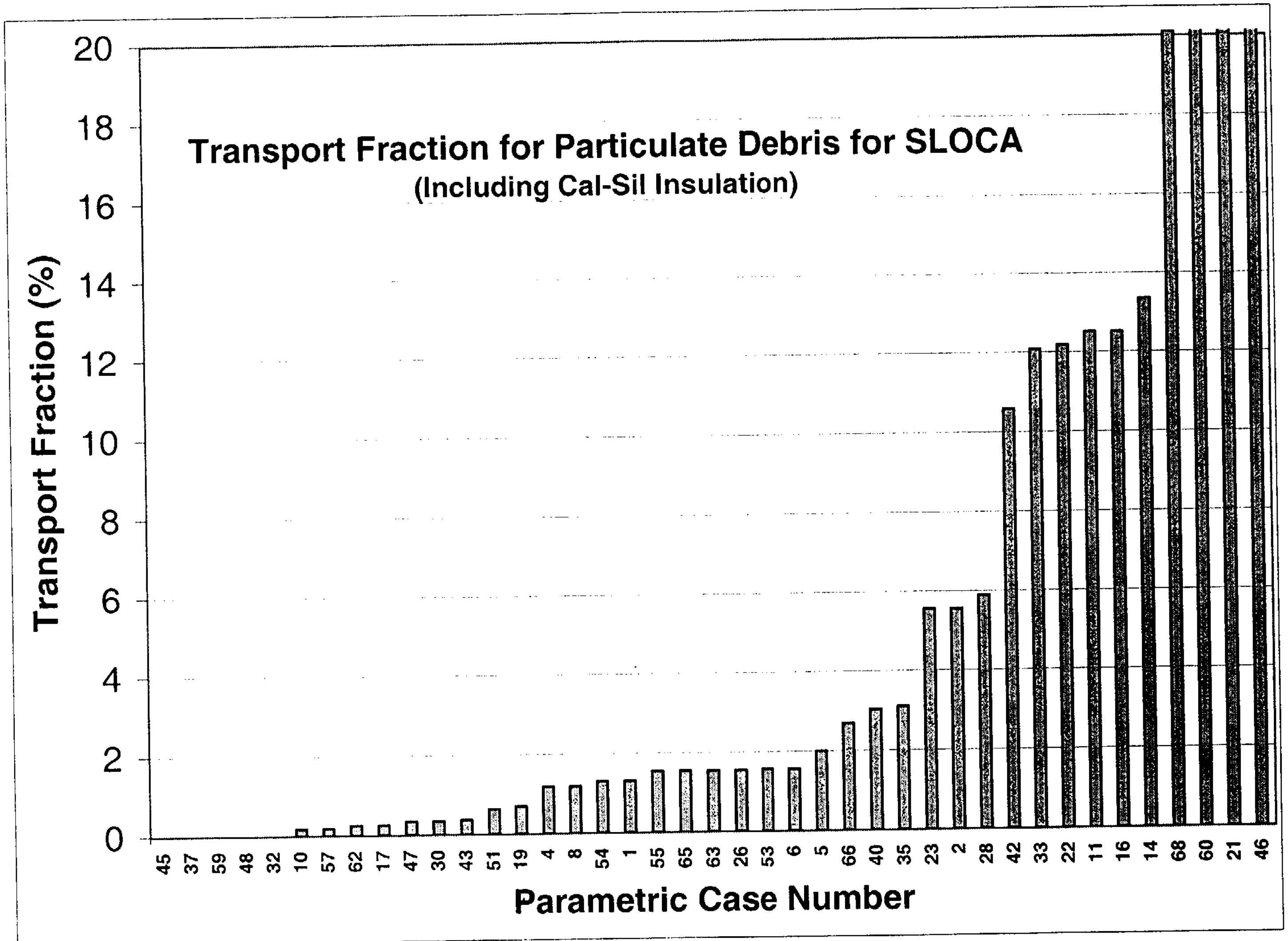

Fig. 5-11. Minimum Transport Fraction for Particulate Debris Corresponding to SLOCA.

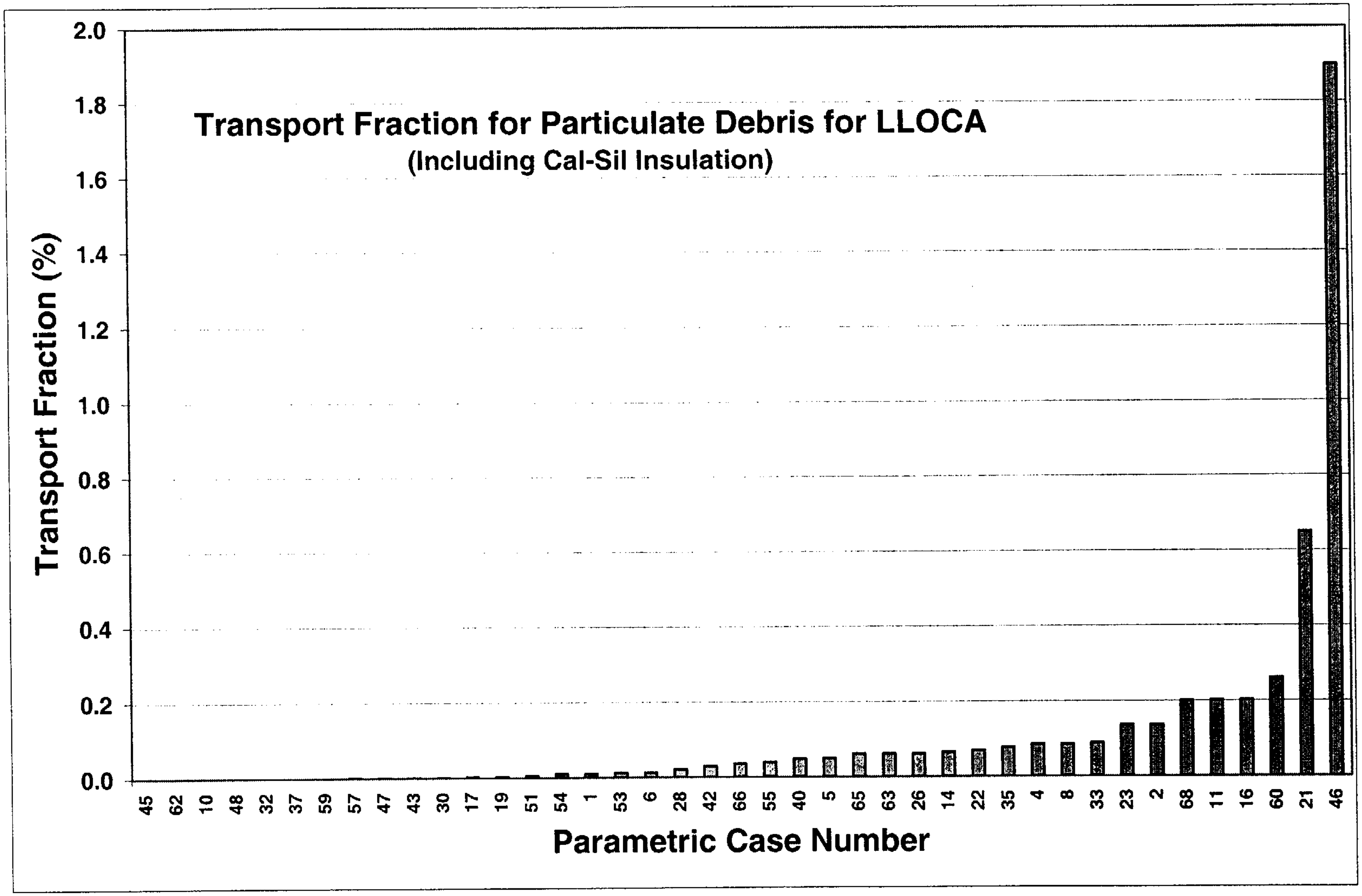

Fig. 5-12. Minimum Transport Fraction for Particulate Debris Corresponding to LLOCA.

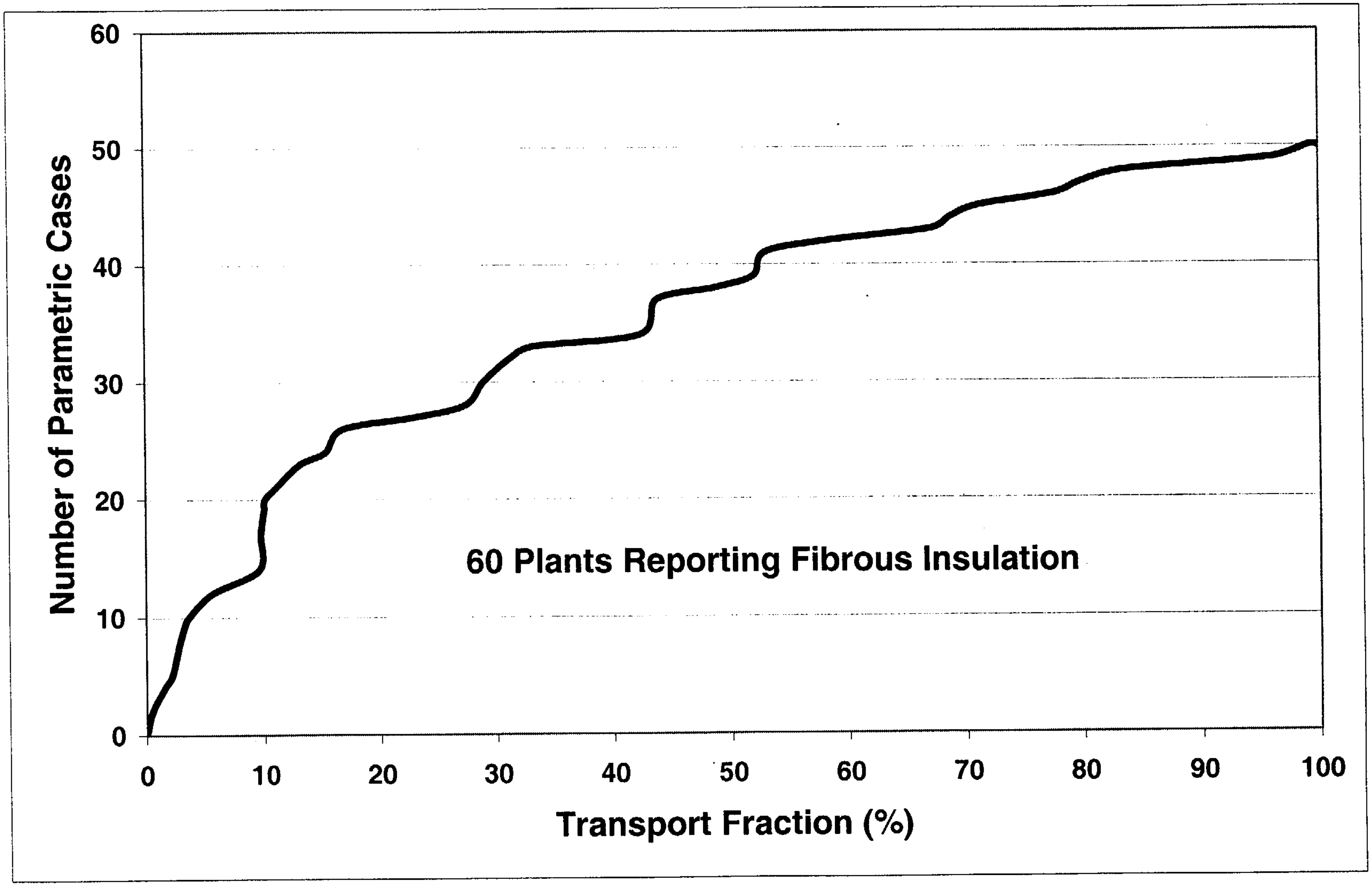

Fig. 5-13. Cumulative Distribution of Minimum Transport Fraction for Fibrous Insulation for SLOCA.

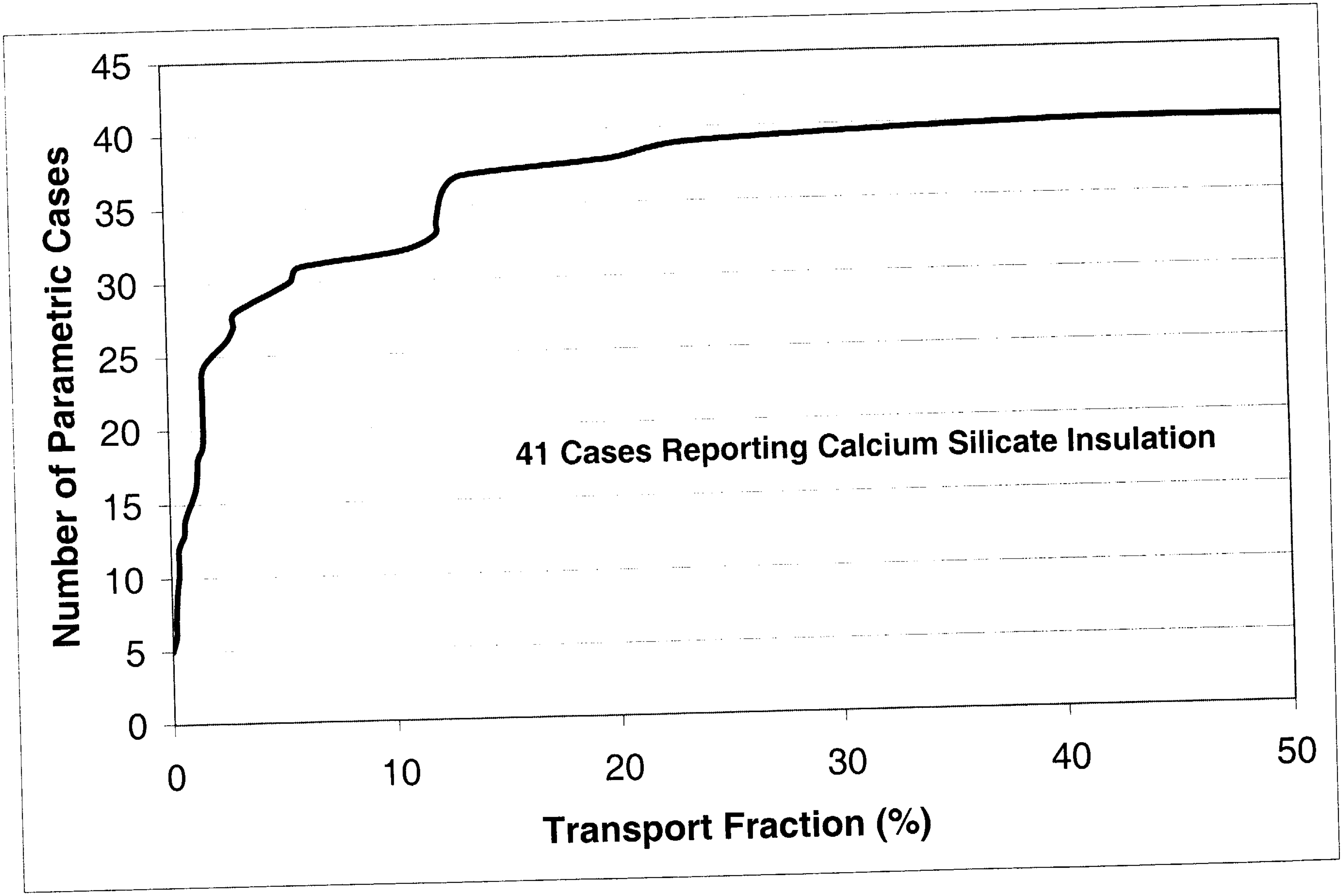

Fig. 5-14. Cumulative Distribution of Minimum Transport Fraction for Particulates Corresponding to SLOCA.

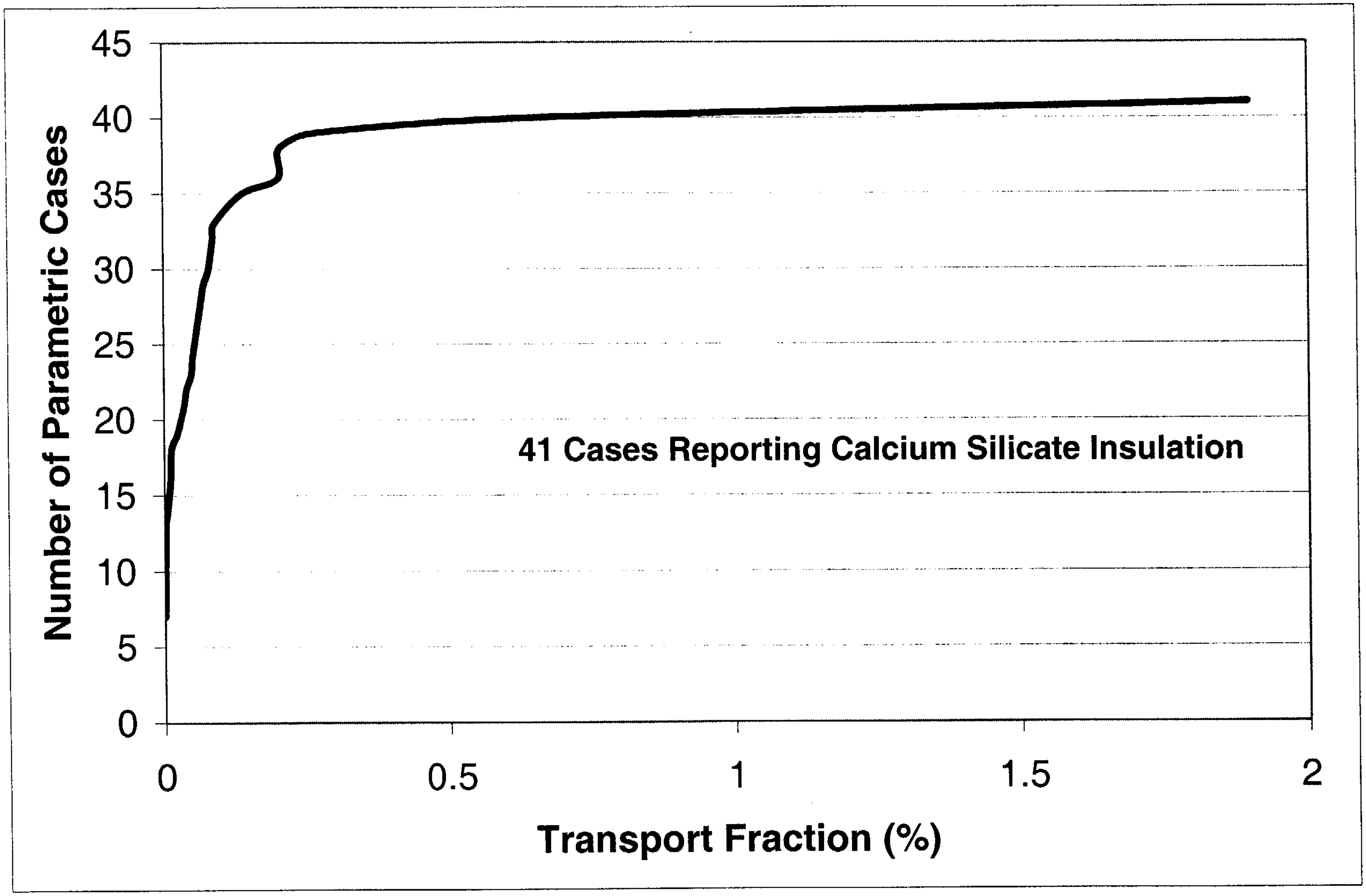

Fig. 5-15. Cumulative Distribution of Minimum Transport Fraction for Particulate Corresponding to LLOCA.

Table 5-4. Fiber Debris Volumes on Screen (ft^3).

	SLOCA		MLOCA		LLOCA	
Case	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
1	0.06	1.25	0.2	5	8.5	212.5
2	0.17	0.34	0.54	1.34	22.78	56.95
3	0.5	1.25	0.8	2	34	85
4	1.25	3.12	2	5	85	212.5
5	0.12	3.12	0.2	5	8.5	212.5
6	0.52	1.31	0.84	2.1	35.7	89.25
7	0	0	0	0	0	0
8	1.25	3.12	2	5	85	212.5
9	1.25	2.5	4	10	170	425
10	0.06	1.25	0.2	5	8.5	212.5
11	2.5	6.25	3.2	8	136	340
12	0.12	6.19	0.2	9.9	8.5	420.75
13	0.11	0.23	0.36	0.9	15.3	38.25
14	0.22	0.44	0.7	1.74	29.58	73.95
15	1.25	2.5	4	10	170	425
16	2.5	6.25	3.2	8	136	340
17	1.87	4.66	2.98	7.46	126.82	317.05
18	0	0	0	0	0	0
19	0.88	1.75	1.44	3.6	61.2	153
20	1.25	2.5	4	10	170	425
21	2.12	5.31	3.4	8.5	144.5	361.25
22	1	2	3.2	8	136	340
23	0.17	0.34	0.54	1.34	22.78	56.95
24	0	0	0	0	0	0
25	0.12	6.19	0.2	9.9	8.5	420.75
26	1	2.5	1.6	4	34	85
27	0.06	2.48	0.2	9.9	8.5	420.75
28	0.69	1.38	2.2	5.5	93.5	233.75
29	0	0	0	0	0	0
30	0.01	0.03	0.04	0.1	1.7	4.25
31	0	0	0	0	0	0
32	1.62	4.06	2.6	6.5	110.5	276.25
33	0.06	1.25	0.2	5	8.5	212.5

Table 5-4. Fiber Debris Volumes on Screen (ft^3) (cont)

	SLOCA		MLOCA		LLOCA	
Case	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
34	0.05	0.09	0.15	0.37	6.29	15.73
35	0.12	3.12	0.2	5	8.5	212.5
36	1.25	2.5	2	5	85	212.5
37	0.88	2.19	1.4	3.5	59.5	148.75
38	0.5	1.25	0.8	2	34	85
39	1	2.5	1.6	4	68	170
40	0.25	0.62	0.4	1	17	42.5
41	1.5	3.75	2.4	6	102	255
42	0.69	1.38	2.2	5.5	93.5	233.75
43	0.01	0.03	0.04	0.1	1.7	4.25
44	0.01	0.01	0.02	0.05	0.85	2.12
45	0.12	3.12	0.2	5	8.5	212.5
46	2.17	5.44	3.48	8.7	147.9	369.75
47	0.88	1.75	1.28	3.19	54.23	135.57
48	1.62	4.06	2.6	6.5	110.5	276.25
49	0	0	0	0	0	0
50	0.5	1.25	0.8	2	34	85
51	0.23	0.58	0.37	0.93	15.81	39.53
52	0.5	1.25	0.8	2	34	85
53	0.52	1.31	0.84	2.1	35.7	89.25
54	0.06	1.25	0.2	5	8.5	212.5
55	0.12	3.12	0.2	5	8.5	212.5
56	0.01	0.01	0.02	0.05	0.85	2.12
57	0.01	0.03	0.04	0.1	1.7	4.25
58	0.12	5	0.2	8	8.5	340
59	0.88	2.19	1.4	3.5	59.5	148.75
60	0.56	1.11	1.78	4.45	75.65	189.12
61	0.05	0.09	0.15	0.37	6.29	15.73
62	0.06	1.25	0.2	5	8.5	212.5
63	1	2.5	1.6	4	34	85
64	0	0	0	0	0	0
65	1	2.5	1.6	4	34	85
66	0	0	0	0	0	0
67	0.12	6.19	0.2	9.9	8.5	420.75
68	0.38	0.94	0.6	1.5	25.5	63.75
69	0.03	0.05	0.08	0.2	3.4	8.5

Table 5-5. Particulate Insulation Debris Mass on Screen (lb).

	SLOCA		MLOCA		LLOCA	
Case	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
1	12	122	40	490	1700	20825
2	1	2	4	9	153	382
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	25	306	40	490	1700	20825
6	115	288	184	460	7820	19550
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	12	122	40	490	1700	20825
11	50	125	80	200	3400	8500
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	19	38	61	152	2584	6460
15	0	0	0	0	0	0
16	50	125	80	200	3400	8500
17	64	159	102	254	4318	10795
18	0	0	0	0	0	0
19	38	75	157	393	6681	16702
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	25	50	80	200	3400	8500
23	1	2	4	9	153	382
24	0	0	0	0	0	0
25	0	0	0	0	0	0
26	12	31	20	50	850	2125
27	0	0	0	0	0	0
28	19	38	60	150	2550	6375
29	0	0	0	0	0	0
30	60	120	192	480	8160	20400
31	0	0	0	0	0	0
32	12	31	20	50	850	2125
33	12	122	40	490	1700	20825

Note: Only contribution from cal-sil particulate. Miscellaneous particulate contribution is determined using information in Tables 5-1 and 5-2.

Table 5-5. Particulate Insulation Debris Mass on Screen (lb) (cont).

	SLOCA		MLOCA		LLOCA	
Case	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
34	0	0	0	0	0	0
35	25	306	40	490	1700	20825
36	0	0	0	0	0	0
37	12	31	20	50	850	2125
38	0	0	0	0	0	0
39	0	0	0	0	0	0
40	38	94	60	150	2550	6375
41	0	0	0	0	0	0
42	19	38	60	150	2550	6375
43	60	120	192	480	8160	20400
44	0	0	0	0	0	0
45	25	306	40	490	1700	20825
46	8	19	12	30	510	1275
47	38	75	169	422	7174	17935
48	12	31	20	50	850	2125
49	0	0	0	0	0	0
50	0	0	0	0	0	0
51	147	369	236	590	10030	25075
52	0	0	0	0	0	0
53	115	288	184	460	7820	19550
54	12	122	40	490	1700	20825
55	25	306	40	490	1700	20825
56	0	0	0	0	0	0
57	48	95	152	380	6460	16150
58	25	125	40	200	1700	8500
59	12	31	20	50	850	2125
60	16	32	51	127	2159	5398
61	0	0	0	0	0	0
62	12	122	40	490	1700	20825
63	12	31	20	50	850	2125
64	0	0	0	0	0	0
65	12	31	20	50	850	2125
66	50	125	80	200	3400	8500
67	0	0	0	0	0	0
68	62	156	100	250	4250	10625
69	0	0	0	0	0	0

Note: Only contribution from cal-sil particulate. Miscellaneous particulate contribution is determined using information in Tables 5-1 and 5-2.

Table 5-6. Difference Between Calculated Head Loss and Failure Criterion for Favorable and Unfavorable Conditions (ft).

		SLOCA		MLOCA				LLOCA			
		Single Flow		Half-Flow		Full-Flow		Half-Flow		Full-Flow	
Case	Failure Criterion	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.
1	2.65	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
2	1.12	-1.1	-1.1	-1.1	29	-1.1	>>50	44.3	>>50	>>50	>>50
3	3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.1	27.7	-2	>>50
4	1.7	3.4	45.7	2.8	>>50	11.2	>>50	20	>>50	>>50	>>50
5	8.2	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
6	9	Cal-Sil	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
7	0.41	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
8	1.7	3.4	45.7	2.8	>>50	11.2	>>50	20	>>50	>>50	>>50
9	2.6	20.5	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
10	0.96	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
11	3	Cal-Sil	4.7	Cal-Sil	2.8	0.9	8.9	>>50	>>50	>>50	>>50
12	0	Uncertain	35.7	Uncertain	16.8	Uncertain	34.6	5.1	>>50	12.3	>>50
13	0	0	0	0	0	0	0	0.2	1.3	0.4	3.3
14	0.96	-1	-1	-1	-1	-1	-1	>>50	>>50	>>50	>>50
15	0.54	-0.5	-0.5	-0.5	1	-0.4	2.5	0	1	0.7	3.3
16	3	Cal-Sil	4.7	Cal-Sil	2.8	0.9	8.9	>>50	>>50	>>50	>>50
17	1.1	43	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
18	1.25	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2
19	3.3	13.6	41.9	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
20	2.6	20.5	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
21	7.35	-7.3	-1.7	-7.2	-1.6	-6.9	4.5	-5.8	45.7	-3.2	>>50
22	4.2	Uncertain	2.1	10	39.1	25.4	>>50	>>50	>>50	>>50	>>50
23	1.12	-1.1	-1.1	-1.1	29	-1.1	>>50	44.3	>>50	>>50	>>50
24	0.41	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
25	3.5	-3.5	-2.1	-3.5	-2.1	-3.5	-0.6	-3.4	0	-3.4	5.4
26	1.5	3.8	29	2.7	17.7	7.2	38.6	>>50	>>50	>>50	>>50
27	0.9	-0.9	2.1	-0.9	31.8	-0.9	>>50	1.1	>>50	4.5	>>50
28	1.1	-1.1	1.2	6.7	24.3	15.2	>>50	>>50	>>50	>>50	>>50
29	0.41	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
30	1.37	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	>>50	>>50	>>50	>>50
31	0.41	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
32	0.45	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
33	0.9	Uncertain	Uncertain	Uncertain	16	Uncertain	33.5	48	>>50	>>50	>>50

Note: Several cases that had insufficient fiber to form a debris bed or did not exceed the failure criterion also had large amounts of cal-sil applied preferentially to small pipes. Technically, these cases should receive an entry of <zero, but they are annotated with the entry 'Cal-Sil' as a reminder of potential concern. Similarly, cases with zero head loss and poorly defined insulation compositions were annotated with the entry "Uncertain" to indicate that major uncertainties exist.

Table 5-6. Difference Between Calculated Head Loss and Failure Criterion for Favorable and Unfavorable Conditions (ft) (cont)

		SLOCA		MLOCA				LLOCA			
		Single Flow		Half-Flow		Full-Flow		Half-Flow		Full-Flow	
Case	Failure Criterion	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.
34	13	-13	-13	-13	-13	-13	-13	-10.9	>>50	-7.3	>>50
35	8.2	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
36	1.3	-1	2.3	0.8	18.6	3	40.5	12.7	42	37.7	>>50
37	0.35	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
38	3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.1	27.7	-2	>>50
39	0	0	0	0	1.6	0	3.2	0.2	0.9	0.6	2.4
40	0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	>>50	>>50	>>50	>>50
41	5.25	-5.2	-3.4	-5.2	-2.9	-5.2	-0.5	-4.8	9.3	-4.1	38.1
42	1.84	-1.8	0.4	5.9	23.6	14.5	>>50	>>50	>>50	>>50	>>50
43	1.37	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	>>50	>>50	>>50	>>50
44	1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	21.4	>>50	>>50	>>50
45	0	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
46	1.07	-1.1	-1.1	-1.1	-0.3	-1.1	0.5	0	3.1	1.4	9.4
47	0.97	8.4	25	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
48	0.45	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
49	1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7
50	5.25	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.1	1.1	-4.8	14.9
51	0.62	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	>>50	>>50	>>50	>>50
52	3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.8	-3.1	27.7	-2	>>50
53	9	Cal-Sil	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
54	2.65	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
55	1.01	Uncertain	>>50	Uncertain	46.4	Uncertain	>>50	>>50	>>50	>>50	>>50
56	1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	21.4	>>50	>>50	>>50
57	1.75	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	>>50	>>50	>>50	>>50
58	0	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
59	0.35	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50	>>50
60	5.6	-5.6	-5.6	-2.7	5.6	0.3	17.2	>>50	>>50	>>50	>>50
61	13	-13	-13	-13	-13	-13	-13	-10.9	>>50	-7.3	>>50
62	1.9	Uncertain	>>50	Uncertain	>>50	Uncertain	>>50	>>50	>>50	>>50	>>50
63	1.5	3.8	29	2.7	17.7	7.2	38.6	>>50	>>50	>>50	>>50
64	1.25	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2
65	1.5	3.8	29	2.7	17.7	7.2	38.6	>>50	>>50	>>50	>>50
66	0.6	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	-0.6	-0.6	-0.6	-0.6
67	3.5	-3.5	-2.1	-3.5	-2.1	-3.5	-0.6	-3.4	0	-3.4	5.4
68	2.1	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	Cal-Sil	45.7	>>50	>>50	>>50
69	2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2.4	-2	7.6	-1.4	18.3

Note: Several cases that had insufficient fiber to form a debris bed or did not exceed the failure criterion also had large amounts of cal-sil applied preferentially to small pipes. Technically, these cases should receive an entry of <zero, but they are annotated with the entry 'Cal-Sil' as a reminder of potential concern. Similarly, cases with zero head loss and poorly defined insulation compositions were annotated with the entry "Uncertain" to indicate that major uncertainties exist.

5.4 Sump-Blockage Likelihood

The analyses described above were used to draw conclusions regarding sump-blockage likelihood. The final list is provided in Table 5-7. The qualitative grades were assigned by comparing the debris accumulated on the sump screen with that necessary for sump failure. Appendix B provides this comparison for each parametric case and for each accident sequence. The following criteria were generally applied.

1. A **very likely** grade was assigned when debris accumulated on the sump screen under 'favorable' transport conditions exceeded the FTDL. In Appendix B, corresponding figures would have the dashed box indicating "range of transported debris" located to the right of the solid line indicating "failure threshold debris loading." The corresponding head-loss entry in Table 5-6 would be larger than the $NPSH_{Margin}$ (or alternately ½-pool height).

2. An **unlikely** grade was assigned when debris accumulated on the sump screen under 'unfavorable' transport conditions were lower than the FTDL. In Appendix B, corresponding figures would have the dashed box indicating "range of transported debris" located to the left of the solid line indicating "failure threshold debris loading." The corresponding head-loss entry in Table 5-6 would be zero (because no head-loss calculations were performed for these cases).

3. For all other cases (or sequences), the qualitative grades **likely** and **possible** were assigned. A variety of qualitative rationales was used to distinguish between these two cases, including plant and sump design features and types and locations of debris. In all these cases, the dashed box in the Appendix B figures intersected the solid line, indicating that the favorable estimates for debris transported are lower than threshold values, but unfavorable estimates exceeded threshold values.

After determining a qualitative grade for each case using the method described above, one additional step was required before a final qualitative grade was assigned. There were certain factors that were identified for each of the parametric calculations that would certainly make the vulnerability assessment "worse" than that one would assign based on review of the Appendix B figures alone. No methodology was identified that would allow consideration of these factors in the numeric calculations that were performed to generate the figures in Appendix B. For example, as described in Section 3.5, cal-sil debris was treated in the calculations as if it was a "generic particulate." That is, the contribution of cal-sil debris to total head loss across the sump screen was calculated as if it were common particulate material, such as dirt or dust. However, previous experimental programs have provided overwhelming evidence to suggest that the effect of cal-sil may be to increase head loss by a factor of 5-10 more than that of a more "generic" particulate. Therefore, qualitative assessments were made for specific cases that increased the vulnerability ranking (e.g., from **possible** to **likely**) based on these types of considerations. Table 5-8 shows the dominant factors that were considered for making these qualitative judgments.

It should be noted that the qualitative ranking provided above is not intended to imply an estimate of frequency for a sump blockage event but rather is best interpreted as the comparative concern placed on groups of cases with similar ranking. For example, cases with ratings of **very likely** are found to have the following general characteristics.

1. A significant fraction of the containment inventory of insulation is made up of fibrous materials and/or cal-sil.

2. The sump-screen area and $NPSH_{Margin}$ (or pool height) are such that the FTDLs and minimum transport fractions are very small. These plants generally generated and transported significantly larger quantities than necessary for sump failure. Finally, the estimates for head loss far exceeded the failure criterion.

Cases with ratings of **unlikely** are found to have the following general characteristics.

1. A very small fraction of the containment inventory of insulation is made up of fibrous materials. Most of the insulation is in the form of RMI and foam-type insulations. These types of debris are less likely to be transported, and when accumulated, they would not result in significant head loss.

The rating of unlikely should be interpreted judiciously because it is based almost entirely on the assumption that amount of fibrous insulation in that containment is insignificant. These data should be validated further before screening these cases from further considerations.

Other important findings of the parametric study can be summarized as follows.

- Accumulation of very large quantities of RMI fragments would be necessary to induce sump failure by the assumed head-loss criteria. The potential for sump failure as a result of transport of RMI debris was found to be **unlikely** for all parametric cases except 3 (3 out of 69) that have unique sump features. It is concluded that the industry-wide potential for sump failure as a result of LOCA-generated RMI debris alone is very low.

- Transport and accumulation of small quantities of fibrous and particulate debris is sufficient to cause sump failure by the assumed head-loss criteria. Approximately ½ ft^3 of fibrous insulation combined with only 10 lb of particulates would be sufficient to raise sump blockage concerns for a significant number of parametric cases (30 out of 69). This finding is a direct reflection of the fact that a significant number of PWR units have sump screen areas less than 100 ft^2 and NPSH margins less than 4 ft-water.

- Postulated small, medium, and large breaks in the RCS piping could generate more than 25 ft^3, 40 ft^3, and 1700 ft^3 of insulation debris, respectively. Only a small fraction of this insulation may actually be composed of transportable, problematic debris.[†] Nevertheless, transport of only 5% of the damaged volume is sufficient to raise ECCS operability concerns for a significant number of the parametric cases in this study.

- In numerous parametric cases, the estimated quantities of debris reaching the sump (evaluated using both favorable and unfavorable assumptions) far exceeded the threshold values necessary to induce sump failure. The actual number of parametric cases where failure was predicted varied depending on the break size. In general, an LLOCA tended to generate and transport substantially larger quantities than the FTDLs. Although estimates for the quantity of debris transported following an SLOCA depended strongly on assumptions related to CS actuation, a small subset of parametric cases were capable of transporting quantities of debris sufficient for failure even without sprays. In these parametric cases, recirculation sumps are located inside the missile shield and have special features such as horizontal screens at or below the containment floor level.

[†]Transportable problematic debris includes small fragments of fiber and particulates (such as fiberglass and cal-sil) that can move readily to the sump and induce large pressure drops when they accumulate on the screen.

- For many parametric cases, head-loss estimates (evaluated using both favorable and unfavorable assumptions) exceeded the $NPSH_{Margin}$ for the ECCS and/or CS pump(s). Typically, head-loss estimates following a LLOCA were much larger than the $NPSH_{Margin}$. This finding eliminates the need to perform numerous sensitivity analyses to examine whether the blockage is a reflection of 'conservative' assumptions made while calculating the $NPSH_{Margin}$. (For example, if the head-loss estimates were to be only 1 or 2 ft above the $NPSH_{Margin}$, it could be argued that the blockage concern is purely a reflection of conservative assumptions that are part of any plant $NPSH_{Margin}$ calculations).

Table 5-7. Results of Parametric Evaluations Regarding Potential for Blockage.

ID	SLOCA	MLOCA	LLOCA	ID	SLOCA	MLOCA	LLOCA
1	Likely[+]	Very Likely[+]	Very Likely	36	Very Likely[+]	Very Likely	Very Likely
2	Unlikely	Possible	Very Likely	37	Very Likely	Very Likely	Very Likely
3	Unlikely	Unlikely	Likely	38	Unlikely	Unlikely	Likely
4	Very Likely	Very Likely	Very Likely	39	Unlikely	Possible	Very Likely
5	Very Likely[+]	Very Likely[+]	Very Likely	40	Unlikely	Unlikely	Very Likely
6	Likely	Very Likely	Very Likely	41	Unlikely	Unlikely	Likely
7*	Unlikely	Unlikely	Unlikely	42	Likely[+]	Very Likely	Very Likely
8	Very Likely	Very Likely	Very Likely	43	Unlikely	Unlikely	Very Likely
9	Very Likely	Very Likely	Very Likely	44	Unlikely	Unlikely	Very Likely
10	Very Likely[+]	Very Likely[+]	Very Likely	45	Very Likely[+]	Very Likely[+]	Very Likely
11	Very Likely[+]	Very Likely[+]	Very Likely	46	Unlikely	Possible	Very Likely
12	Possible	Very Likely[+]	Very Likely	47	Very Likely	Very Likely	Very Likely
13	Unlikely	Unlikely	Very Likely	48	Very Likely	Very Likely	Very Likely
14	Unlikely	Unlikely	Very Likely	49*	Unlikely	Unlikely	Unlikely
15	Unlikely	Likely	Very Likely	50	Unlikely	Unlikely	Possible
16	Very Likely[+]	Very Likely[+]	Very Likely	51	Very Likely[+]	Very Likely[+]	Very Likely[+]
17	Very Likely	Very Likely	Very Likely	52	Unlikely	Unlikely	Likely
18*	Unlikely	Unlikely	Unlikely	53	Likely	Very Likely	Very Likely
19	Very Likely	Very Likely	Very Likely	54	Likely[+]	Likely	Very Likely
20	Very Likely	Very Likely	Very Likely	55	Possible	Likely[+]	Very Likely
21	Unlikely	Possible	Likely	56	Unlikely	Unlikely	Very Likely
22	Very Likely[+]	Very Likely	Very Likely	57	Unlikely	Unlikely	Very Likely
23	Unlikely	Possible	Very Likely	58	Very Likely	Very Likely	Very Likely
24*	Unlikely	Unlikely	Unlikely	59	Very Likely	Very Likely	Very Likely
25	Possible[+]	Possible[+]	Very Likely	60	Unlikely	Likely	Very Likely
26	Very Likely	Very Likely	Very Likely	61	Unlikely	Unlikely	Likely
27	Likely[+]	Likely	Very Likely	62	Very Likely[+]	Very Likely[+]	Very Likely
28	Likely[+]	Very Likely	Very Likely	63	Very Likely	Very Likely	Very Likely
29*	Unlikely	Unlikely	Unlikely	64*	Unlikely	Unlikely	Unlikely
30	Possible[+]	Unlikely	Very Likely	65	Very Likely	Very Likely	Very Likely
31*	Unlikely	Unlikely	Unlikely	66*	Unlikely	Unlikely	Unlikely
32	Very Likely	Very Likely	Very Likely	67	Unlikely	Unlikely	Very Likely[+]
33	Unlikely	Likely[+]	Very Likely	68	Unlikely	Unlikely	Very Likely
34	Unlikely	Unlikely	Very Likely[+]	69	Unlikely	Unlikely	Likely
35	Very Likely[+]	Very Likely[+]	Very Likely				

Tally	SLOCA	MLOCA	LLOCA
Very Likely	25	31	53
Likely	7	6	7
Possible	4	6	1
Unlikely	33	26	8

[*] Zero-Fiber Plant
[+] Ranking Elevated due to Factors Not Considered in Calculations

Table 5-8. Factors Not Considered in Parametric Calculations.

Case	Insulation Quantity Not Reported	Insulation Fractions Not Reported	Significant Cal-Sil (>5%)	High Approach Velocity	Exposed Sump	Sprays Expected for SLOCA
1	x	x	unknown	L	x	
2	x			L		
3	x					x
4	x			L		x
5	x	x	unknown	L		x
6	x		x (>40%)	S, M, L	x	x
7	x			S, M, L		
8	x			L		x
9	x			S, M, L		
10	x	x	unknown	M, L		
11	x		x (>20%)		x	x
12	x	x				x
13						
14			X		x	
15	x					
16	x		x (>20%)		x	x
17			x (>20%)	S, M, L		x
18	x			S, M, L	x	x
19			x (>30%)	M, L		
20	x			S, M, L		
21	x					x
22	x	x	Unknown			
23	x			L		
24	x			S, M, L		
25	x	x				x
26	x		X		x	x
27	x	x		L		
28	x		X			
29	x			S, M, L		
30	x		x (>40%)	M, L		
31	x			S, M, L		
32	x		X	M, L	x	x
33	x	x	Unknown			

Table 5-8. Factors Not Considered in Parametric Calculations (cont).

Case	Insulation Quantity Not Reported	Insulation Fractions Not Reported	Significant Cal-Sil (>5%)	High Approach Velocity	Exposed Sump	Sprays Expected for SLOCA
34				L		
35	x	x	Unknown	L		x
36	x			L		
37	x		X	S, M, L	x	x
38	x					x
39						x
40	x		X			x
41	x					x
42	x		X			
43	x		x (>40%)	M, L		
44				M, L		
45	x	x	Unknown		x	x
46	x					x
47			x (>40%)	M, L		
48	x		X	M, L	x	x
49	x					x
50	x					x
51			x (>50%)			x
52	x					x
53	x		x (>40%)	S, M, L		x
54	x	x	Unknown	L		
55	x	x	Unknown		x	x
56				M, L		
57	x		x (>30%)	M, L		
58	x	x	Unknown	?		x
59	x		X	S, M, L		x
60	x		X			
61				L		
62	x	x	Unknown	M, L		
63	x		X		x	x
64	x			S, M, L	x	x
65	x		X			x
66	x		x (>20%)			x
67	x	x				x
68	x		x (>20%)			x
69	x					

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APPENDIX A

DESCRIPTIVE DATA ASSUMED FOR EACH PARAMETRIC CASE

Table A-1(a) Plant Parameters for Parametric Study.

Parametric Case	Containment Type	Cont. Inside Diameter	Cont. Free Volume	Cont. Spray Act. Set Point	Switchover Pool Height	Switchover Time	Maximum Pool Height	Maximum Time to Switchover	Sump Location	Sump-Screen Hole Size
Units	-	ft	ft^3	psig	ft	min	ft	min	-	in.
1	Dry	105	?	30	5.3	30	5.5	65	exposed	0.125
2	Dry	135	2.980	18.2	2.24	9.59	4.7	18.37	remote	0.115
3	Dry	146	2.600	8.5	4.5	20	11	20	remote	0.09
4	Ice	115	?	2.9	5.5	20	14	58	?	0.204
5	Dry	116	1.550	?	2.93	15.2	4.75	43	int. exp.	0.25
6	Ice	115	?	2.9	?	?	?	?	int. exp.	0.250
7	Dry	140	2.900	20	0.82	13.23	6.1	15	?	0.152
8	Ice	115	?	2.9	5.5	20	14	58	?	0.204
9	Dry	140	2.700	21.5	3.5	35	9.41	63	remote	0.12
10	Dry	150	2.340	14	1.92	20	7.5	30	int. exp.	0.3
11	Dry	130	2.000	4.75	5.25	480	5.25	480	exposed	0.224
12	Dry	126	?	?	5.33	25	6.89	33	?	0.25
13	Dry	130	2.000	30	1.74	29.17	5.89	29.17	remote	0.125
14	Dry	116	2.090	30	6	25	9.18	25	exposed	0.132
15	Dry	140	2.700	18	3.84	21.3	4.14	25.9	?	0.097
16	Dry	130	2.000	4.75	5.25	480	5.25	480	exposed	0.224
17	Dry	110	1.050	5	5.4	20	6.78	24	remote	0.1783
18	Ice	106	?	2.81	2.5	30	13.2	60	exposed	0.25
19	Dry	135	2.610	22	2.1	13.3	4.1	166.1	int. exp.	0.125
20	Dry	140	2.700	21.5	3.5	35	9.41	63	remote	0.12
21	Dry	140	2.680	3	5.43	20	11.45	20	remote	0.078
22	Dry	130	2.100	25	1.5	25	5.5	52	?	0.221
23	Dry	135	2.980	18.2	2.24	9.59	4.7	18.37	remote	0.115
24	Dry	140	2.900	20	0.82	13.23	6.1	15	?	0.152
25	Dry	150	3.300	9.5	3.6	?	?	?	remote	0.25
26	Dry	116	1.910	10	4.27	30	4.27	30	exposed	0.12
27	Dry	135	2.500	27	2.12	14	4.41	26	remote	0.125
28	Dry	140	2.620	25.3	3.67	15	5.5	23	remote	0.125
29	Dry	140	2.900	20	0.82	13.23	6.1	15	?	0.152
30	Dry	140	2.630	22	2.73	14.4	5.42	57.5	int. exp.	0.125
31	Dry	140	2.900	20	0.82	13.23	6.1	15	?	0.152
32	Sub	126	?	13.05	0.9	3.42	6.1	89	exposed	0.1197
33	Dry	140	2.500	27	1.9	13	4.5	26	?	0.25
34	Dry	105	?	23	3.25	12	8.5	24	int. exp.	?
35	Dry	116	1.550	?	2.93	15.2	4.75	43	int. exp.	0.25
36	Dry	130	2.000	30	4	27	7	40	remote	0.25
37	Sub	126	1.800	10.3	0.7	2.2	4.7	73	exposed	0.75
38	Dry	146	2.600	8.5	4.5	20	11	20	remote	0.09

Table A-1(a) Plant Parameters for Parametric Study (cont).

Parametric Case	Containment Type	Cont. Inside Diameter	Cont. Free Volume	Cont. Spray Act. Set Point	Switchover Pool Height	Switchover Time	Maximum Pool Height	Maximum Time to Switchover	Sump Location	Sump-Screen Hole Size
Units	-	ft	ft^3	psig	ft	min	ft	min	-	in.
39	Dry	130	2.500	10	3	25	7.3	29	int. exp.	0.125
40	Sub	126	1.800	8	5.8	45	9.9	201	remote	0.094
41	Ice	115	1.220	3	7	20	21	100	?	0.12
42	Dry	140	2.620	25.3	3.67	15	5.5	23	remote	0.125
43	Dry	140	2.630	22	2.73	14.4	5.42	57.5	int. exp.	0.125
44	Dry	130	2.030	27	3.5	21.67	9.5	29	int. exp.	0.12
45	Dry	116	1.600	3.7	3.5	20	6.83	20	?	0.132
46	Dry	140	2.500	?	2.13	25.54	2.25	26	int. exp.	0.25
47	Dry	135	2.610	24	1.75	22.12	3.5	45	int. exp.	0.25
48	Sub	126	?	13.05	0.9	3.42	6.1	89	exposed	0.1197
49	Ice	115	?	3	8.52	10.2	14.42	15	exposed	0.25
50	Ice	115	1.220	3	7	20	21	100	?	0.12
51	Dry	116	1.780	8.6	7	30	11.5	30	remote	0.1875
52	Dry	146	2.600	8.5	4.5	20	11	20	remote	0.09
53	Ice	115	?	2.9	?	?	?	?	int. exp.	0.250
54	Dry	105	?	30	5.3	30	5.5	65	exposed	0.125
55	Dry	130	1.920	9.48	4.59	30	7.6	30	exposed	0.09375
56	Dry	130	2.030	27	3.5	21.67	9.5	29	int. exp.	0.12
57	Dry	108	?	23	3.5	12.4	8	30.9	int. exp.	1
58	Sub	140	1.030	8	?	?	?	?	?	?
59	Sub	126	1.800	10.3	0.7	2.2	4.7	73	exposed	0.75
60	Dry	105	0.997	28	2.78	43	5.4	43	exposed	0.1875
61	Dry	105	?	23	3.25	12	8.5	24	int. exp.	?
62	Dry	150	2.340	14	1.92	0.33	7.5	0.5	int. exp.	0.3
63	Dry	116	1.910	10	4.27	30	4.27	30	exposed	0.12
64	Ice	106	?	2.81	2.5	30	13.2	60	exposed	0.25
65	Dry	116	1.910	10	4.27	30	4.27	30	exposed	0.12
66	Sub	126	1.800	8	5.8	45	9.9	201	remote	?
67	Dry	150	3.300	9.5	3.6	?	?	?	remote	0.25
68	Dry	140	2.500	?	0.5	20	2.75		int. exp.	0.25
69	Dry	130	2.870	23	2	35	6.7	35	?	0.25

Table A-1(b) Additional Plant Parameters for Parametric Study.

Parametric Case	Total Screen Area	Height of Sump Screen	Area at Switchover	Area at Maximum Pool Depth	Reported NPSH Margin	Fibrous Insulation	Reflective Metallic Insulation	Part. (Cal-Sil) Insulation	Other Insulation	Dominant Fiber	Type of Other Insulation
Units	ft²	ft	ft²	ft²	ft-water	%	%	%	%	-	-
1	42.4	6	37.5	38.9	10.02	yes	yes	yes	0	FG/Wool/Tmat	
2	260	6.25	93.2	195.5	5	13.4	85.7	0.9	0	Transco	
3	210	4.5	210	210	3.8	20.0	80.0	0	0	NUKON/Tmat	
4	135	?	67.5	135	1.7	50	50	<1	<<1	?	
5	51.31	1	51.31	51.31	8.2	yes	yes	yes	0	NUKON/Wool	
6	66	5.25	66	66	9	21	33	46	0	?	
7	12.67	1.5	6.93	12.67	4.3	0	100	0	0	?	
8	135	?	67.5	135	1.7	50	50	<1	<<1	?	
9	11.64	0	11.64	11.64	2.6	100.0	0	0	0	NUKON	
10	104	3.5	20.4	104	1.9	yes	yes	yes	yes	FG/Wool	Foam
11	229	3.5	229	229	3	80.0	0	20.0	0	FG/Wool/Tmat	
12	93.2	below	93.2	93.2		yes	yes	0	0	Temp Mat	
13	214.4	below	214.4	214.4		9.0	91.0	0	0	NUKON	
14	204	4.75	204	204	0.96	17.4	67.5	15.2	0	?	
15	368	2.2	368	368	0.54	100	0	0	0	NUKON	
16	229	3.5	229	229	3	80.0	0	20.0	0	FG/Wool/Tmat	
17	57	3.5	57	57	1.1	74.6	0	25.4	0	FG/Wool	
18	28.4	3	23.67	28.4	9.26	0	100	0	0	?	
19	36.1	below	36.1	36.1	3.3	36.0	10.0	39.3	14.7	Wool/FG	Gyp, Foam, Poly
20	11.64	0	11.64	11.64	2.6	100.0	0	0	0	NUKON	
21	225	5	225	225	7.35	85	15	0	0	FG/Tmat	
22	85.4	0	85.4	85.4	4.2	yes	yes	yes	0	FG/Wool/Tmat	
23	260	6.25	93.2	195.5	5	13.4	85.7	0.9	0	Transco	
24	12.67	1.5	6.93	12.67	4.3	0	100	0	0	?	
25	414	3	414	414	3.5	yes	yes	0	0	?	
26	93	below	93	93	1.5	20.0	75.0	5.0	0	FG/Wool	
27	392	8.667	95.9	199.5	0.9	yes	yes	0	yes	NUKON	
28	134	3.75	131.1	134	1.1	55.0	30.0	15.0	0	NUKON/Wool	
29	12.67	1.5	6.93	12.67	4.3	0	100	0	0	?	
30	127.93	5	44.94	62.1	3.6	1	50	48	1	?	
31	12.67	1.5	6.93	12.67	4.3	0	100	0	0	?	
32	168	6.25	24.2	164	0.7	65.0	30.0	5.0	0	FG/Wool	
33	692	7	187.8	444.9	0.9	yes	yes	yes	?	?	
34	51	2.75	51	51	13	3.7	96.3	0	0	?	
35	62.75	1	62.75	62.75	8.2	yes	yes	yes	0	NUKON/Wool	
36	86.4	below	86.4	86.4	1.3	50.0	30.0	0	20.0	NUKON/Wool	Neoprene
37	158	5	22.1	148.5	0.83	35.0	60.0	5.0	0	FG/Wool	

Table A-1(b) Additional Plant Parameters for Parametric Study (cont).

Parametric Case	Total Screen Area	Height of Sump Screen	Area at Switchover	Area at Maximum Pool Depth	Reported NPSH Margin	Fibrous Insulation	Reflective Metallic Insulation	Part. (Cal-Sil) Insulation	Other Insulation	Dominant Fiber	Type of Other Insulation
Units	ft²	ft	ft²	ft²	ft-water	%	%	%	%	-	-
38	210	4.5	210	210	3.8	20.0	80.0	0	0	NUKON/Tmat	
39	318	3	318	318	?	40.0	60.0	0	0	NUKON/Tranco	
40	201	5	201	201	0.9	10	75	15	0	?	
41	330	6	330	330	5.25	60.0	40.0	0	0	?	Armaflex (Foam)
42	134	3.75	131.1	134	3.9	55.0	30.0	15.0	0	NUKON/Wool	
43	127.93	5	45.65	59.89	3.6	1	50	48	1	?	
44	37.5	2.5	37.5	37.5	1.3	0.5	80.0	0.0	19.5	Temp Mat	Foam
45	70	0	70	70	0	yes	yes	yes	0	FG/Wool	
46	571	0	571	571	1.07	87.0	10.0	3.0	0	NUKON/Wool	
47	48	0	48	48	0.97	31.9	8.9	42.2	17.0	Tmat/FG	Foam
48	168	6.25	24.2	164	0.7	65.0	30.0	5.0	0	FG/Wool	
49	187.2	8	187.2	187.2	1.7	0	95.0	0	5.0	?	
50	330	6	330	330	5.25	20.0	80.0	0	0	?	Armaflex (Foam)
51	150	7	150	150	0.62	9.3	31.7	59.0	0	?	
52	210	4.5	210	210	3.8	20.0	80.0	0	0	NUKON/Tmat	
53	66	5.25	66	66	9	21	33	46	0	?	
54	42.4	6	37.5	38.9	10.02	yes	yes	yes	0	FG/Wool/Tmat	
55	115.4	0	115.4	115.4	1.01	yes	yes	yes	0.0	NUKON/Wool	
56	37.5	2.5	37.5	37.5	1.3	0.5	80.0	0.0	19.5	Temp Mat	Foam
57	39.62	5.083	27.3	39.6	17	1	61	38	0	?	
58	?	?	?	?	15.1	?	?	?	?	?	
59	158	5	22.1	148.5	0.83	35.0	60.0	5.0	0	FG/Wool	
60	108	below	108	108	5.6	44.5	6.4	12.7	36.4	?	Vinycel (resin)
61	51	2.75	51	51	13	3.7	96.3	0	0	?	
62	104	3.5	20.4	104	1.9	yes	yes	yes	yes	FG/Wool	Foam
63	93	below	93	93	1.5	20.0	75.0	5.0	0	FG/Wool	
64	28.4	3	23.67	28.4	9.26	0	100	0	0	?	
65	93	below	93	93	1.5	20.0	75.0	5.0	0	FG/Wool	
66	224	5	224	224	0.6	0	80	20	0	?	
67	414	3	414	414	3.5	yes	yes	0	0	?	
68	370	0	370	370	2.1	15.0	60.0	25.0	0	NUKON/Wool	
69	125	2	125	125	2.4	2.0	98.0	0	0	NUKON	

Table A-2. Data Used in Calculation of Head Loss – ECCS/Screen Characteristics.

#	SLOCA Flow Rate (gpm)	Full Flow (gpm)	Fav. Screen Area (ft^2)	Unfav. Screen Area (ft^2)	Fav. ΔH_f (ft)	Unfav. ΔH_f (ft)
1	2500	7600	38.87	37.45	0	0
2	2500	18424	195.52	93.18	1.1	1.1
3	8900	19740	210.00	210.00	3.9	1.84
4	8900	18416	135.00	67.50	4.3	0.41
5	8900	10000	51.31	51.31	1.5	1.5
6	8900	15600	66.00	66.00	2.35	1.12
7	2500	14200	12.67	6.93	4.3	0.41
8	8900	18416	135.00	67.50	0.7	0.45
9	2500	14200	11.64	11.64	2.75	2.65
10	2500	16000	104.00	20.40	3.8	3.8
11	8900	10498	229.00	229.00	12	0
12	8900	7600	93.20	93.20	12	0
13	2500	10000	214.40	214.40	12	0
14	2500	10720	204.00	204.00	3.8	3.8
15	2500	14200	368.00	368.00	9	9
16	8900	10498	229.00	229.00	12	0
17	8900	15100	57.00	57.00	4.3	0.41
18	8900	15600	28.40	23.67	2.75	2.65
19	2500	10300	36.10	36.10	0.9	0.9
20	2500	14200	11.64	11.64	2.35	1.12
21	8900	16000	225.00	225.00	3.5	3.5
22	2500	10498	85.40	85.40	3.5	3.5
23	2500	18424	195.52	93.18	3	3
24	2500	14200	12.67	6.93	2.6	2.6
25	8900	17400	414.00	414.00	15.1	0
26	8900	10720	93.00	93.00	12	0
27	2500	19920	199.46	95.89	2.4	2.4
28	2500	17500	134.00	131.14	1.7	1.7
29	2500	14200	12.67	6.93	1.9	0.96
30	2500	11836	62.10	44.94	7.35	7.35
31	2500	14200	12.67	6.93	1.7	1.7
32	8900	12100	163.97	24.19	1.3	1.3
33	2500	10008	444.86	187.83	3	3
34	2500	7600	51.00	51.00	0.97	0.97
35	8900	10000	62.75	62.75	9.26	1.25

Table A-2. Data used in Calculation of Head Loss – ECCS/Screen Characteristics (cont).

#	SLOCA Flow Rate (gpm)	Full Flow (gpm)	Fav. Screen Area (ft^2)	Unfav. Screen Area (ft^2)	Fav. ΔH_f (ft)	Unfav. ΔH_f (ft)
36	2500	11000	86.40	86.40	9.26	1.25
37	8900	10000	148.52	22.12	13	13
38	8900	19740	210.00	210.00	5.25	5.25
39	8900	12114	318.00	318.00	12	0
40	8900	15960	201.00	201.00	9	9
41	8900	15600	330.00	330.00	0.54	0.54
42	2500	17500	134.00	131.14	5.25	5.25
43	2500	11836	59.89	45.65	2.6	2.6
44	2500	17610	37.50	37.50	4.3	0.41
45	8900	9625	70.00	70.00	0.9	0.9
46	8900	15330	571.00	571.00	5.6	5.6
47	2500	13314	48.00	48.00	1.5	1.5
48	8900	12100	163.97	24.19	8.2	8.2
49	8900	15600	187.20	187.20	2.1	2.1
50	8900	15600	330.00	330.00	0.96	0.96
51	8900	17050	150.00	150.00	1.7	1.7
52	8900	19740	210.00	210.00	3.6	1.37
53	8900	15600	66.00	66.00	4.2	4.2
54	2500	7600	38.87	37.45	1.3	1.3
55	8900	10480	115.40	115.40	0.9	0.9
56	2500	17610	37.50	37.50	1.1	1.1
57	2500	9200	39.62	27.28	3.6	1.37
58	8900	15900	800.00	10.00	13	0
59	8900	10000	148.52	22.12	1.9	1.9
60	2500	5600	108.00	108.00	0.7	0.45
61	2500	7600	51.00	51.00	1.07	1.07
62	2500	16000	104.00	20.40	0.62	0.62
63	8900	10720	93.00	93.00	3.8	3.8
64	8900	15600	28.40	23.67	1.01	1.01
65	8900	10720	93.00	93.00	0.83	0.35
66	8900	15800	224.00	224.00	8.2	8.2
67	8900	17400	414.00	414.00	17	1.75
68	8900	15300	370.00	370.00	0.83	0.35
69	2500	11000	125.00	125.00	3.3	3.3

Table A-3. Data Used in Calculation of Head Loss – Insulation Characteristics.

#	Favorable Fiber	Favorable RMI	Favorable Particulate	Unfav. Fiber	Unfav. RMI	Unfav. Particulate	Favorable Fiber Fab Density (lbm/ft^3)	Unfav. Fiber Fab Density (lbm/ft^3)	Favorable Fiber Mat Density (lbm/ft^3)	Unfav. Fiber Mat Density (lbm/ft^3)	Favorable Svf (ft^2/ft^3)	Unfav. Svf (ft^2/ft^3)
1	0.050	0.850	0.010	0.500	0.010	0.490	2.4	11.3	175	159	171000	137000
2	0.134	0.857	0.009	0.134	0.857	0.009	2.4	2.4	175	175	171000	171000
3	0.200	0.800	0.000	0.200	0.800	0.000	2.4	11.3	175	159	171000	137000
4	0.500	0.500	0.000	0.500	0.500	0.000	2.4	11.3	175	159	171000	137000
5	0.050	0.850	0.100	0.500	0.010	0.490	2.4	8.0	175	160	171000	96000
6	0.210	0.330	0.460	0.210	0.330	0.460	2.4	11.3	175	159	171000	137000
7	0.000	1.000	0.000	0.000	1.000	0.000	2.4	11.3	175	159	171000	137000
8	0.500	0.500	0.000	0.500	0.500	0.000	2.4	11.3	175	159	171000	137000
9	1.000	0.000	0.000	1.000	0.000	0.000	2.4	2.4	175	175	171000	171000
10	0.050	0.850	0.100	0.500	0.010	0.490	2.4	8.0	175	160	171000	96000
11	0.800	0.000	0.200	0.800	0.000	0.200	2.4	11.3	175	159	171000	137000
12	0.050	0.950	0.000	0.990	0.010	0.000	11.3	11.3	159	159	137000	137000
13	0.090	0.910	0.000	0.090	0.910	0.000	2.4	2.4	175	175	171000	171000
14	0.174	0.675	0.152	0.174	0.675	0.152	2.4	11.3	175	159	171000	137000
15	1.000	0.000	0.000	1.000	0.000	0.000	2.4	2.4	175	175	171000	171000
16	0.800	0.000	0.200	0.800	0.000	0.200	2.4	11.3	175	159	171000	137000
17	0.746	0.000	0.254	0.746	0.000	0.254	2.4	8.0	175	160	171000	96000
18	0.000	1.000	0.000	0.000	1.000	0.000	2.4	8.0	175	160	171000	96000
19	0.360	0.100	0.393	0.360	0.100	0.393	2.4	8.0	175	160	171000	96000
20	1.000	0.000	0.000	1.000	0.000	0.000	2.4	2.4	175	175	171000	171000
21	0.850	0.150	0.000	0.850	0.150	0.000	2.4	11.3	175	159	171000	137000
22	0.800	0.000	0.200	0.800	0.000	0.200	2.4	11.3	175	159	171000	137000
23	0.134	0.857	0.009	0.134	0.857	0.009	2.4	2.4	175	175	171000	171000
24	0.000	1.000	0.000	0.000	1.000	0.000	2.4	11.3	175	159	171000	137000

Table A-3 Data used in Calculation of Head Loss – Insulation Characteristics (cont.)

#	Favorable Fiber	Favorable RMI	Favorable Particulate	Unfav. Fiber	Unfav. RMI	Unfav. Particulate	Favorable Fiber Fab Density (lbm/ft³)	Unfav. Fiber Fab Density (lbm/ft³)	Favorable Fiber Mat Density (lbm/ft³)	Unfav. Fiber Mat Density (lbm/ft³)	Favorable Svf (ft²/ft³)	Unfav. Svf (ft²/ft³)
25	0.050	0.950	0.000	0.990	0.010	0.000	2.4	8.0	175	160	171000	96000
26	0.200	0.750	0.050	0.200	0.750	0.050	2.4	8.0	175	160	171000	96000
27	0.050	0.950	0.000	0.990	0.010	0.000	2.4	2.4	175	175	171000	171000
28	0.550	0.300	0.150	0.550	0.300	0.150	2.4	8.0	175	160	171000	96000
29	0.000	1.000	0.000	0.000	1.000	0.000	2.4	11.3	175	159	171000	137000
30	0.010	0.500	0.480	0.010	0.500	0.480	2.4	11.3	175	159	171000	137000
31	0.000	1.000	0.000	0.000	1.000	0.000	2.4	11.3	175	159	171000	137000
32	0.650	0.300	0.050	0.650	0.300	0.050	2.4	8.0	175	160	171000	96000
33	0.050	0.850	0.100	0.500	0.010	0.490	2.4	11.3	175	159	171000	137000
34	0.037	0.963	0.000	0.037	0.963	0.000	2.4	11.3	175	159	171000	137000
35	0.050	0.850	0.100	0.500	0.010	0.490	2.4	8.0	175	160	171000	96000
36	0.500	0.300	0.000	0.500	0.300	0.000	8.0	8.0	160	160	96000	96000
37	0.350	0.600	0.050	0.350	0.600	0.050	2.4	8.0	175	160	171000	96000
38	0.200	0.800	0.000	0.200	0.800	0.000	2.4	11.3	175	159	171000	137000
39	0.400	0.600	0.000	0.400	0.600	0.000	2.4	2.4	175	175	171000	171000
40	0.100	0.750	0.150	0.100	0.750	0.150	2.4	11.3	175	159	171000	137000
41	0.600	0.400	0.000	0.600	0.400	0.000	2.4	11.3	175	159	171000	137000
42	0.550	0.300	0.150	0.550	0.300	0.150	2.4	8.0	175	160	171000	96000
43	0.010	0.500	0.480	0.010	0.500	0.480	2.4	11.3	175	159	171000	137000
44	0.005	0.800	0.000	0.005	0.800	0.000	11.3	11.3	159	159	137000	137000
45	0.050	0.850	0.100	0.500	0.010	0.490	2.4	8.0	175	160	171000	96000
46	0.870	0.100	0.030	0.870	0.100	0.030	2.4	8.0	175	160	171000	96000
47	0.319	0.089	0.422	0.319	0.089	0.422	2.4	11.3	175	159	171000	137000
48	0.650	0.300	0.050	0.650	0.300	0.050	2.4	8.0	175	160	171000	96000
49	0.000	0.950	0.000	0.000	0.950	0.000	2.4	11.3	175	159	171000	137000

Table A-3 Data used in Calculation of Head Loss – Insulation Characteristics (cont.)

#	Fav. Fib	Fav. RMI	Fav. Mic	Unfav. Fib	Unfav. RMI	Unfav. Mic	Fav. Fiber Fab Den (lbm/ft3)	Unfav. Fiber Fab Den (lbm/ft3)	Fav. Fiber Mat Den (lbm/ft3)	Unfav. Fiber Mat Den (lbm/ft3)	Fav. Svf (ft2/ft3)	Unfav. Svf (ft2/ft3)
50	0.200	0.800	0.000	0.200	0.800	0.000	2.4	11.3	175	159	171000	137000
51	0.093	0.317	0.590	0.093	0.317	0.590	2.4	11.3	175	159	171000	137000
52	0.200	0.800	0.000	0.200	0.800	0.000	2.4	11.3	175	159	171000	137000
53	0.210	0.330	0.460	0.210	0.330	0.460	2.4	11.3	175	159	171000	137000
54	0.050	0.850	0.100	0.500	0.010	0.490	2.4	11.3	175	159	171000	137000
55	0.050	0.850	0.100	0.500	0.010	0.490	2.4	11.3	175	159	171000	137000
56	0.005	0.800	0.000	0.005	0.800	0.000	11.3	11.3	159	159	137000	137000
57	0.010	0.610	0.380	0.010	0.610	0.380	2.4	11.3	175	159	171000	137000
58	0.050	0.850	0.100	0.800	0.000	0.200	2.4	11.3	175	159	171000	137000
59	0.350	0.600	0.050	0.350	0.600	0.050	2.4	8.0	175	160	171000	96000
60	0.445	0.040	0.127	0.445	0.040	0.127	2.4	11.3	175	159	171000	137000
61	0.037	0.963	0.000	0.037	0.963	0.000	2.4	11.3	175	159	171000	137000
62	0.050	0.850	0.100	0.500	0.010	0.490	2.4	8.0	175	160	171000	96000
63	0.200	0.750	0.050	0.200	0.750	0.050	2.4	8.0	175	160	171000	96000
64	0.000	1.000	0.000	0.000	1.000	0.000	2.4	8.0	175	160	171000	96000
65	0.200	0.750	0.050	0.200	0.750	0.050	2.4	8.0	175	160	171000	96000
66	0.000	0.800	0.200	0.000	0.800	0.200	2.4	11.3	175	159	171000	137000
67	0.050	0.950	0.000	0.990	0.010	0.000	2.4	8.0	175	160	171000	96000
68	0.150	0.600	0.250	0.150	0.600	0.250	2.4	8.0	175	160	171000	96000
69	0.020	0.980	0.000	0.020	0.980	0.000	2.4	2.4	175	175	171000	171000

Table A-4. Determination of Screen Submerged Fraction/Area for Use in ΔH Calculations.

ID No.	Switchover		Maximum Pool		Total Screen Area (ft²)	Height of Screen (ft)	Submerged Fraction		Submerged Area	
	Pool Height (ft)	Time (min)	Pool Height (ft)	Time (min)			Low	High	Unfav. Area (ft²)	Fav. Area (ft²)
1	5.3	30	5.5	65	42.4	6	0.88	0.92	37.5	38.9
2	2.24	9.59	4.7	18.37	260	6.25	0.36	0.75	93.2	195.5
3	4.5	20	11	20	210	4.5	1	1	210	210
4	5.5	20	14	58	135	Unknown	0.5	1	67.5	135
5	2.93	15.2	4.75	43	51.31	1	1	1	51.31	51.31
6	Unknown	Unknown	Unknown	Unknown	66	5.25	1	1	66.0	66.0
7	0.82	13.23	6.1	15	12.67	1.5	0.55	1	6.93	12.67
8	5.5	20	14	58	135	Unknown	0.5	1	67.5	135
9	3.5	35	9.41	63	11.64	0	1	1	11.64	11.64
10	1.92	20	7.5	30	104	3.5	0.55	1	20.4	104
11	5.25	480	5.25	480	229	3.5	1	1	229	229
12	5.33	25	6.89	33	93.2	below	1	1	93.2	93.2
13	1.74	29.17	5.89	29.17	214.4	below	1	1	214.4	214.4
14	6	25	9.18	25	204	4.75	1	1	204	204
15	3.84	21.3	4.14	25.9	368	2.2	1	1	368	368
16	5.25	480	5.25	480	229	3.5	1	1	229	229
17	5.4	20	6.78	24	57	3.5	1	1	57	57
18	2.5	30	13.2	60	28.4	3	0.83	1	23.67	28.4
19	2.1	13.3	4.1	166.1	36.1	below	1	1	36.1	36.1
20	3.5	35	9.41	63	11.64	0	1	1	11.64	11.64
21	5.43	20	11.45	20	225	5	1	1	225	225
22	1.5	25	5.5	52	85.4	0	1	1	85.4	85.4
23	2.24	9.59	4.7	18.37	260	6.25	0.36	0.75	93.2	195.5
24	0.82	13.23	6.1	15	12.67	1.5	0.55	1	6.93	12.67
25	3.6	Unknown	Unknown	Unknown	414	3	1	1	414	414
26	4.27	30	4.27	30	93	below	1	1	93	93
27	2.12	14	4.41	26	392	8.667	0.24	0.51	95.9	199.5
28	3.67	15	5.5	23	134	3.75	0.98	1	131.1	134
29	0.82	13.23	6.1	15	12.67	1.5	0.55	1	6.93	12.67
30	2.73	14.4	5.42	57.5	127.93	5	0.55	1	44.94	62.10
31	0.82	13.23	6.1	15	12.67	1.5	0.55	1	6.93	12.67
32	0.9	3.42	6.1	89	168	6.25	0.14	0.98	24.2	164.0
33	1.9	13	4.5	26	692	7	0.27	0.64	187.8	444.9
34	3.25	12	8.5	24	51	2.75	1	1	51	51
35	2.93	15.2	4.75	43	62.75	1	1	1	62.75	62.75

Table A-4. Determination of Screen Submerged Fraction/Area for Use in ΔH Calculations (cont).

	Switchover		Maximum Pool		Total Screen Area (ft^2)	Height of Screen (ft)	Submerged Fraction		Submerged Area	
ID No.	Pool Height (ft)	Time (min)	Pool Height (ft)	Time (min)			Low	High	Unfav. Area (ft^2)	Fav. Area (ft^2)
36	4	27	7	40	86.4	below	1	1	86.4	86.4
37	0.7	2.2	4.7	73	158	5	0.14	0.94	22.1	148.5
38	4.5	20	11	20	210	4.5	1	1	210	210
39	3	25	7.3	29	318	3	1	1	318	318
40	5.8	45	9.9	201	201	5	1	1	201	201
41	7	20	21	100	330	6	1	1	330	330
42	3.67	15	5.5	23	134	3.75	0.98	1	131.1	134
43	2.73	14.4	5.42	57.5	127.93	5	0.55	1	45.65	59.89
44	3.5	21.67	9.5	29	37.5	2.5	1	1	37.5	37.5
45	3.5	20	6.83	20	70	0	1	1	70	70
46	2.13	25.54	2.25	26	571	0	1.00	1.00	571.0	571.0
47	1.75	22.12	3.5	45	48	0	1	1	48	48
48	0.9	3.42	6.1	89	168	6.25	0.14	0.98	24.2	164.0
49	8.52	10.2	14.42	15	187.2	8	1	1	187.2	187.2
50	7	20	21	100	330	6	1	1	330	330
51	7	30	11.5	30	150	7	1	1	150	150
52	4.5	20	11	20	210	4.5	1	1	210	210
53	Unknown	Unknown	Unknown	Unknown	66	5.25	1	1	66.0	66.0
54	5.3	30	5.5	65	42.4	6	0.88	0.92	37.5	38.9
55	4.59	30	7.6	30	115.4	0	1	1	115.4	115.4
56	3.5	21.67	9.5	29	37.5	2.5	1	1	37.5	37.5
57	3.5	12.4	8	30.9	39.62	5.083	0.69	1	27.3	39.6
58	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-	-	-	-
59	0.7	2.2	4.7	73	158	5	0.14	0.94	22.1	148.5
60	2.78	43	5.4	43	108	below	1	1	108	108
61	3.25	12	8.5	24	51	2.75	1	1	51	51
62	1.92	0.33	7.5	0.5	104	3.5	1	1	20.4	104
63	4.27	30	4.27	30	93	below	1	1	93	93
64	2.5	30	13.2	60	28.4	3	0.83	1	23.67	28.4
65	4.27	30	4.27	30	93	below	1	1	93	93
66	5.8	45	9.9	201	224	5	1	1	224	224
67	3.6	Unknown	Unknown	Unknown	414	3	1	1	414	414
68	0.5	20	2.75	Unknown	370	0	1.00	1.00	370.0	370.0
69	2	35	6.7	35	125	2	1	1	125	125

Note: Submerged fractions were estimated for parametric cases where data were not known.

Table A-5. Calculation of ΔH_f.

ID No.	Reported NPSH Margin (ft)	Switchover Pool Height (ft)	Screen Height (ft)	Min Calc	Favorable ΔH_f (ft)	Unfavorable ΔH_f (ft)
1	10.02	5.3	6	2.65	2.75	2.65
2	5	2.24	6.25	1.12	2.35	1.12
3	3.8	4.5	4.5	3.8	3.8	3.8
4	1.7	5.5	Unknown	1.7	1.7	1.7
5	8.2	2.93	1	8.2	8.2	8.2
6	9	Unknown	5.25	9	9	9
7	4.3	0.82	1.5	0.41	4.3	0.41
8	1.7	5.5	Unknown	1.7	1.7	1.7
9	2.6	3.5	0	2.6	2.6	2.6
10	1.9	1.92	3.5	0.96	1.9	0.96
11	3	5.25	3.5	3	3	3
12	None Reported	5.33	0	N.A.	12	0
13	None Reported	1.74	0	N.A.	12	0
14	0.96	6	4.75	0.96	0.96	0.96
15	0.54	3.84	2.2	0.54	0.54	0.54
16	3	5.25	3.5	3	3	3
17	1.1	5.4	3.5	1.1	1.1	1.1
18	9.26	2.5	3	1.25	9.26	1.25
19	3.3	2.1	0	3.3	3.3	3.3
20	2.6	3.5	0	2.6	2.6	2.6
21	7.35	5.43	5	7.35	7.35	7.35
22	4.2	1.5	0	4.2	4.2	4.2
23	5	2.24	6.25	1.12	2.35	1.12
24	4.3	0.82	1.5	0.41	4.3	0.41
25	3.5	3.6	3	3.5	3.5	3.5
26	1.5	4.27	below	1.5	1.5	1.5
27	0.9	2.12	8.667	0.9	0.9	0.9
28	1.1	3.67	3.75	1.1	1.1	1.1
29	4.3	0.82	1.5	0.41	4.3	0.41
30	3.6	2.73	5	1.365	3.6	1.37
31	4.3	0.82	1.5	0.41	4.3	0.41
32	0.7	0.9	6.25	0.45	0.7	0.45
33	0.9	1.9	7	0.9	0.9	0.9
34	13	3.25	2.75	13	13	13
35	8.2	2.93	1	8.2	8.2	8.2

Table A-5. Calculation of ΔH_f (cont).

ID No.	Reported NPSH Margin (ft)	Switchover Pool Height (ft)	Screen Height (ft)	Min Calc	Favorable ΔH_f (ft)	Unfavorable ΔH_f (ft)
36	1.3	4	below	1.3	1.3	1.3
37	0.83	0.7	5	0.35	0.83	0.35
38	3.8	4.5	4.5	3.8	3.8	3.8
39	None Reported	3	3	N.A.	12	0
40	0.9	5.8	5	0.9	0.9	0.9
41	5.25	7	6	5.25	5.25	5.25
42	3.9	3.67	3.75	1.835	3.9	1.84
43	3.6	2.73	5	1.365	3.6	1.37
44	1.3	3.5	2.5	1.3	1.3	1.3
45	0	3.5	0	0	0	0
46	1.07	2.13	0	1.07	1.07	1.07
47	0.97	1.75	0	0.97	0.97	0.97
48	0.7	0.9	6.25	0.45	0.7	0.45
49	1.7	8.52	8	1.7	1.7	1.7
50	5.25	7	6	5.25	5.25	5.25
51	0.62	7	7	0.62	0.62	0.62
52	3.8	4.5	4.5	3.8	3.8	3.8
53	9	Unknown	5.25	9	9	9
54	10.02	5.3	6	2.65	2.75	2.65
55	1.01	4.59	0	1.01	1.01	1.01
56	1.3	3.5	2.5	1.3	1.3	1.3
57	17	3.5	5.083	1.75	17	1.75
58	15.1	Unknown	Unknown	15.1	15.1	0
59	0.83	0.7	5	0.35	0.83	0.35
60	5.6	2.78	0	5.6	5.6	5.6
61	13	3.25	2.75	13	13	13
62	1.9	1.92	3.5	0.96	1.9	1.9
63	1.5	4.27	below	1.5	1.5	1.5
64	9.26	2.5	3	1.25	9.26	1.25
65	1.5	4.27	below	1.5	1.5	1.5
66	0.6	5.8	5	0.6	0.6	0.6
67	3.5	3.6	3	3.5	3.5	3.5
68	2.1	0.5	0	2.1	2.1	2.1
69	2.4	2	2	2.4	2.4	2.4

Notes:

1. Where no $NPSH_{Margin}$ was reported in the survey, values of 0 ft-H_20 and 12 ft-H_20 were assumed for minimum and maximum NPSH margin, respectively.

2. For fully submerged screens, ΔH_f was assumed to be equal to the reported $NPSH_{Margin}$. For partially submerged screens, ΔH_f was calculated to be the lesser of the reported $NPSH_{Margin}$ and half the pool height.

Table A-6. Screen Characteristics.

ID No.	Sump Location	Screen Hole Size (in.)	ID No.	Sump Location	Screen Hole Size (in.)
1	exposed	0.125	36	remote	0.25
2	remote	0.115	37	exposed	0.75
3	remote	0.09	38	remote	0.09
4	Unknown	0.204	39	int. exp.	0.125
5	int. exp.	0.25	40	remote	0.094
6	int. exp.	0.250	41	Unknown	0.12
7	Unknown	0.152	42	remote	0.125
8	Unknown	0.204	43	int. exp.	0.125
9	remote	0.12	44	int. exp.	0.12
10	int. exp.	0.3	45	Unknown	0.132
11	exposed	0.224	46	int. exp.	0.25
12	Unknown	0.25	47	int. exp.	0.25
13	remote	0.125	48	exposed	0.1197
14	exposed	0.132	49	exposed	0.25
15	Unknown	0.097	50	Unknown	0.12
16	exposed	0.224	51	remote	0.1875
17	remote	0.1783	52	remote	0.09
18	exposed	0.25	53	int. exp.	0.250
19	int. exp.	0.125	54	exposed	0.125
20	remote	0.12	55	exposed	0.09375
21	remote	0.078	56	int. exp.	0.12
22	Unknown	0.221	57	int. exp.	1
23	remote	0.115	58	Unknown	Unknown
24	Unknown	0.152	59	exposed	0.75
25	remote	0.25	60	exposed	0.1875
26	exposed	0.12	61	int. exp.	Unknown
27	remote	0.125	62	int. exp.	0.3
28	remote	0.125	63	exposed	0.12
29	Unknown	0.152	64	exposed	0.25
30	int. exp.	0.125	65	exposed	0.12
31	Unknown	0.152	66	remote	Unknown
32	exposed	0.1197	67	remote	0.25
33	Unknown	0.25	68	int. exp.	0.25
34	int. exp.	Unknown	69	Unknown	0.25
35	int. exp.	0.25			

APPENDIX B

FAILURE-THRESHOLD DEBRIS LOADING FOR EACH PARAMETRIC CASE

The minimum mass of particulate needed to cause blockage for a specified fiber volume was determined for

- each parameter case;
- the small-, medium-, and large-break scenarios;
- full-ECCS flow and half-ECCS flow (for MLOCA and LLOCA); and
- both favorable and unfavorable parameter values.

In addition, the range of expected debris generated and transported to the sump screen was compared with fiber/particulate debris combinations predicted to cause blockage. The results for each parameter case were combined into a set of four plots presented on a single page. Because so much input data and synthesized analysis is presented together in a generic format, these figures are, in some cases, relatively complex.

The first plot on each page (upper left) provides tabular data associated with that particular case. These data include the ranges (favorable to unfavorable conditions) of debris expected on the sump screen, the screen area, the $NPSH_{Margin}$, the small-break and full-ECCS flow rates. Also shown in the first plot are the fiber debris volumes and miscellaneous particulate mass plotted on a linear scale.

The second plot (upper right) on each page shows the results for the SLOCA scenario. Both the favorable (solid line) and unfavorable (dashed line) minimum-particulate-mass curves are plotted. Note the log-scales. For example, in parametric case 1, the primary difference between favorable and unfavorable conditions was the composition of insulation. The plant has fiber, RMI, and particulate insulation, but the relative fractions of each were not reported. In addition, the type of fiber was not reported. Therefore, favorable conditions assumed very little fiber and very little particulate insulation; i.e., most of the insulation was assumed to be RMI. Conversely, the unfavorable conditions assumed little RMI but equal quantities of fiber and particulate insulations. Further, the favorable conditions assumed the fiber was LDFG, such as Nukon, but the unfavorable conditions assumed the fibrous insulation was high-density fiberglass, such as Temp Mat. High-density fiberglass will cause a larger head loss than low-density fiberglass. As shown in the second plot for case 1, it would take substantially less particulate to block the screen for the unfavorable conditions than it would for the favorable conditions. The gap between the two curves provides some measure of the uncertainty associated with predicting blockage. The square symbol represents the threshold debris loadings needed to cause blockage, i.e., where induced head loss is equal to the sump failure criterion, ΔH_f. The volume of fiber at the squares is just sufficient to create a uniform 1/8-in. layer of fiber across the sump screen assumed for the associated parametric case. The plotted curves rise vertically at the square symbols indicating that without the threshold layer of fiber (fiber volume less than that of the threshold conditions), an unlimited mass of particulate would not cause blockage. This was a fundamental assumption common to all the head-loss calculations with regard to particulates.

The ranges of expected debris on the screen for the SLOCA are shown as a dashed-line box on the second plot, and the boundaries of the box are highlighted on the axes with the circle symbol. Note that the expected mass of particulate includes both particulate-insulation debris and miscellaneous particulate transported to the screen. The range of particulate for the SLOCA is printed near the top of the plot.

The third plot (lower left) on each page provides information similar to the second plot but for the MLOCA. Where only one flow rate was assumed for the SLOCA scenarios, two flow rates were assumed for the MLOCA and LLOCA scenarios, i.e., full ECCS flow and one-half of the total ECCS flow rate. This was intended to illustrate the effect of operating with one train of the ECCS instead of two trains of the ECCS. Therefore, the third plot has four minimum-particulate curves, i.e., favorable and unfavorable conditions at full- and half-ECCS flow.

The fourth plot (lower right) on each page shows the same information for the LLOCA as the third plot shows for the MLOCA. Actually, the minimum-particulate head-loss curves are the same for the MLOCA and LLOCA scenarios, but the expected debris ranges are substantially different.

When the figures are examined for each parametric case, it becomes evident that the sump failure curves for some plants intersect the dashed box defining the range of fibrous and particulate debris that may be expected to transport to the sump. All debris combinations within the box and to the right of the failure-threshold will induce head loss in excess of the sump failure criterion. For all debris combinations to the left of the failure threshold, the sump will continue to function as required. Thus, the proportion of the area in the expected-range box that lies to the right of the curve provides a rough indication of the sump failure potential for these intermediate cases. For example, in case 1, approximately 73% of all reasonable debris loadings would provide debris conditions leading to sump blockage following an SLOCA. Table B-1, listed at the end of the figures, provides this percentage for the SLOCA, MLOCA and LLOCA for each of the 69 parametric cases.

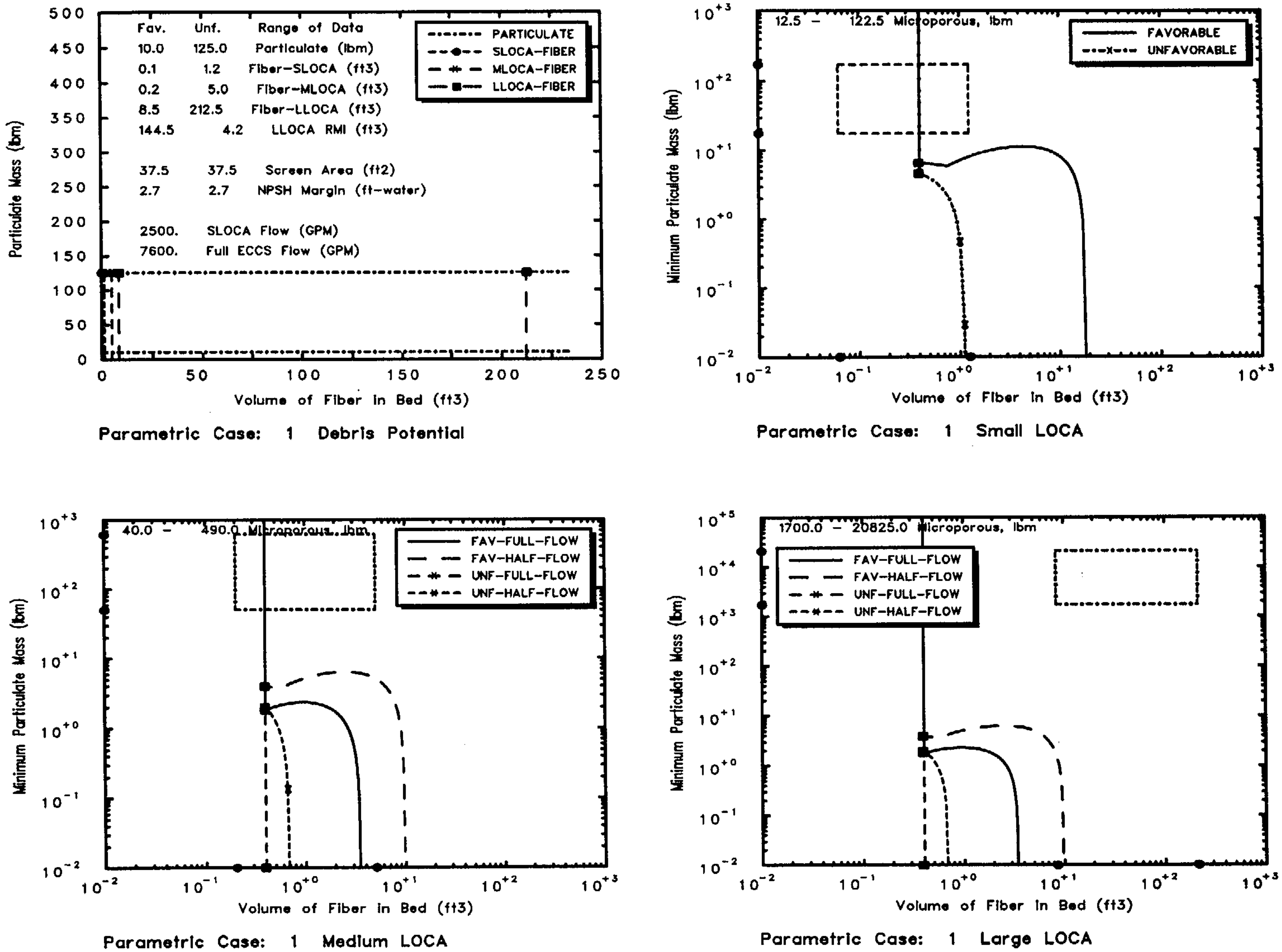


Fig. B-1. Parametric Case 1.

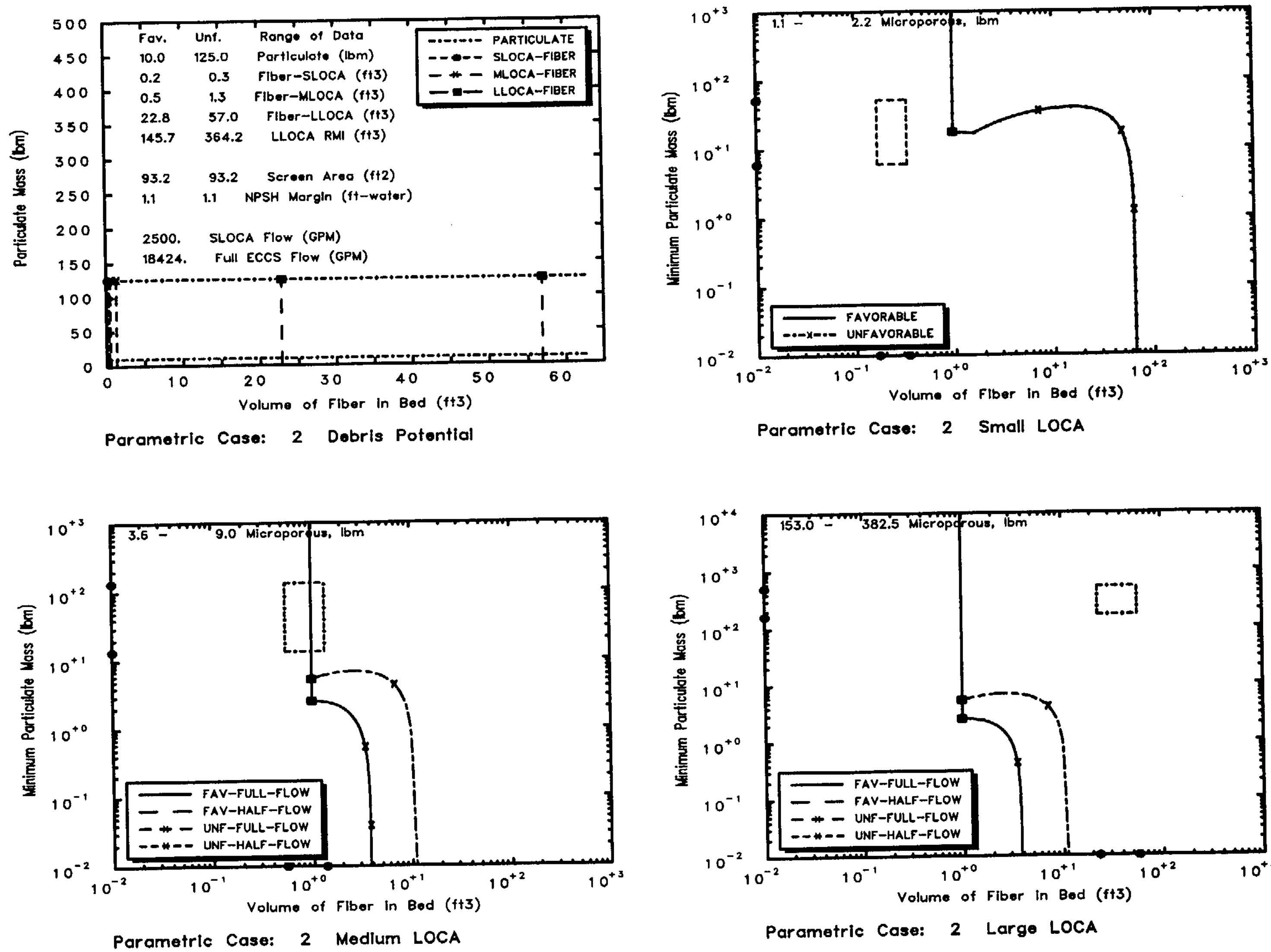


Fig. B-2. Parametric Case 2.

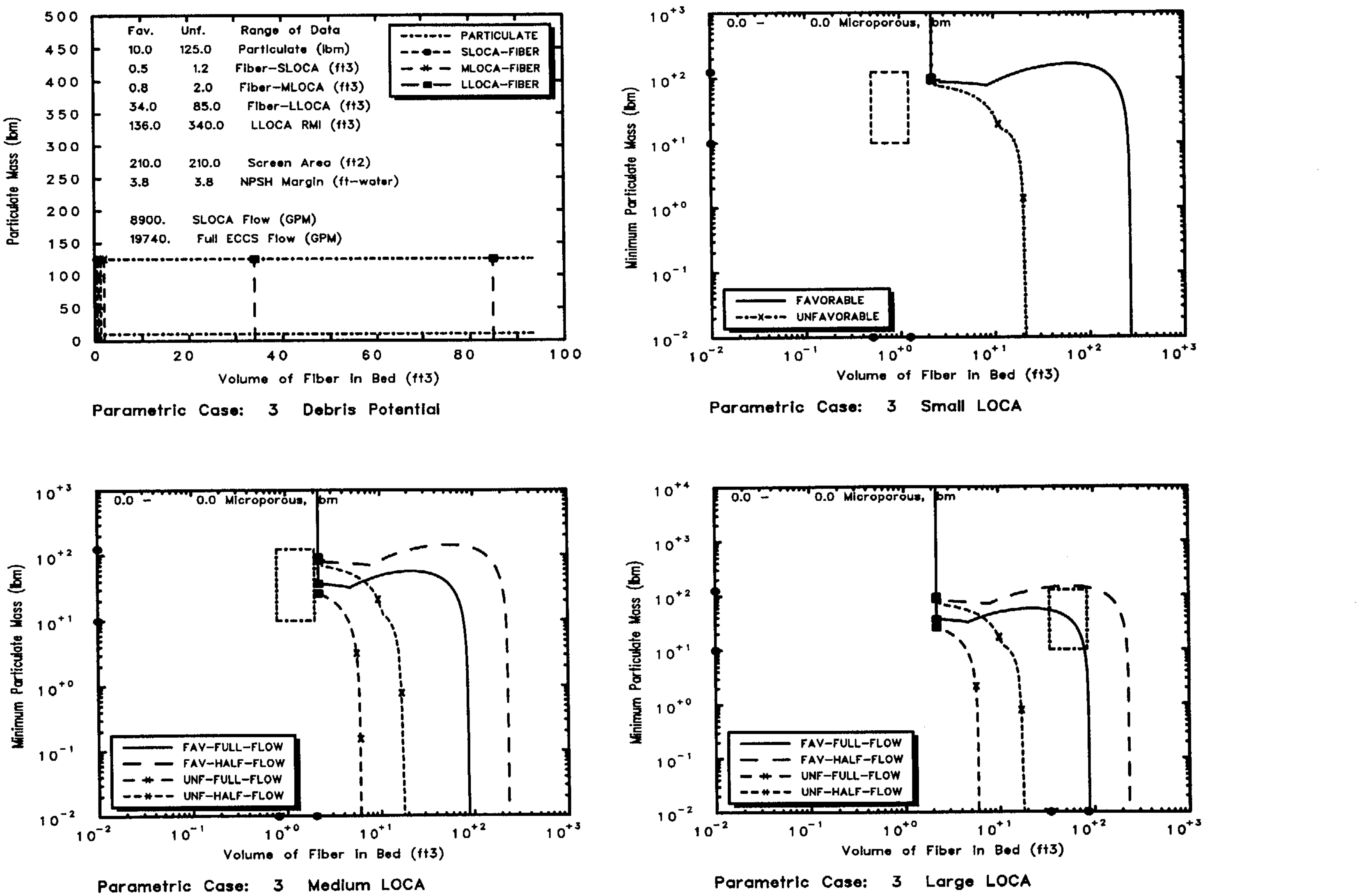


Fig. B-3. Parametric Case 3.

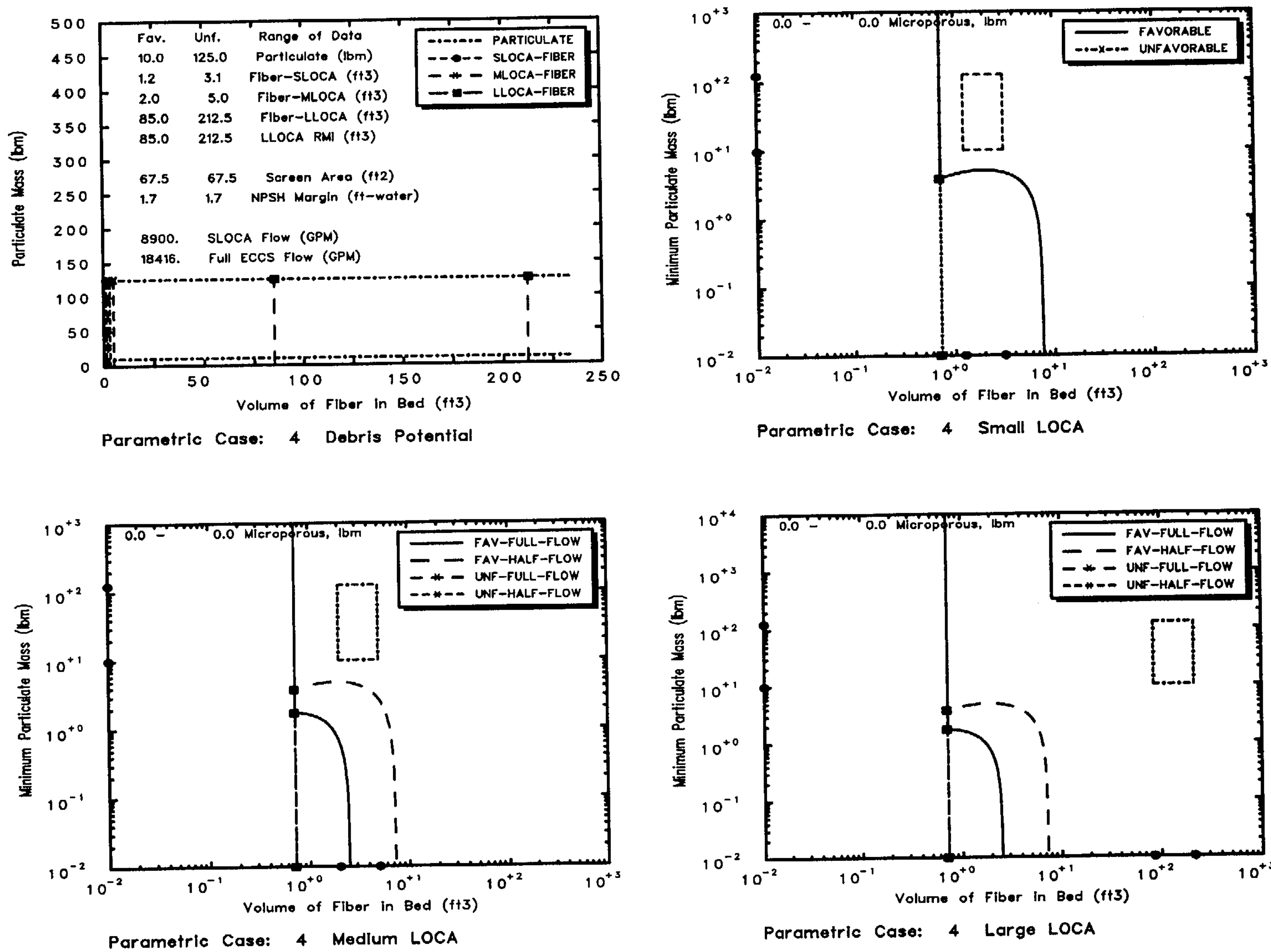


Fig. B-4. Parametric Case 4.

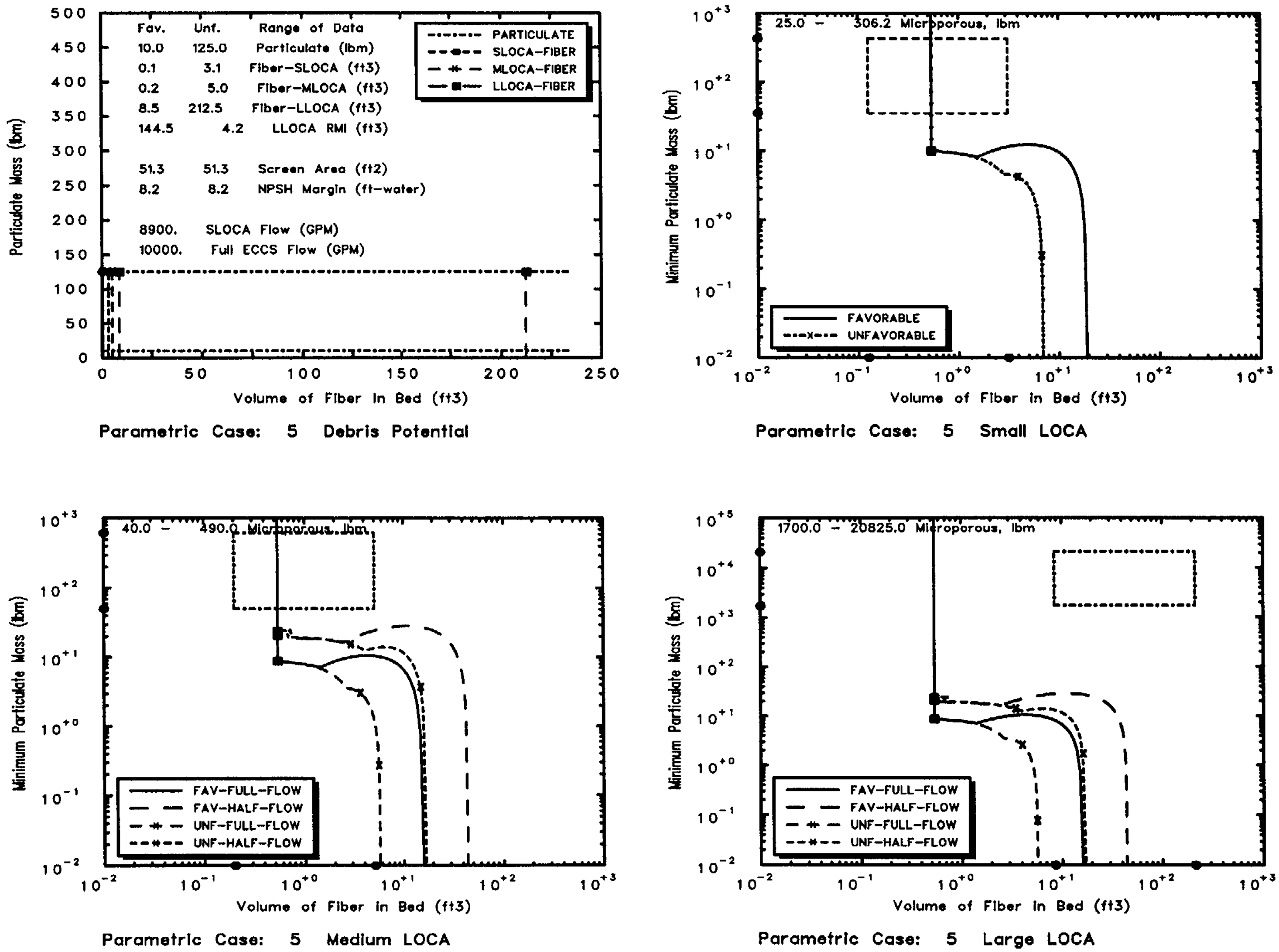


Fig. B-5. Parametric Case 5.

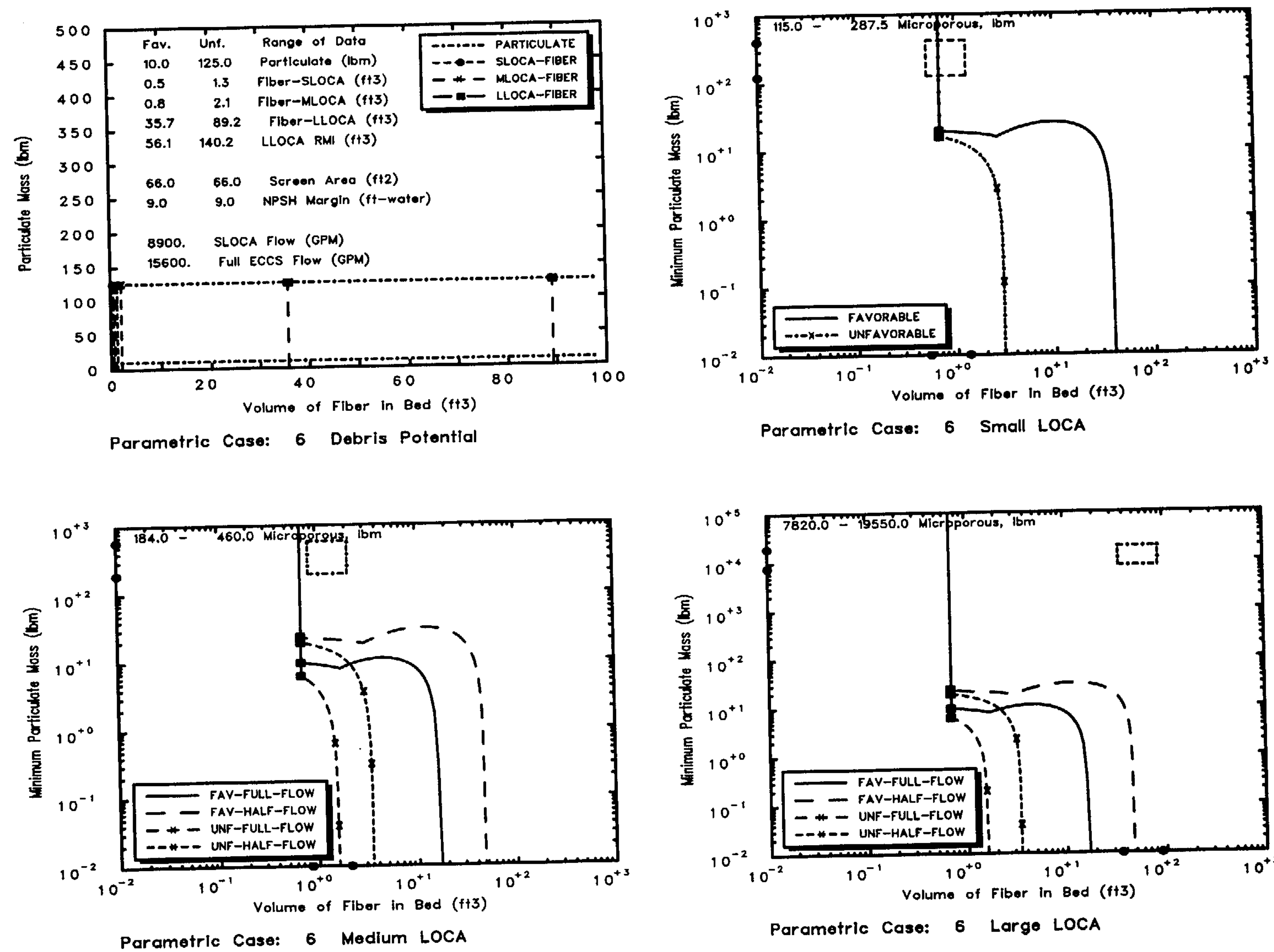


Fig. B-6. Parametric Case 6.

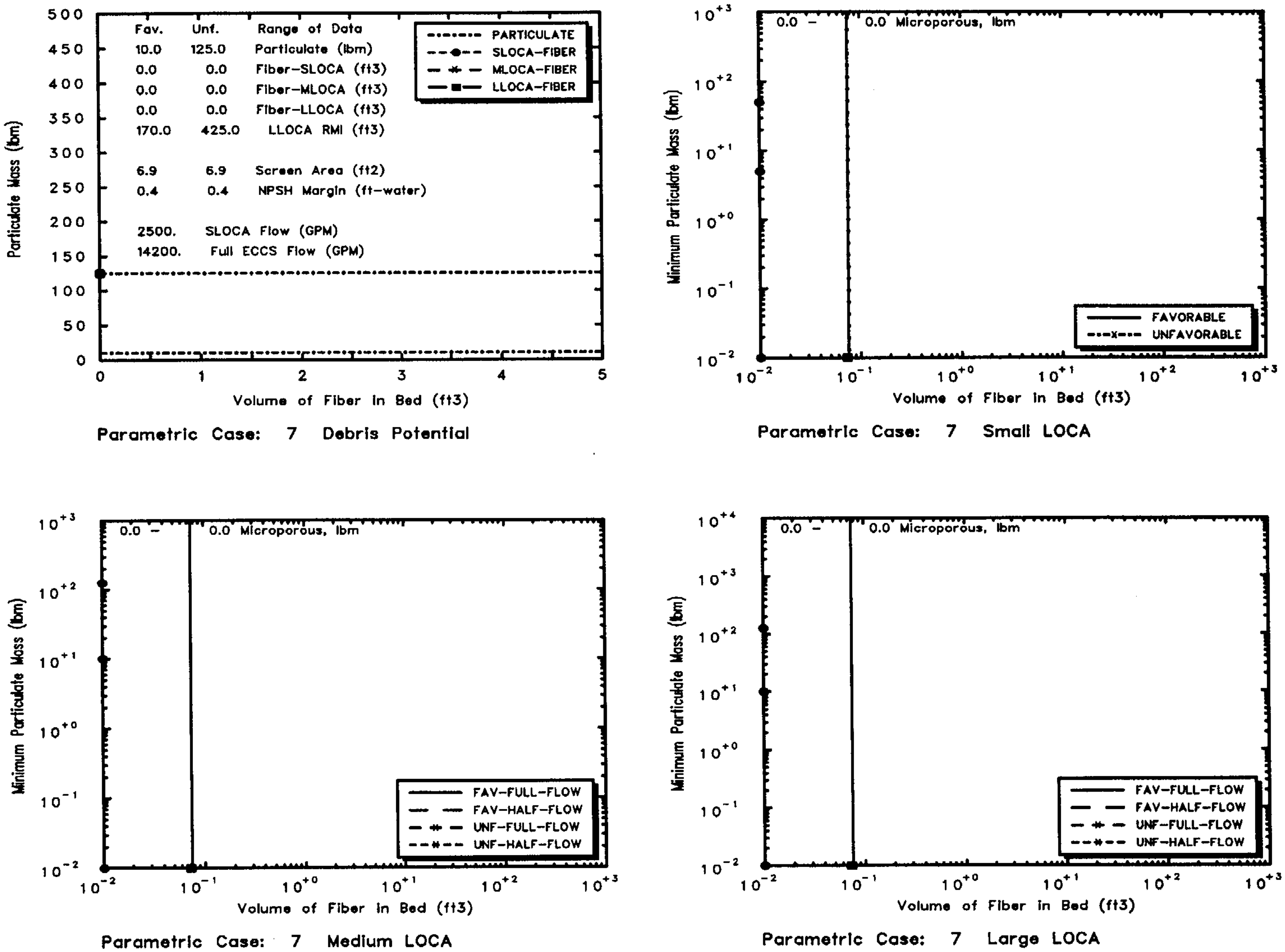


Fig. B-7. Parametric Case 7 (Note: No fiber in this case, so no debris boxes presented).

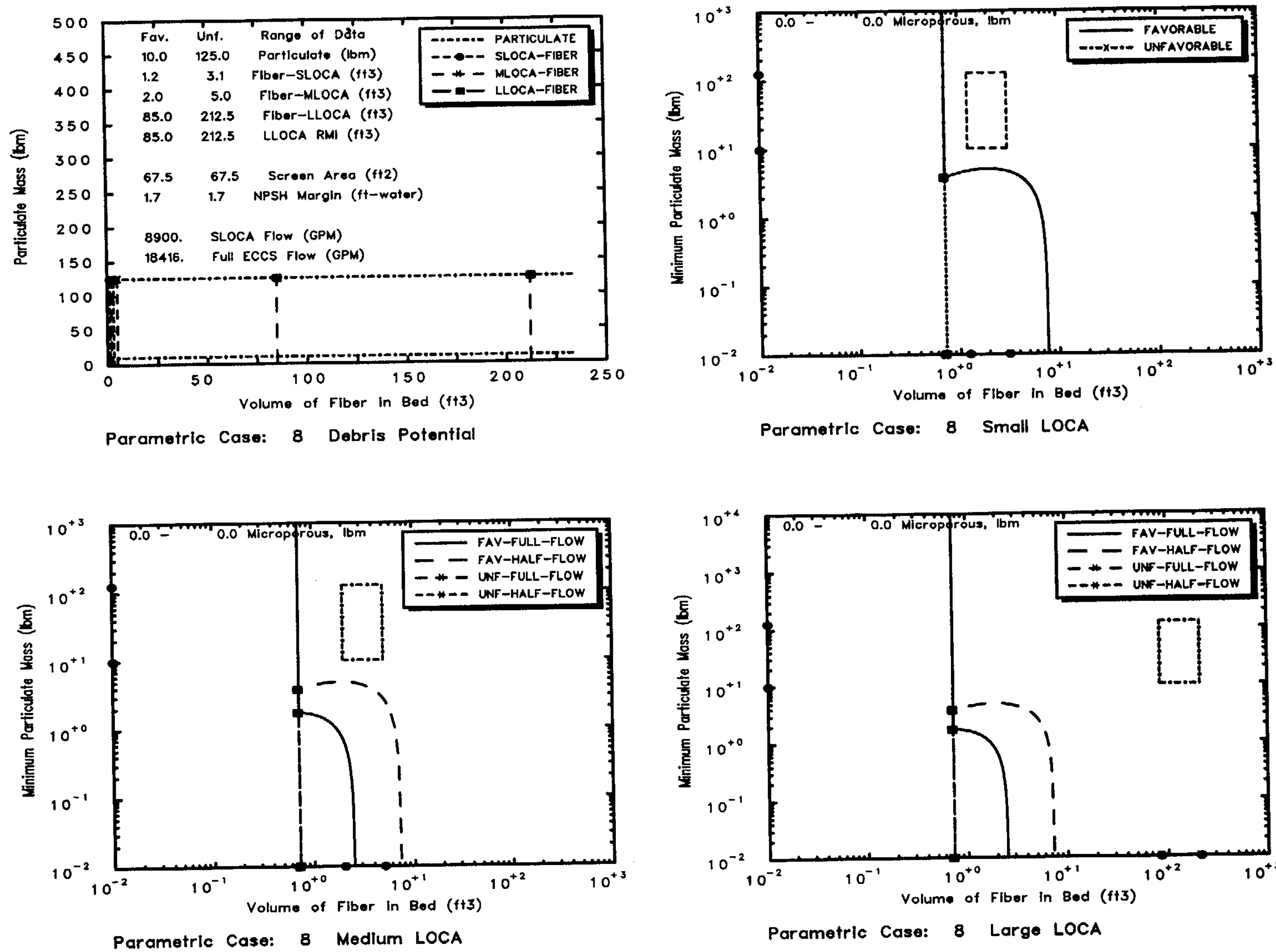


Fig. B-8. Parametric Case 8.

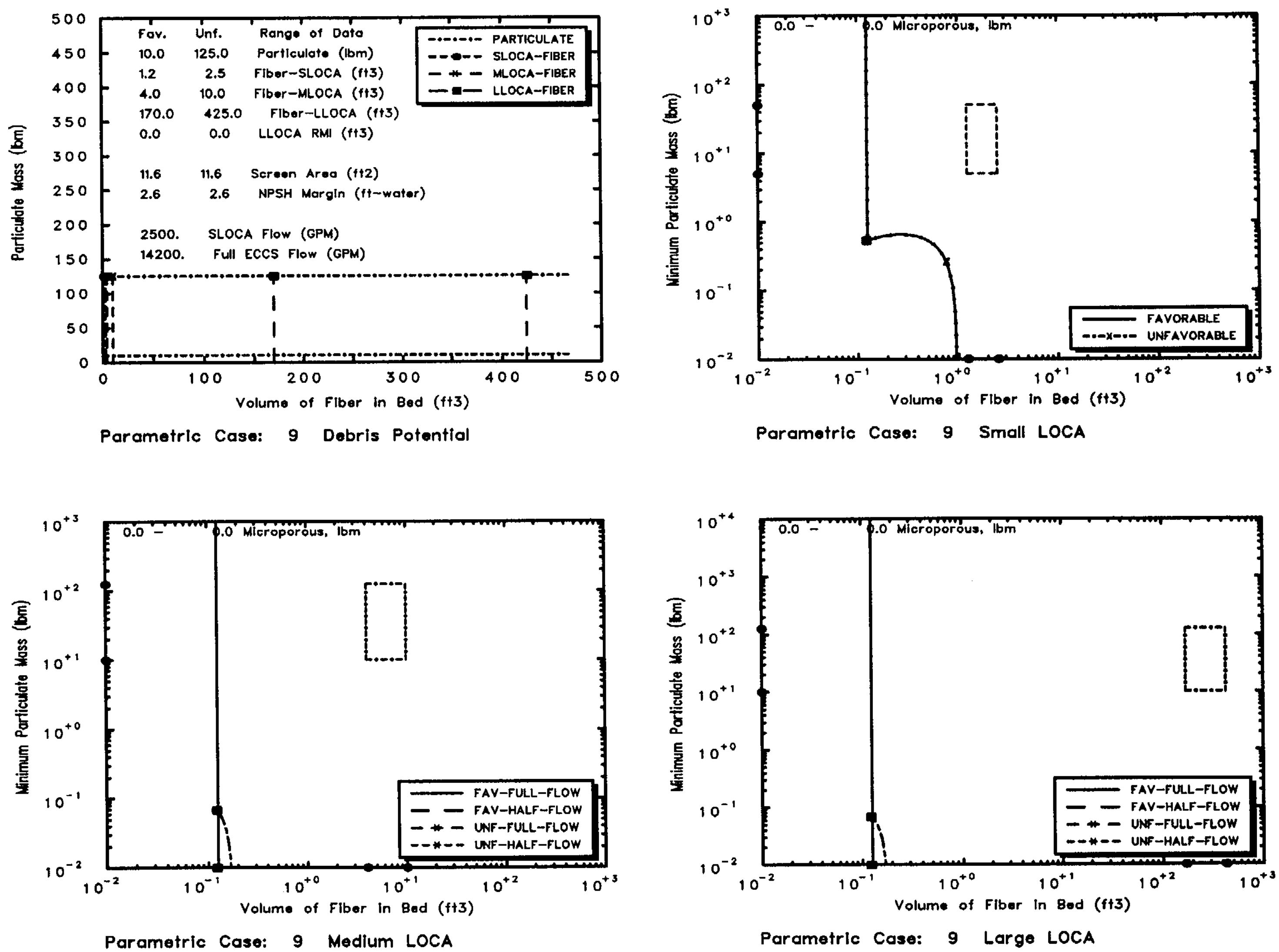


Fig. B-9. Parametric Case 9.

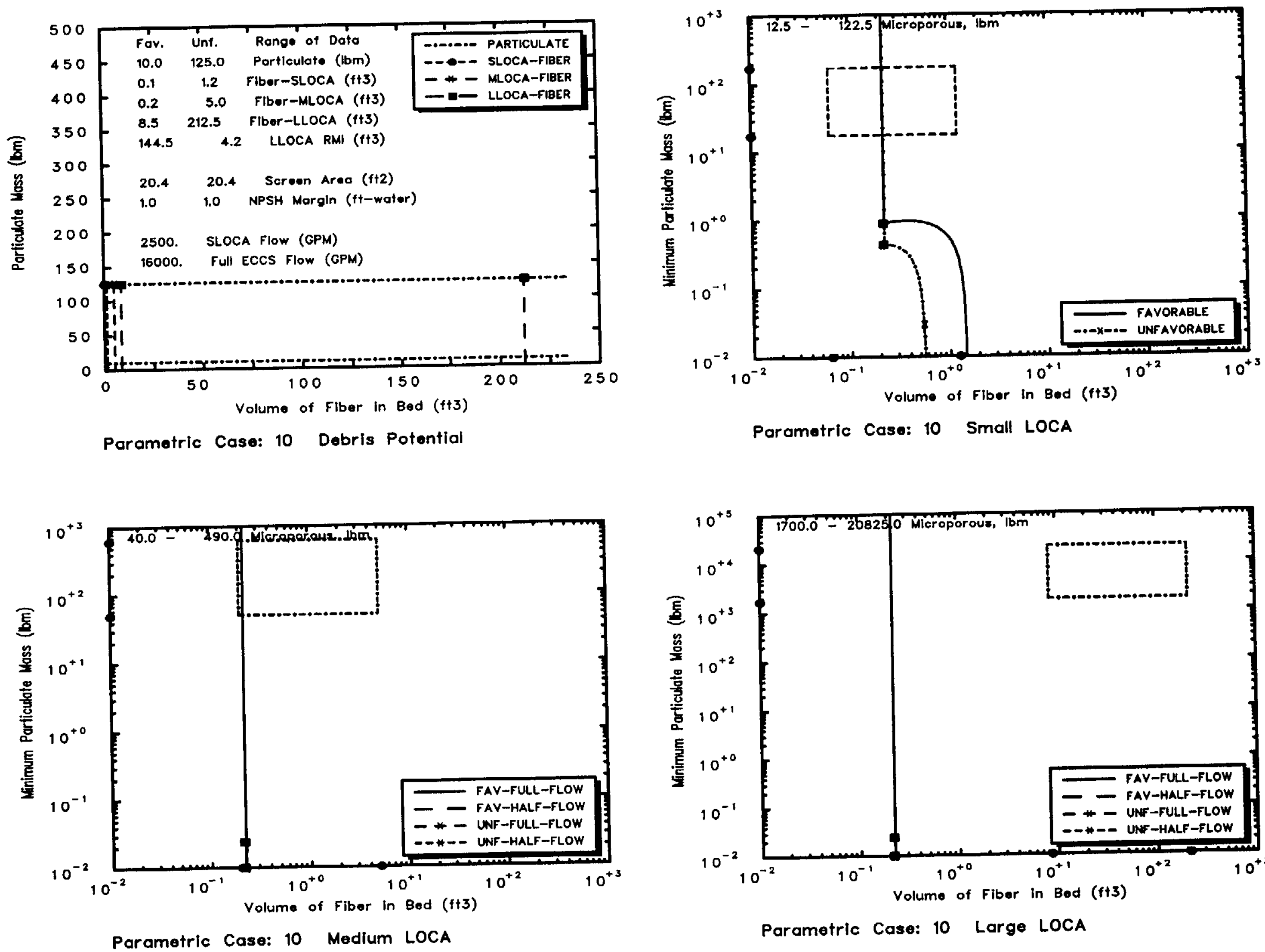


Fig. B-10. Parametric Case 10.

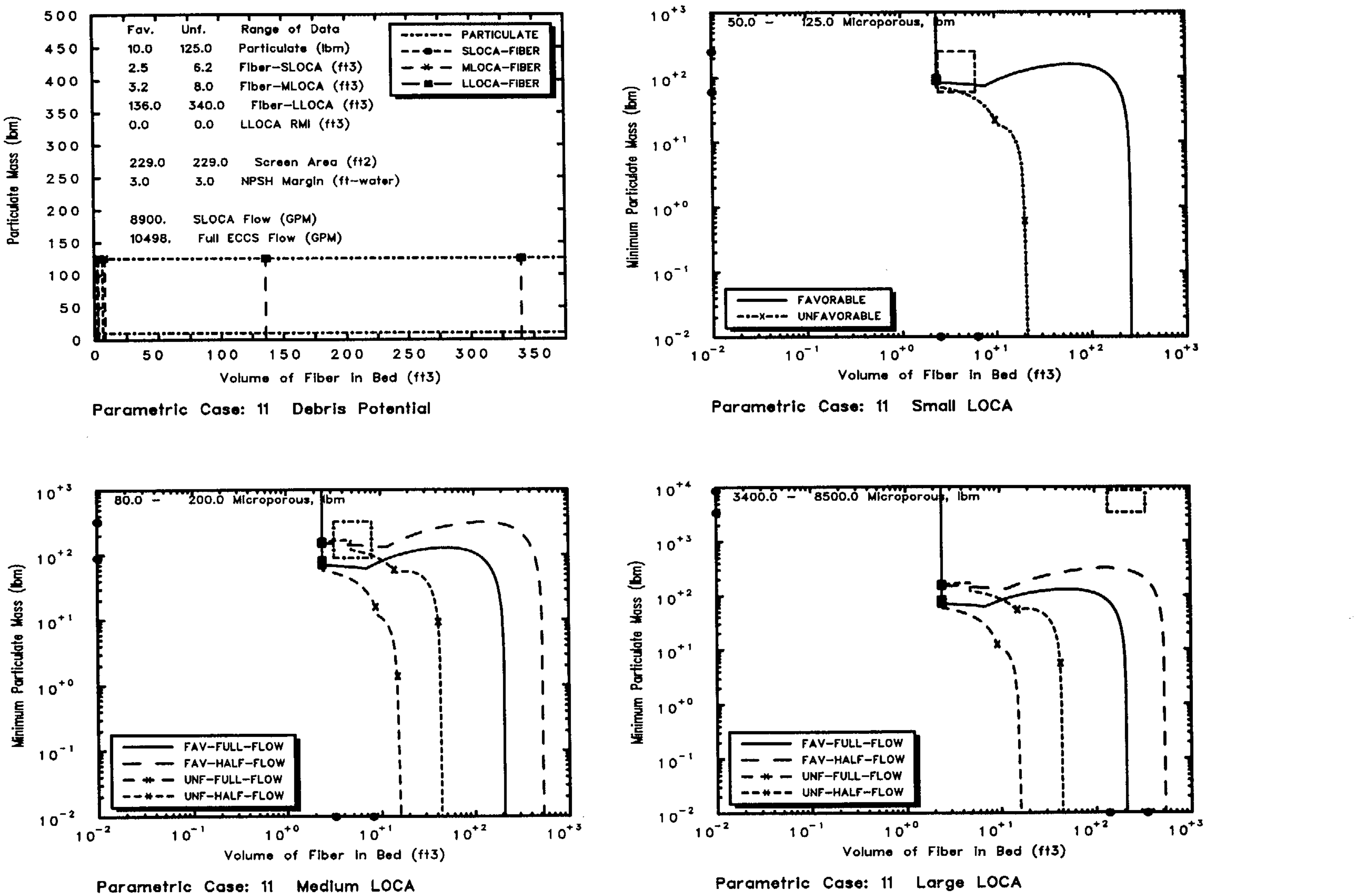


Fig. B-11. Parametric Case 11.

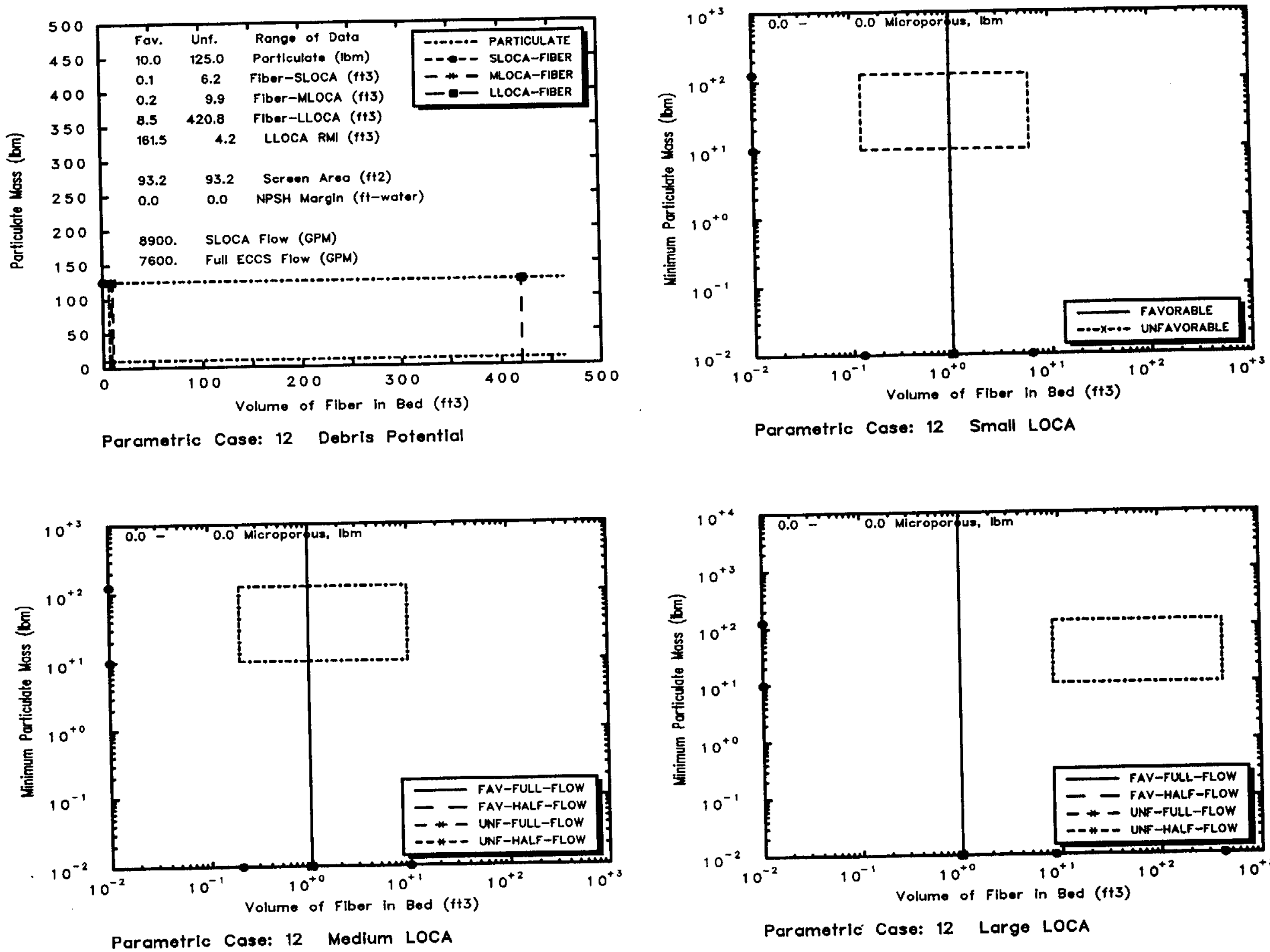


Fig. B-12. Parametric Case 12.

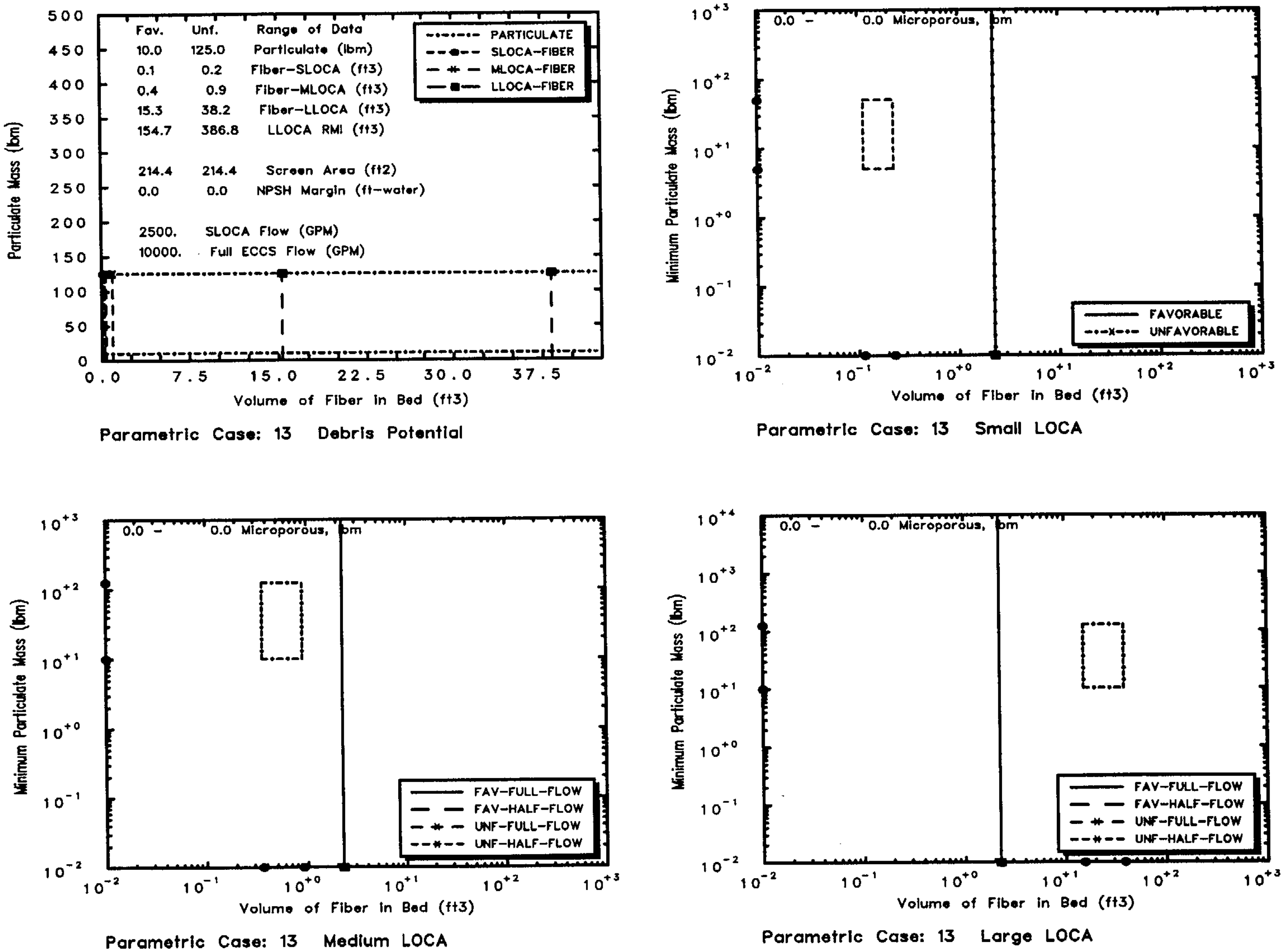


Fig. B-13. Parametric Case 13.

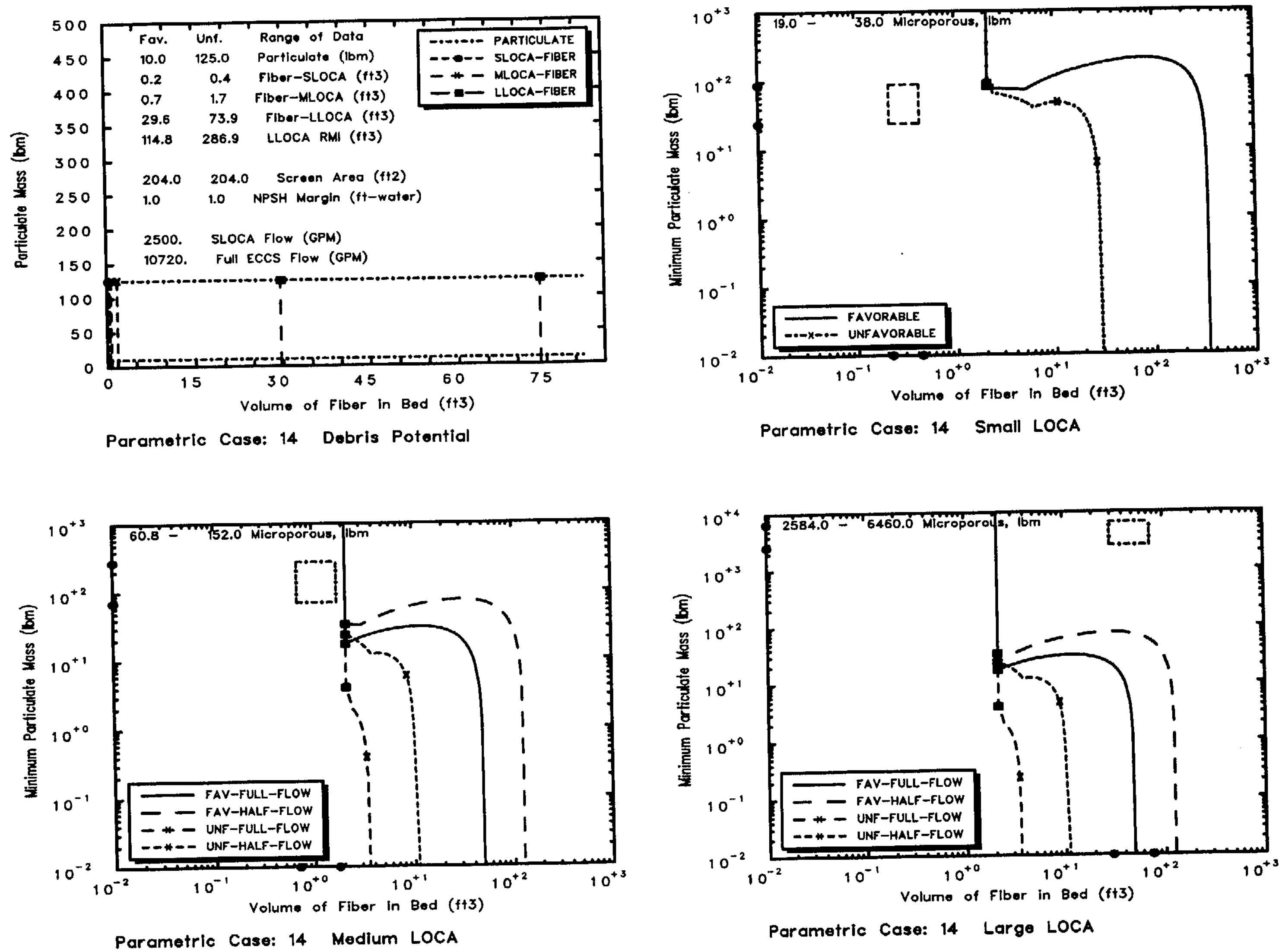


Fig. B-14. Parametric Case 14.

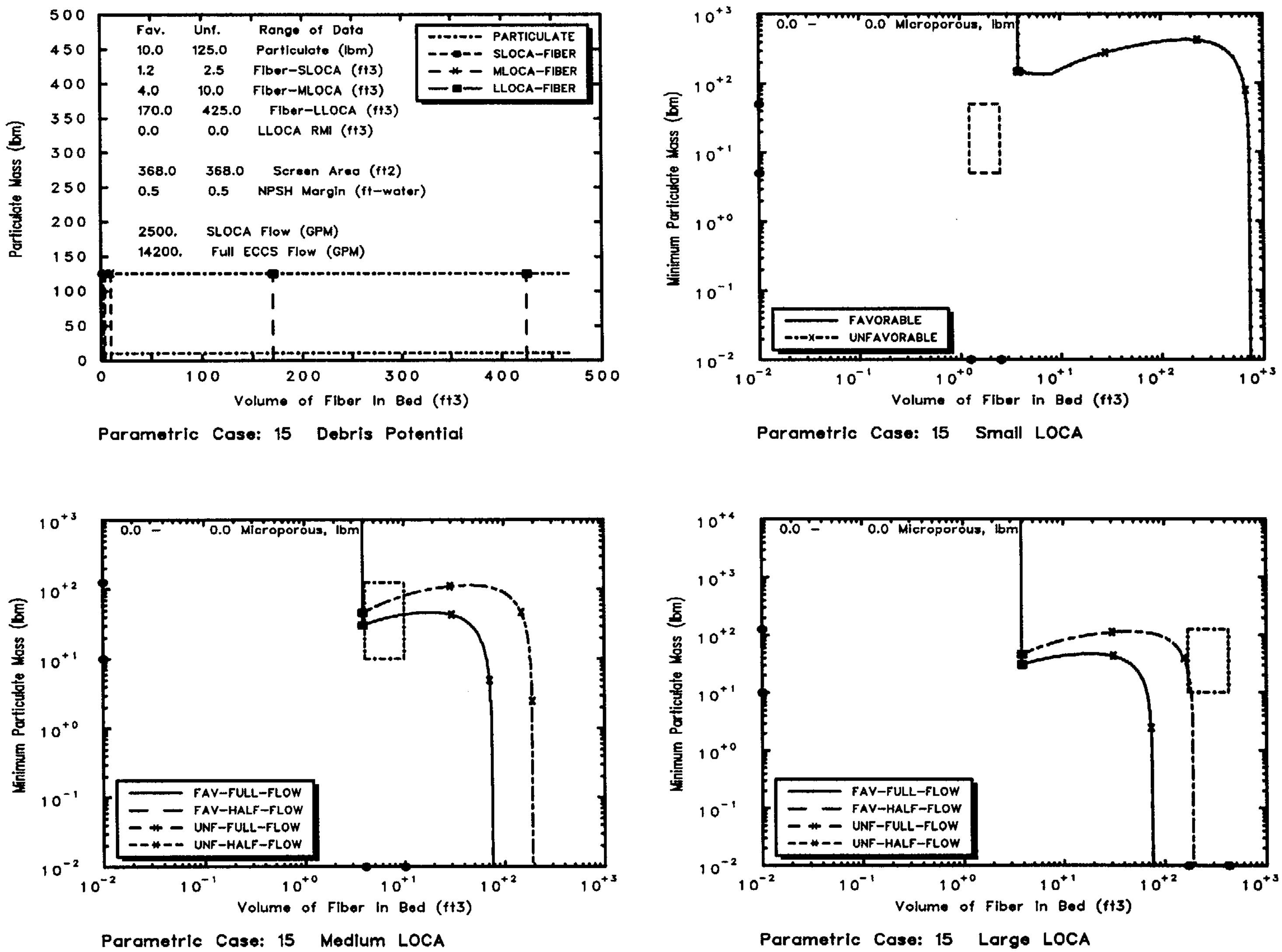


Fig. B-15. Parametric Case 15.

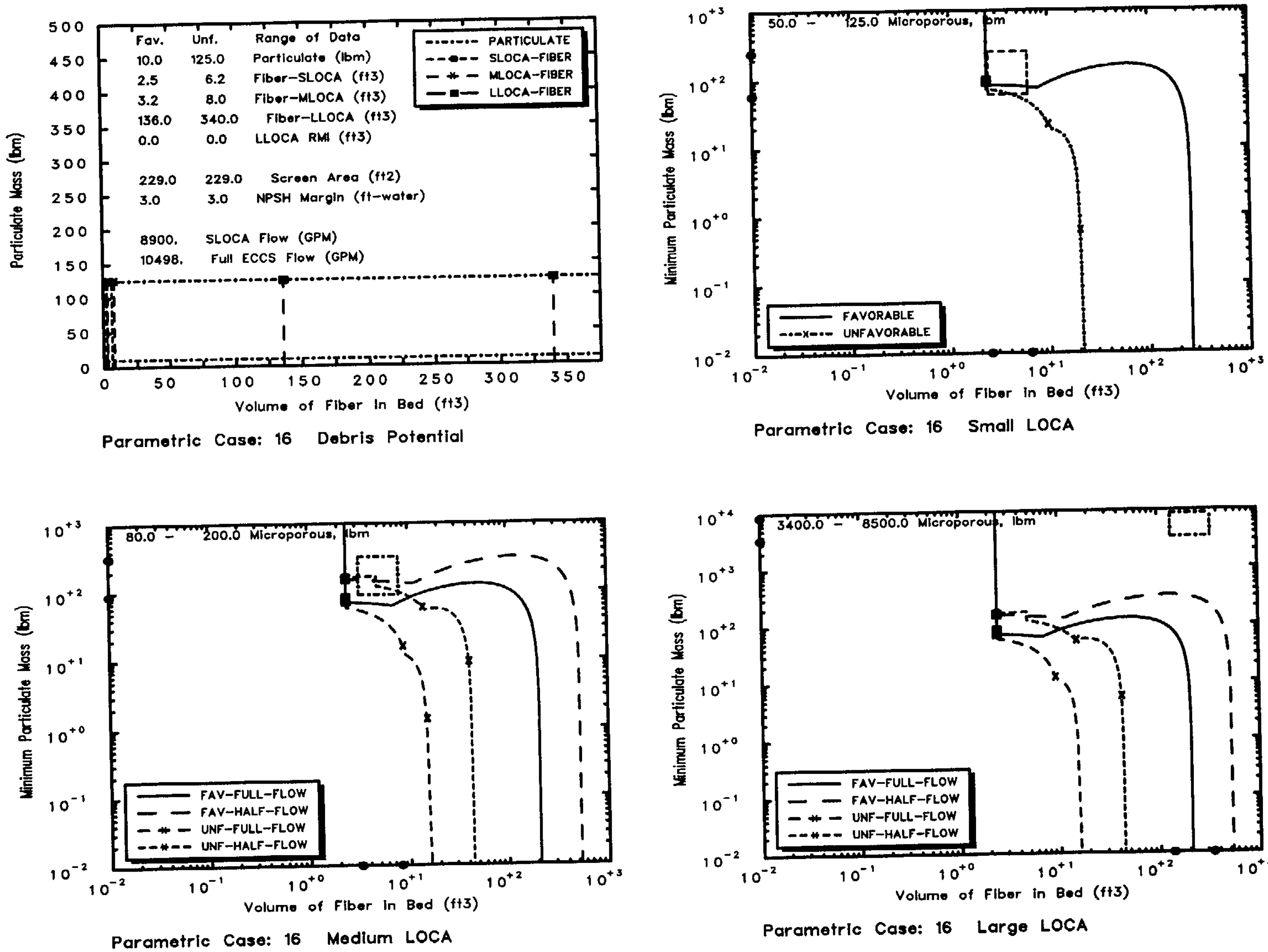


Fig. B-16. Parametric Case 16.

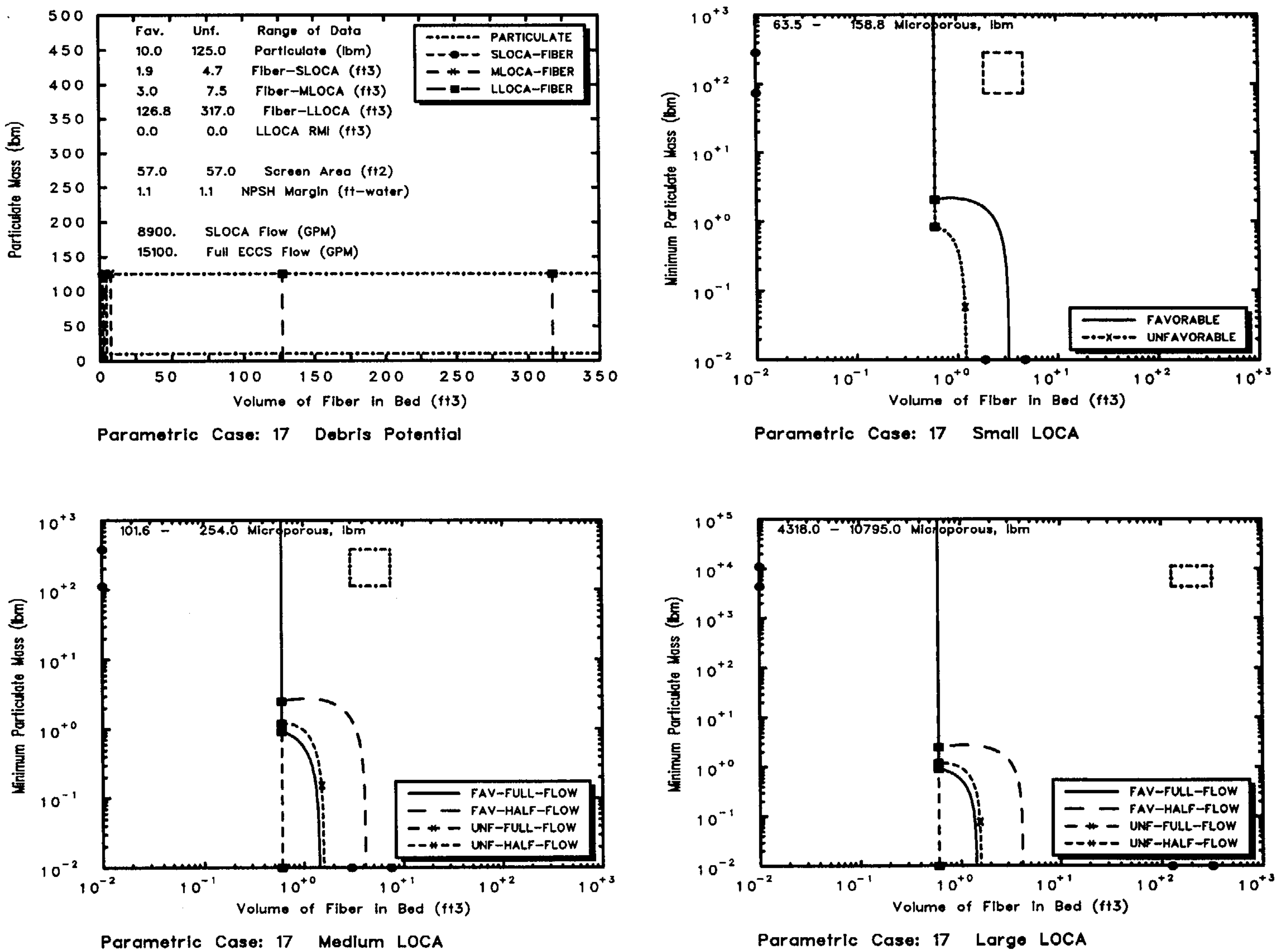


Fig. B-17. Parametric Case 17.

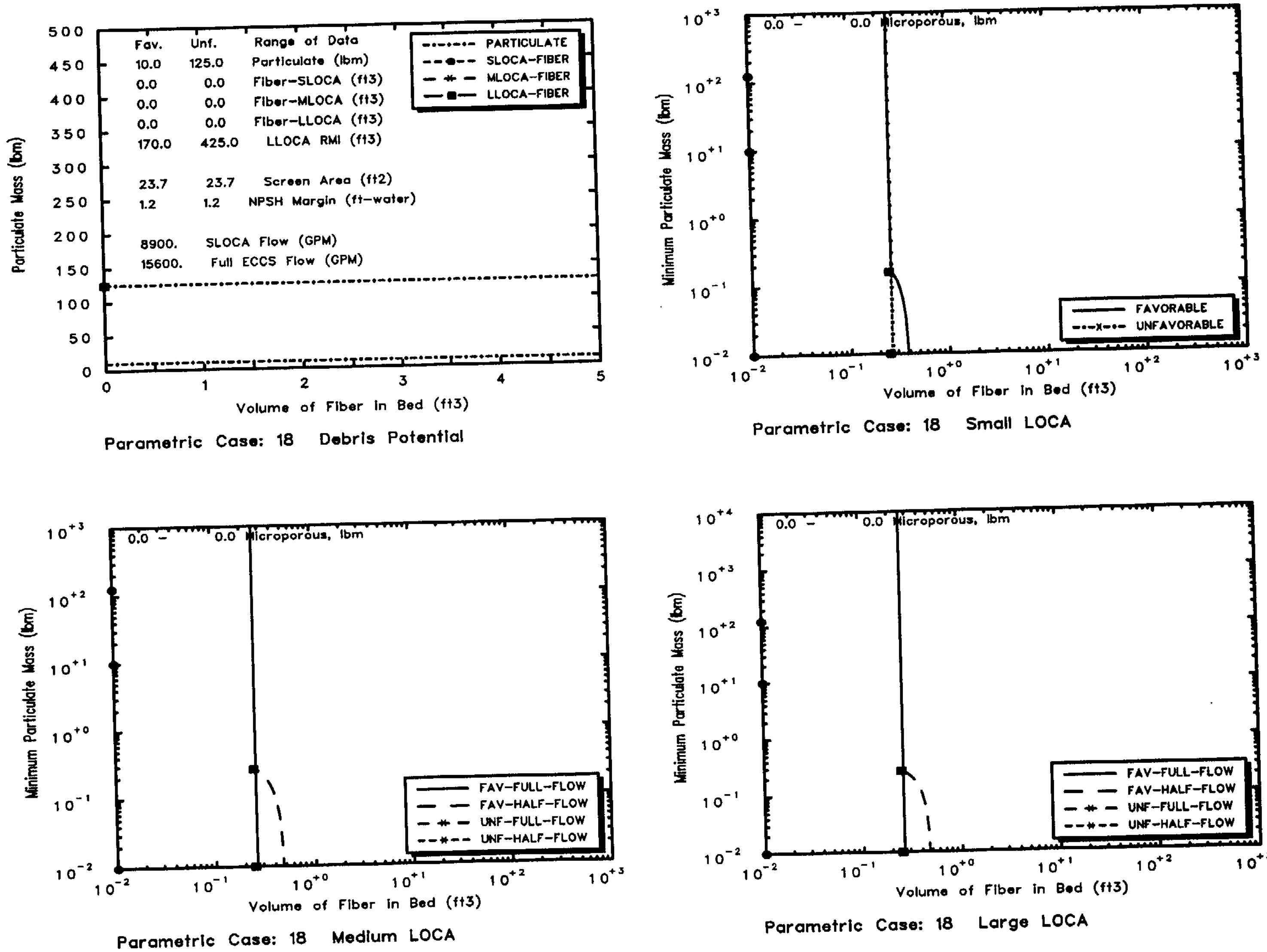


Fig. B-18. Parametric Case 18 (Note: No fiber in this case, so no debris boxes presented).

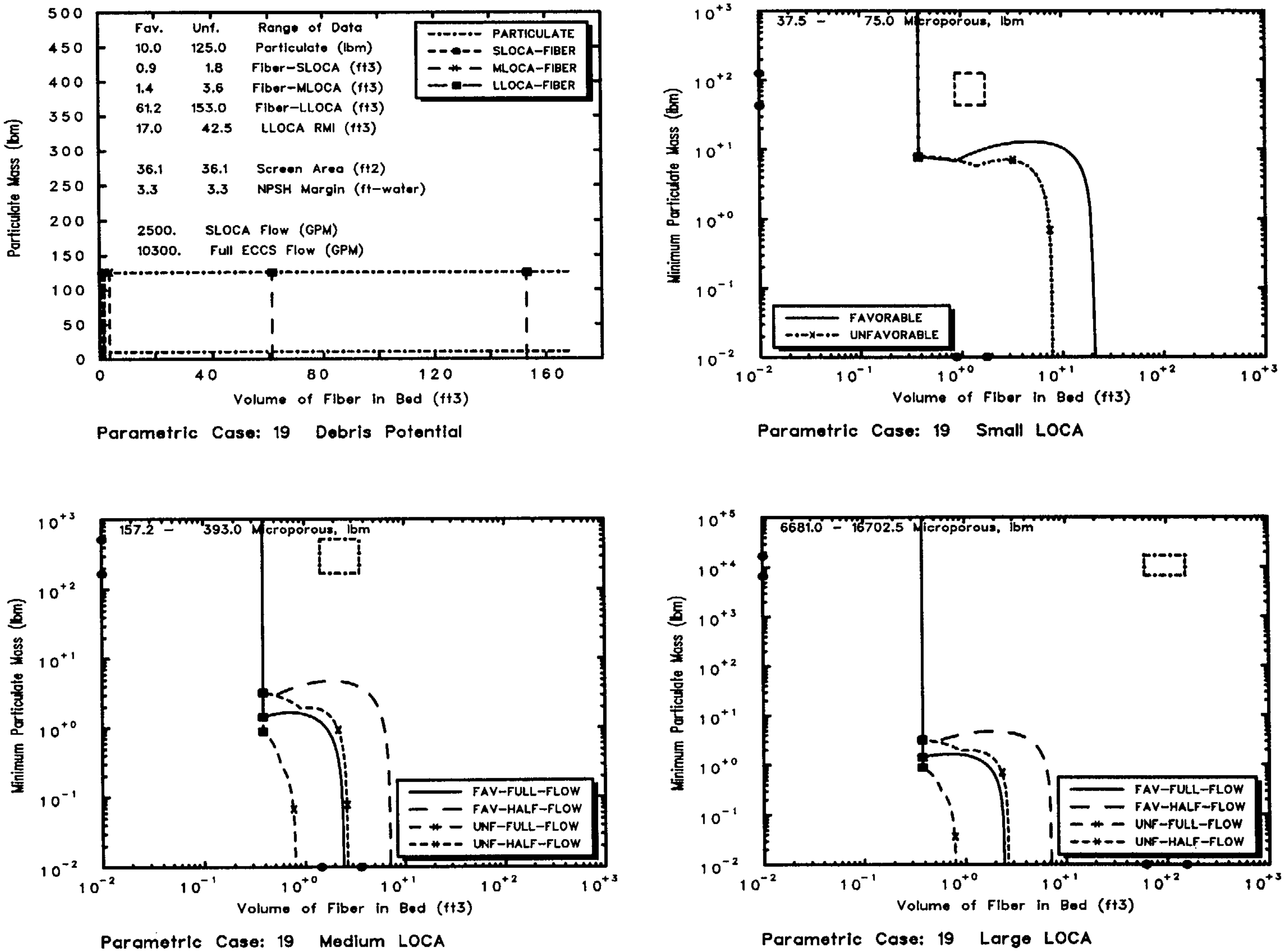


Fig. B-19. Parametric Case 19.

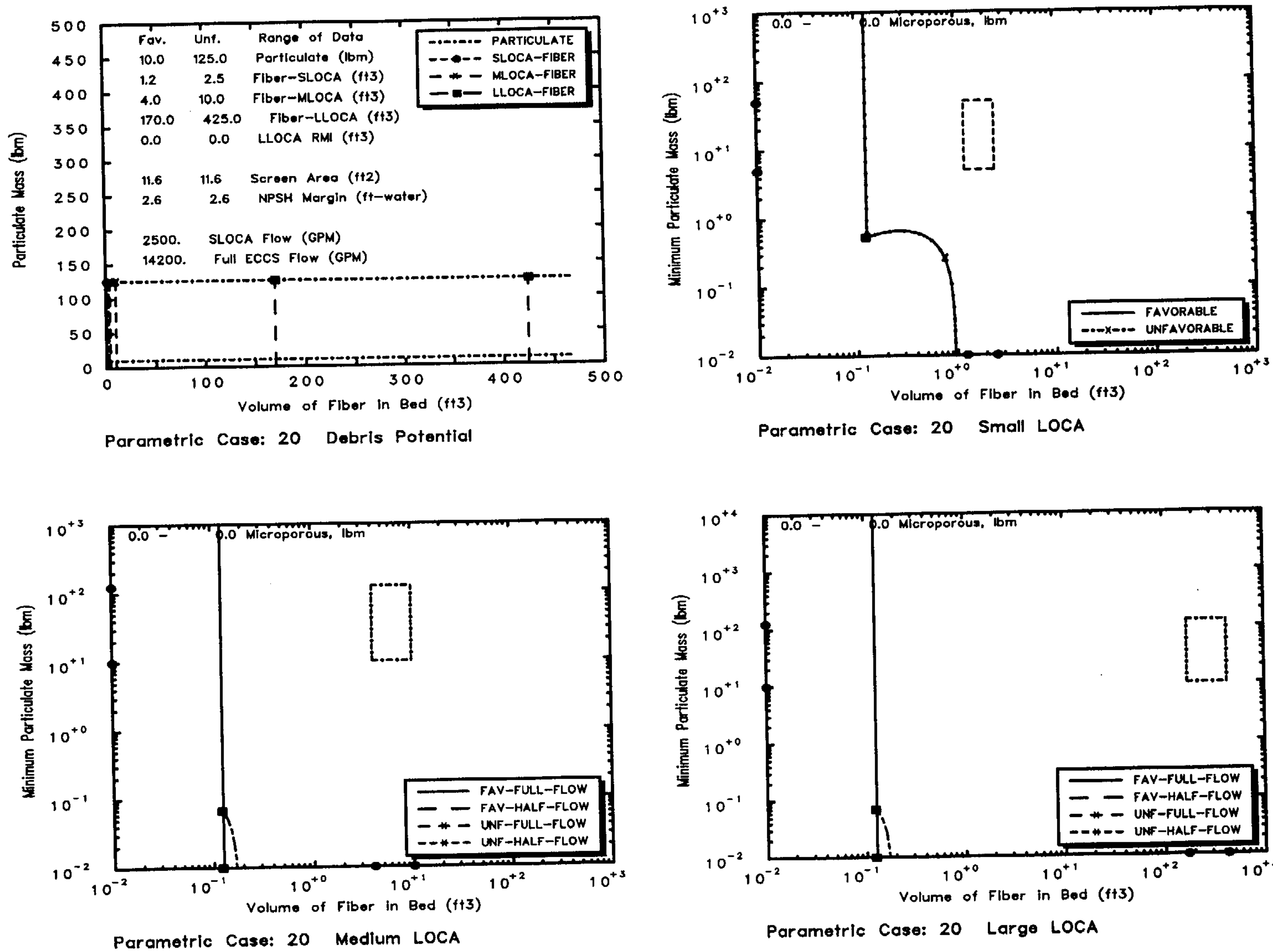


Fig. B-20. Parametric Case 20.

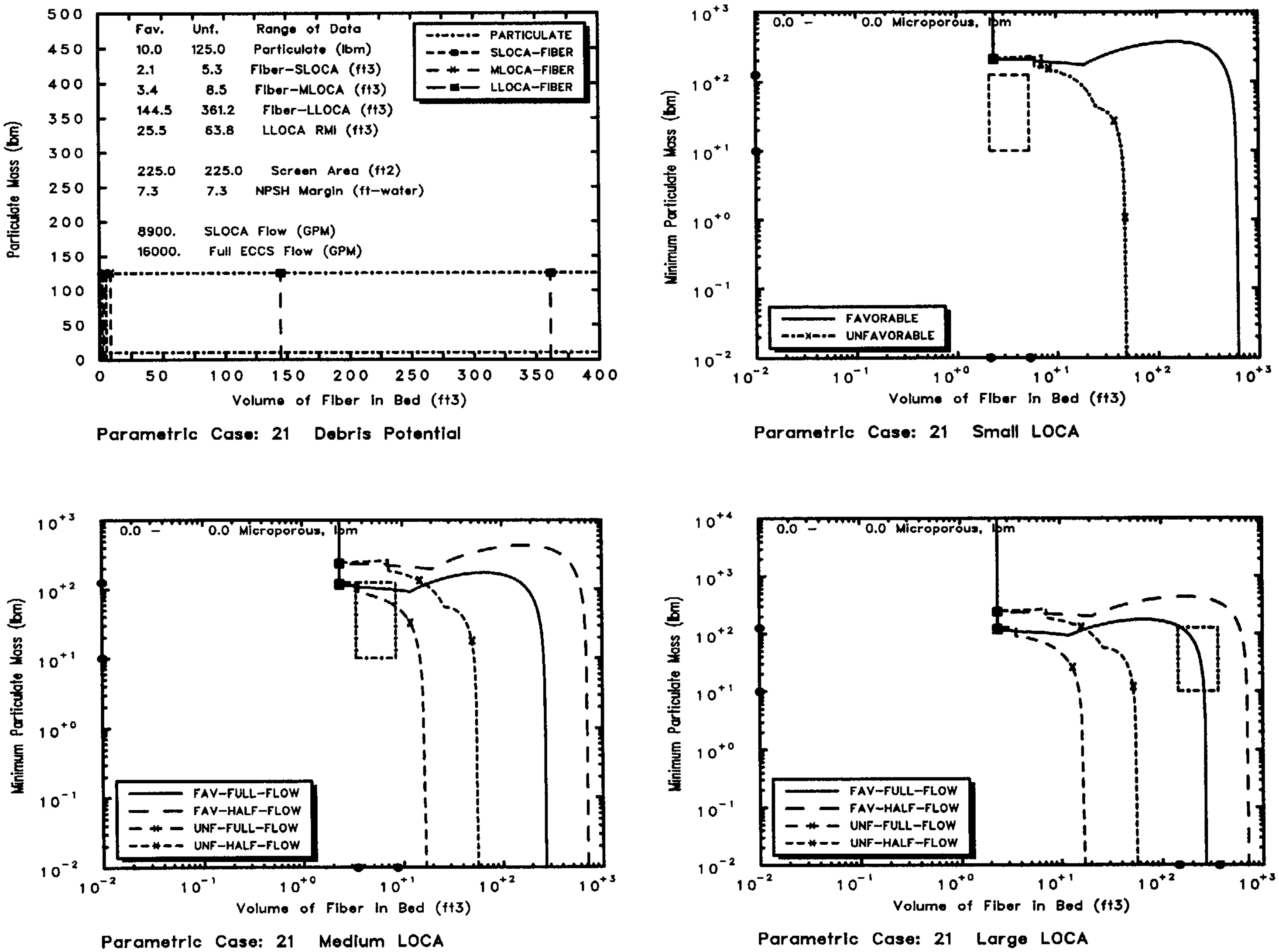


Fig. B-21. Parametric Case 21.

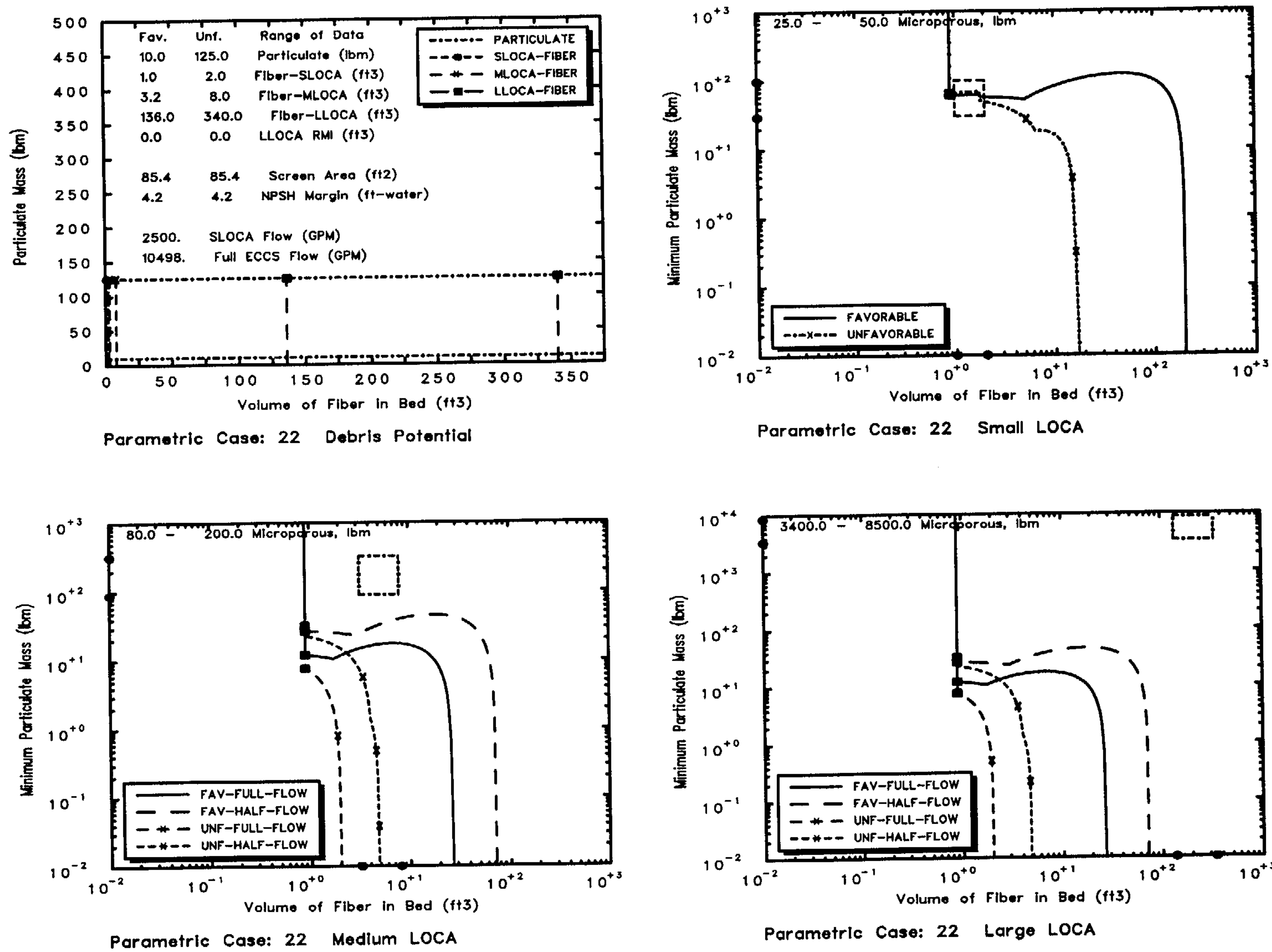


Fig. B-22. Parametric Case 22.

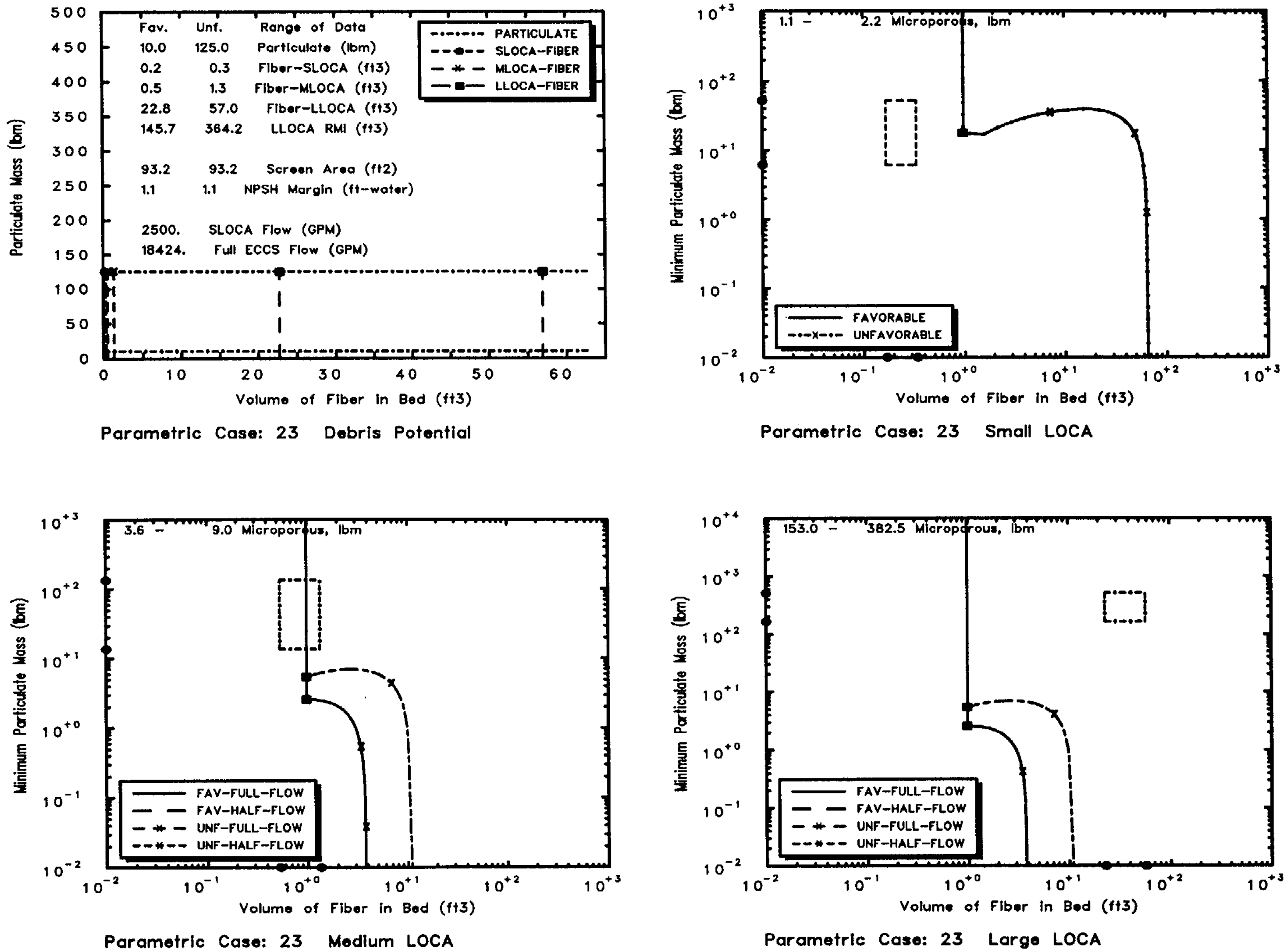


Fig. B-23. Parametric Case 23.

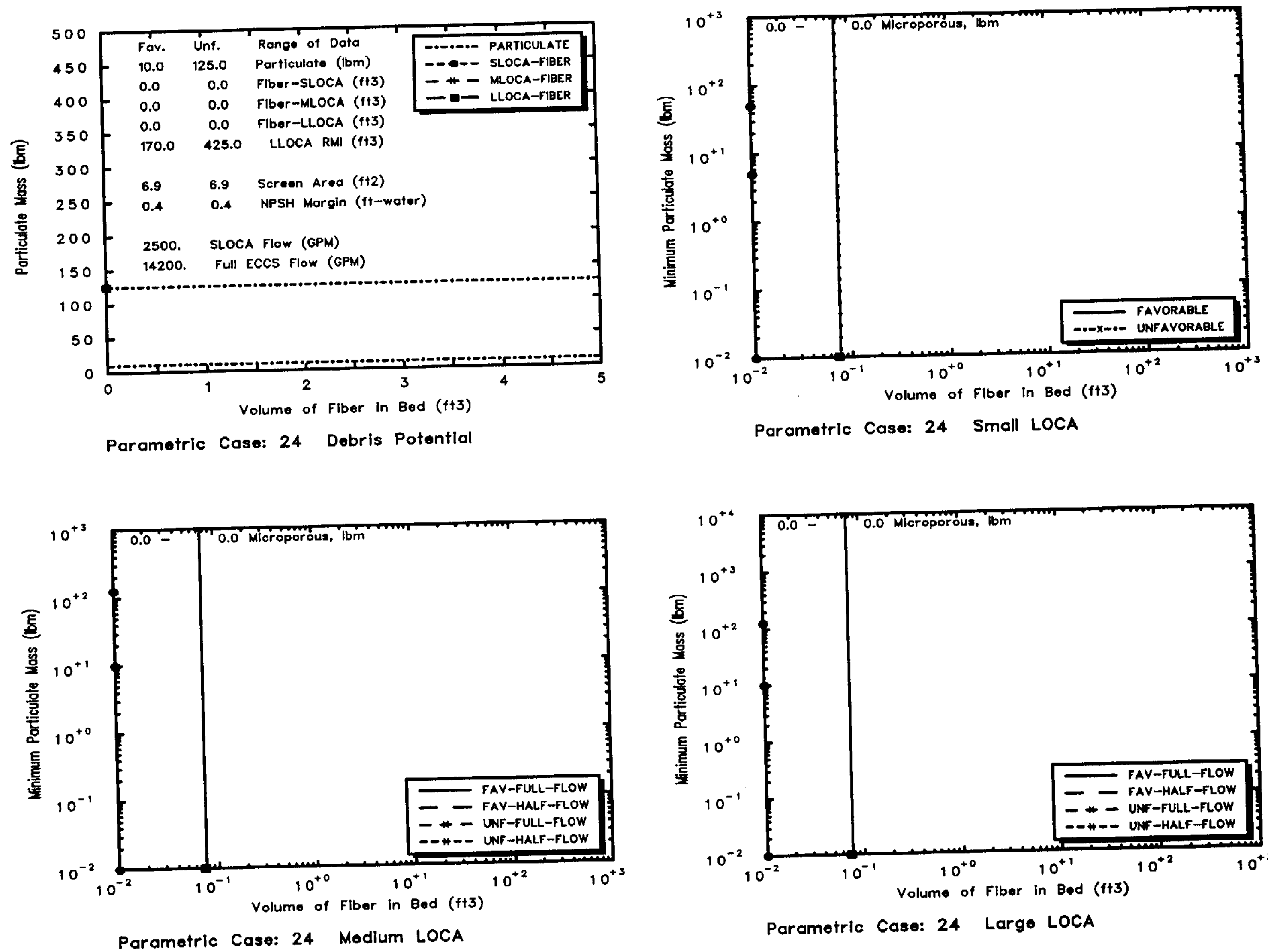


Fig. B-24. Parametric Case 24 (Note: No fiber in this case, so no debris boxes presented).

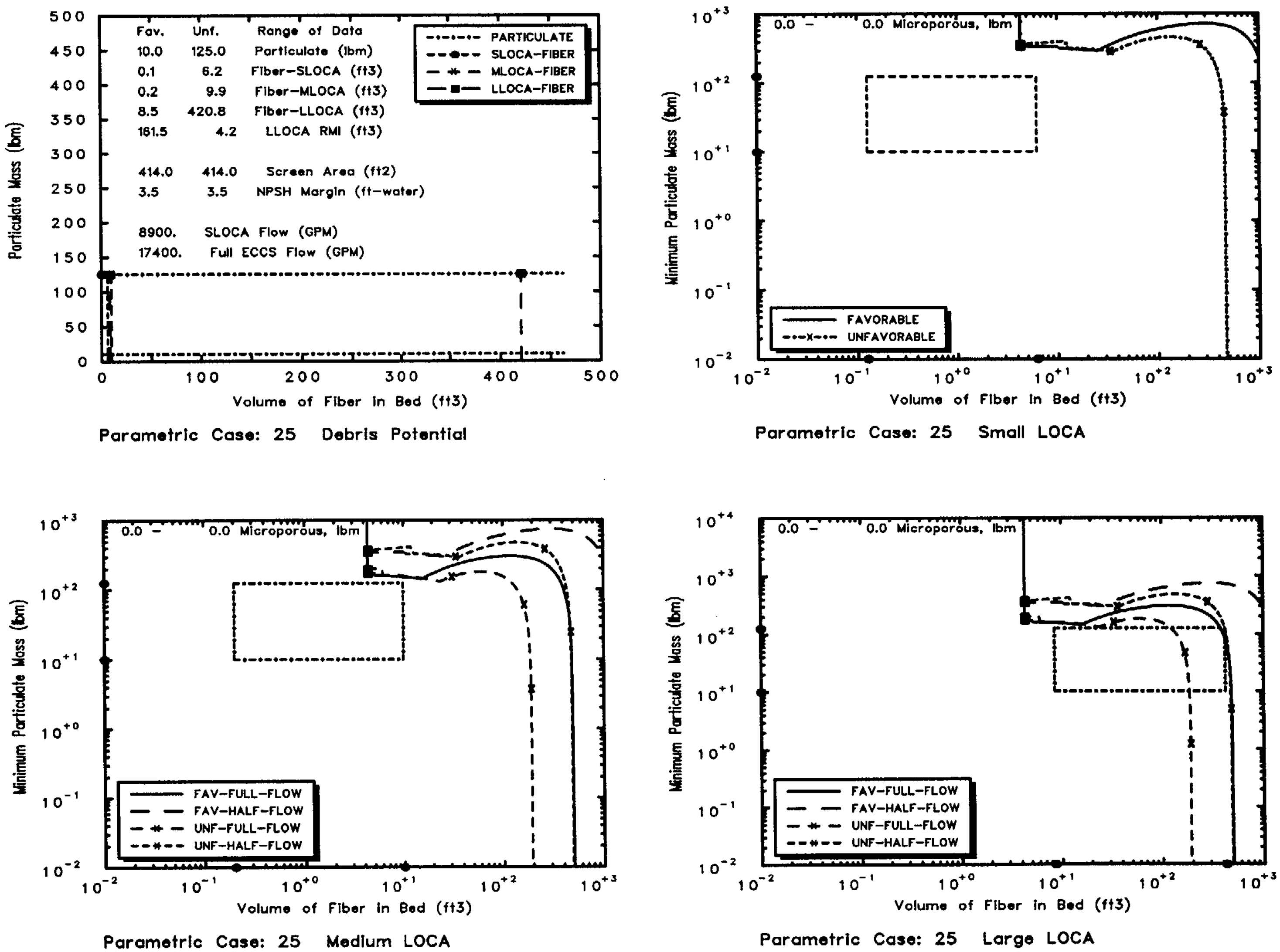


Fig. B-25. Parametric Case 25.

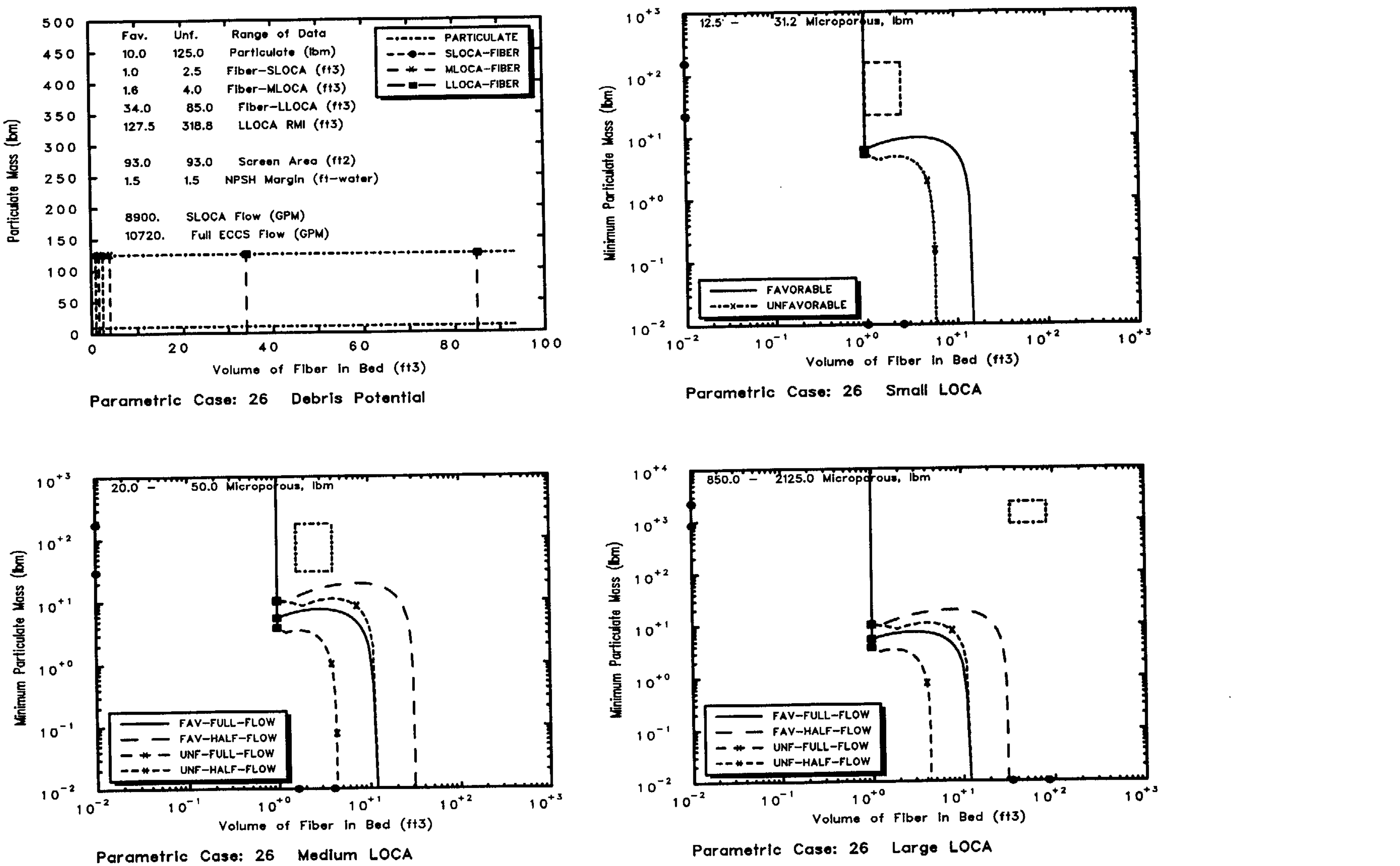
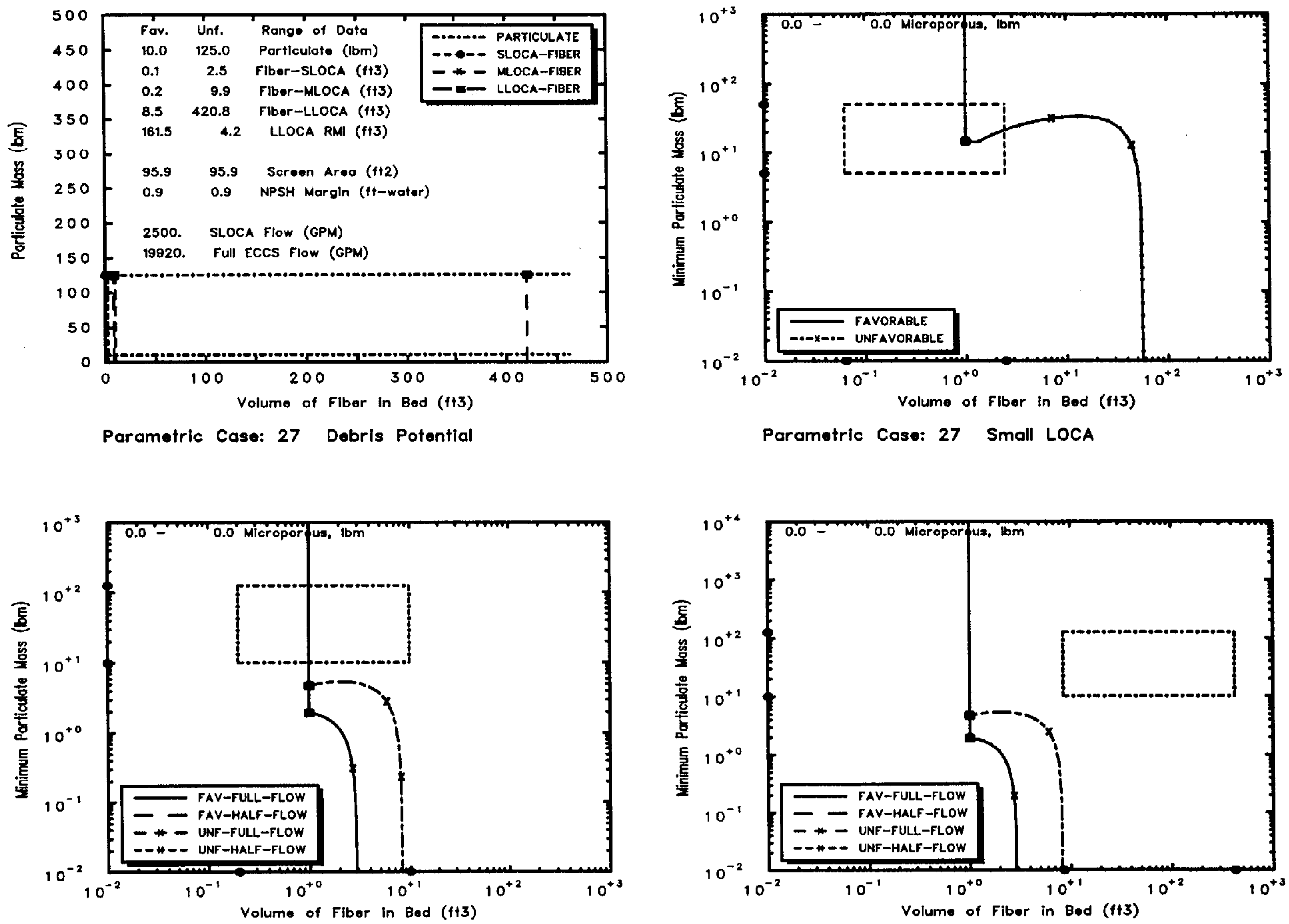


Fig. B-26. Parametric Case 26.



Parametric Case: 27 Debris Potential

Parametric Case: 27 Small LOCA

Parametric Case: 27 Medium LOCA

Parametric Case: 27 Large LOCA

Fig. B-27. Parametric Case 27.

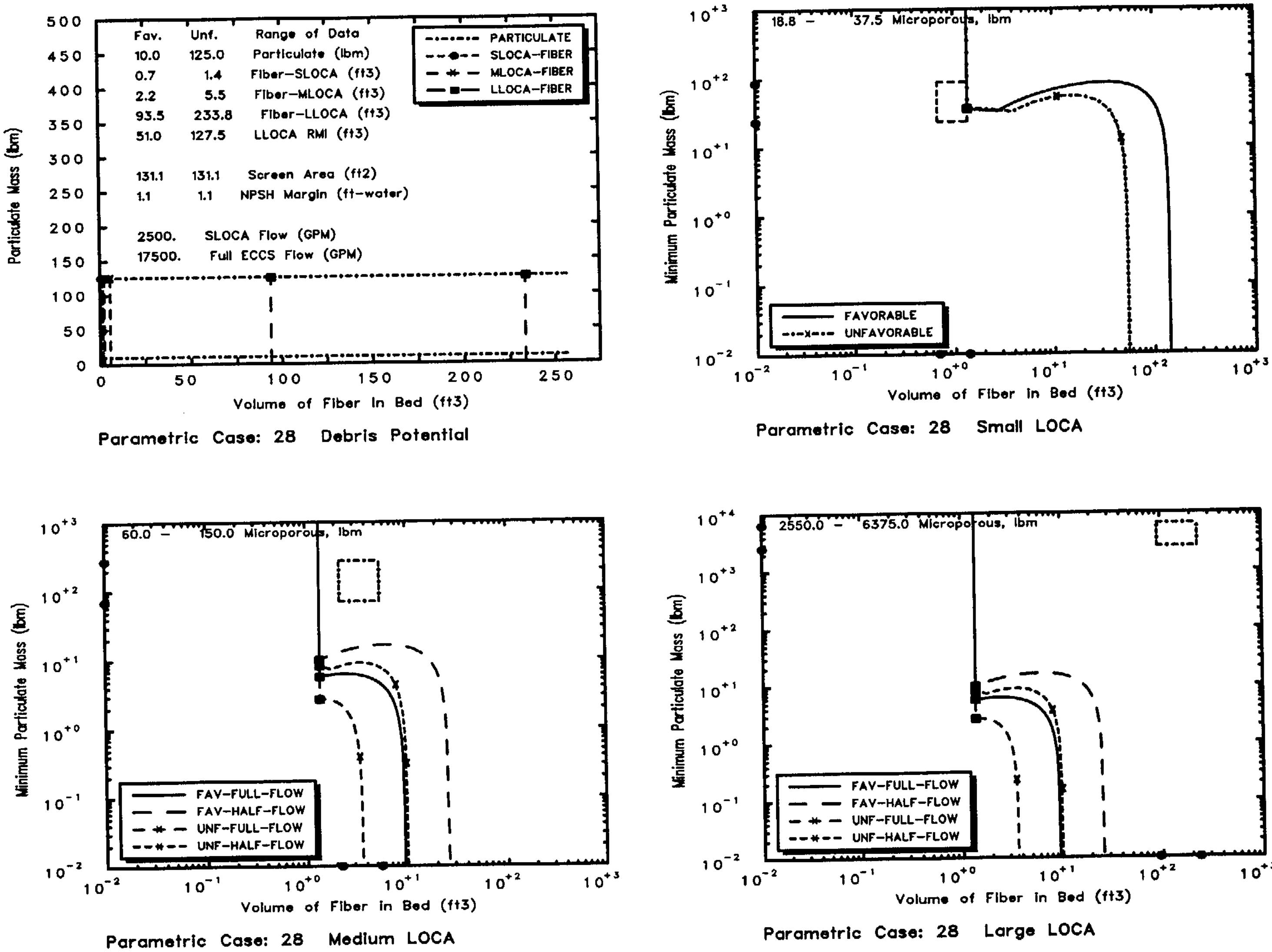


Fig. B-28. Parametric Case 28.

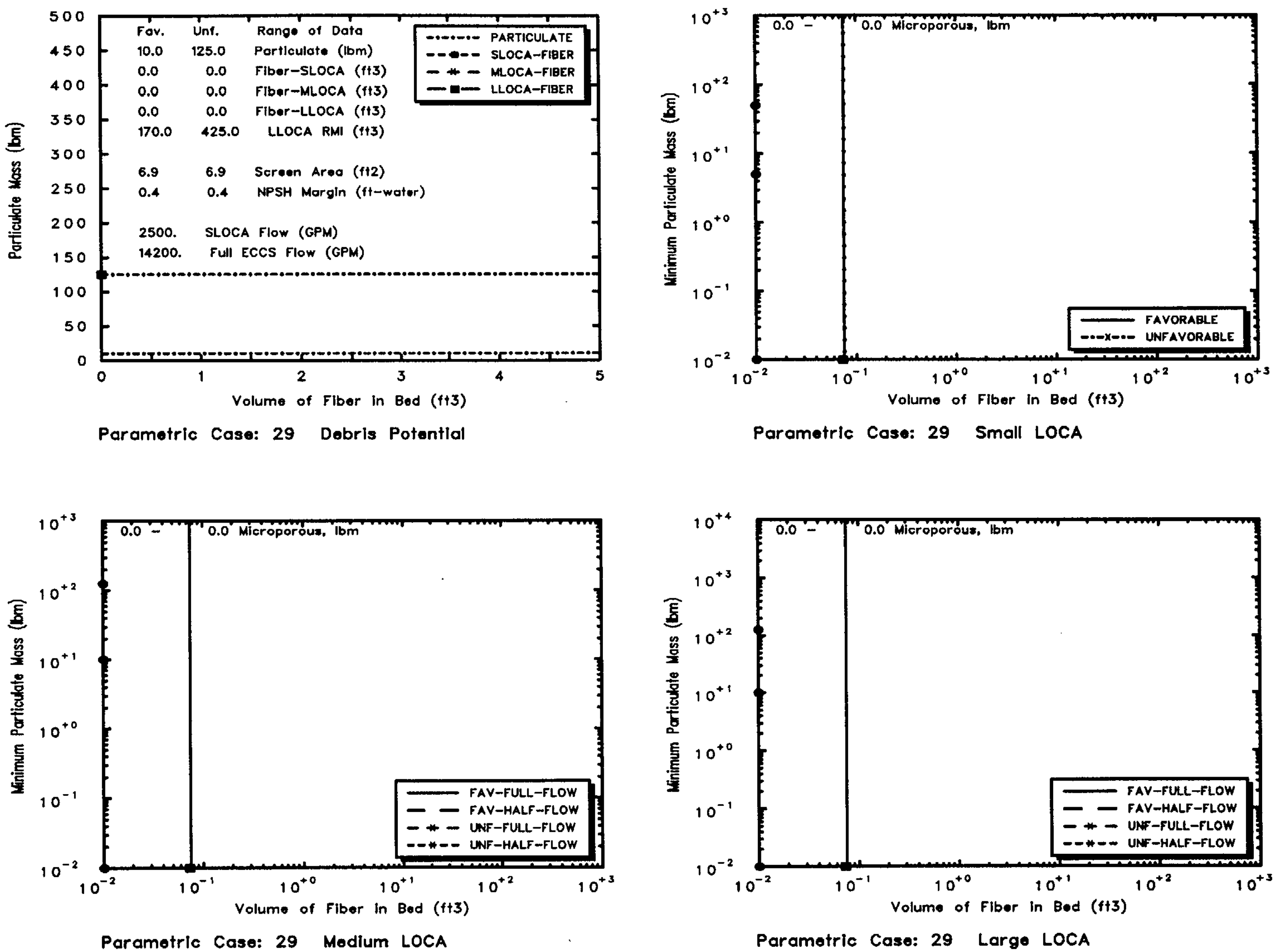


Fig. B-29. Parametric Case 29 (Note: No fiber in this case, so no debris boxes presented).

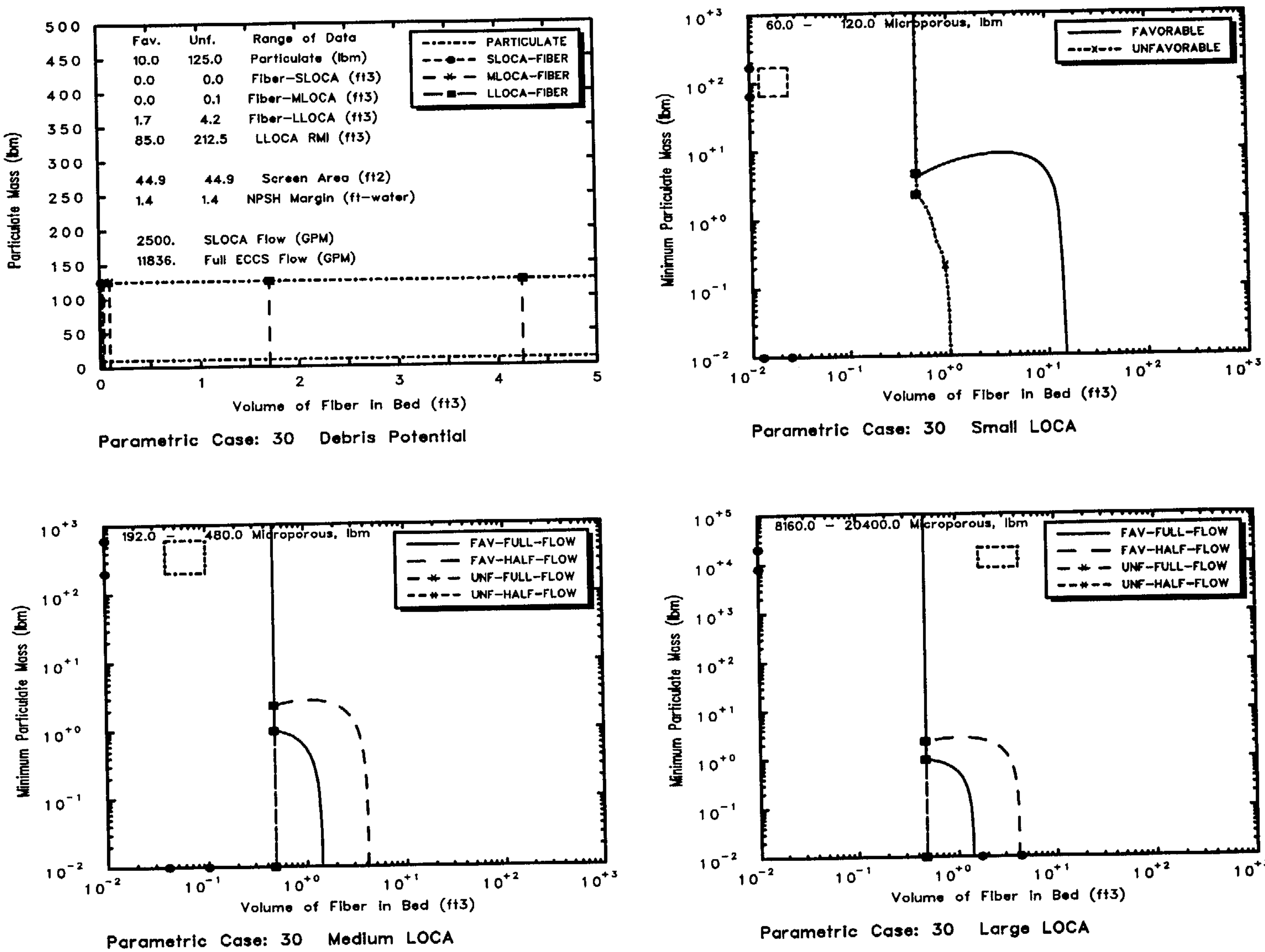


Fig. B-30. Parametric Case 30.

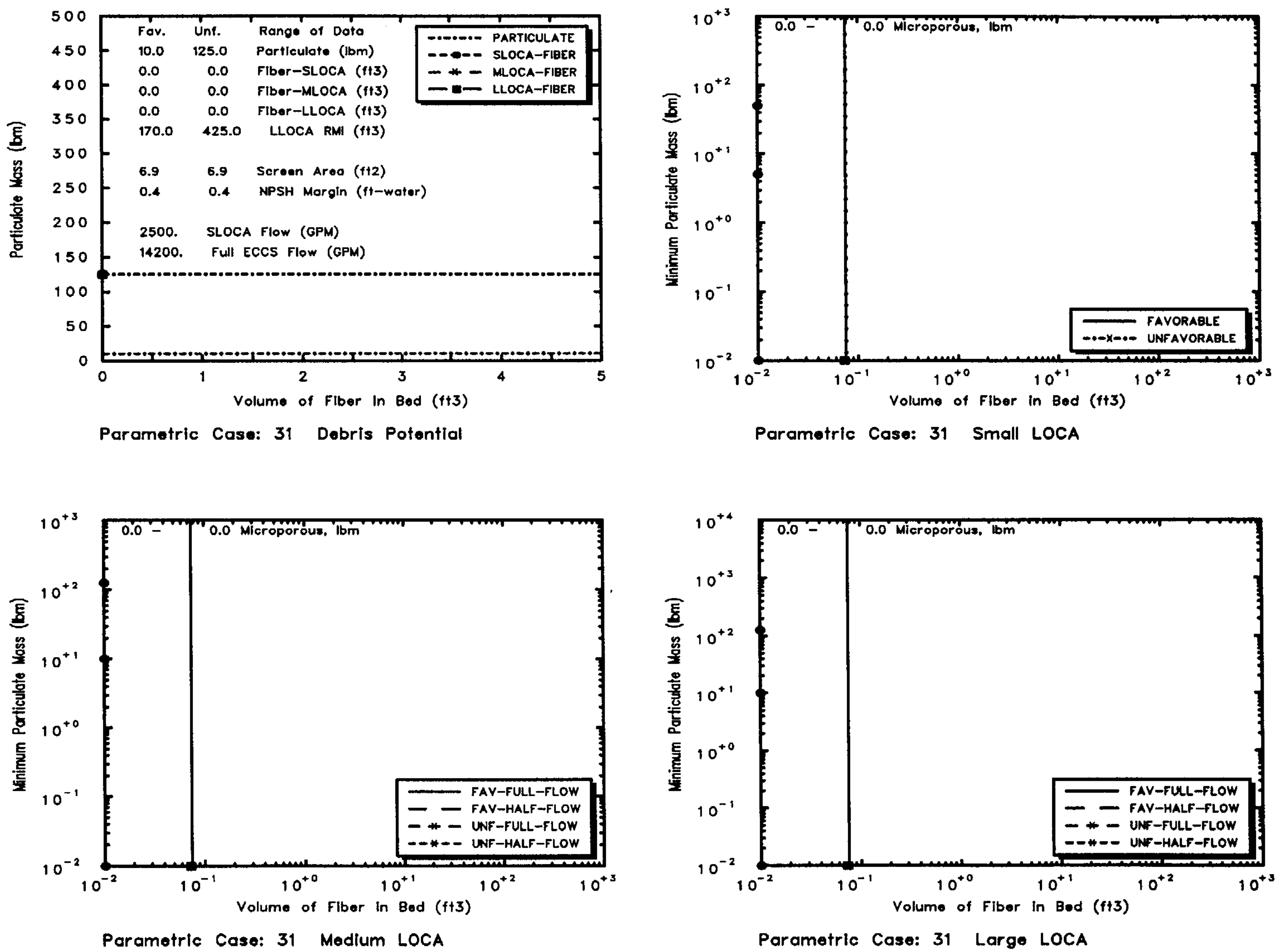


Fig. B-31. Parametric Case 31 (Note: No fiber in this case, so no debris boxes presented).

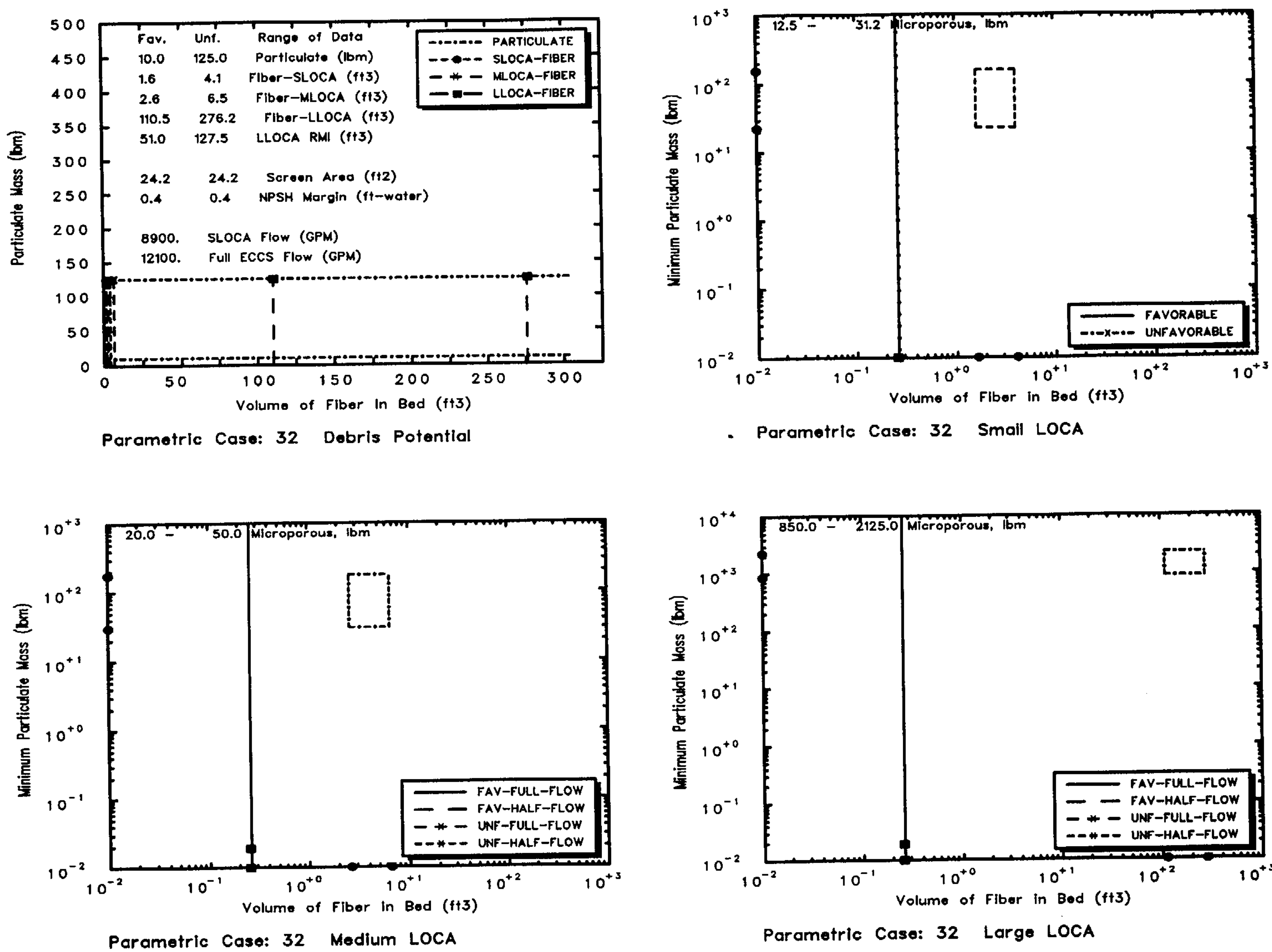


Fig. B-32. Parametric Case 32.

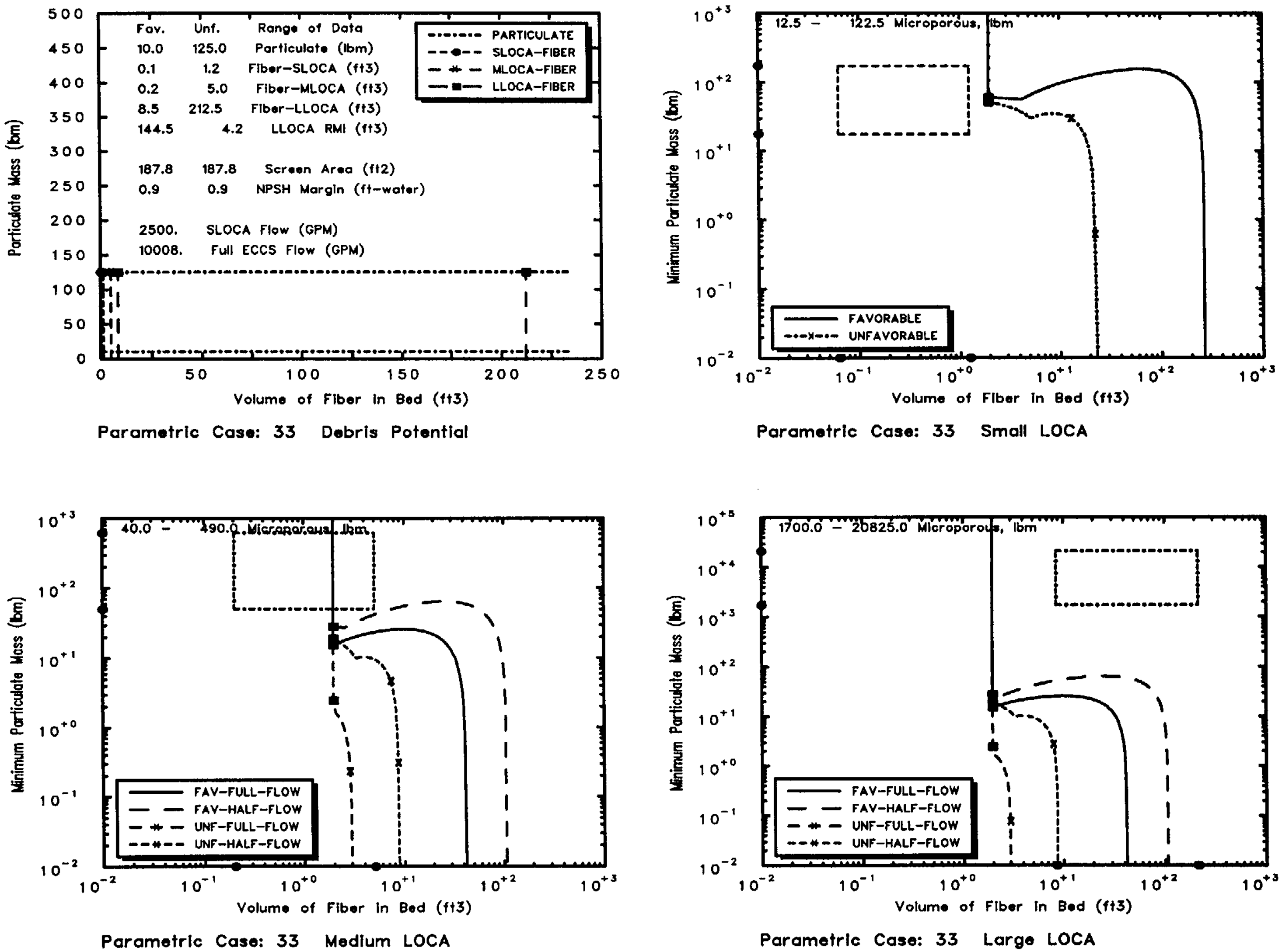


Fig. B-33. Parametric Case 33.

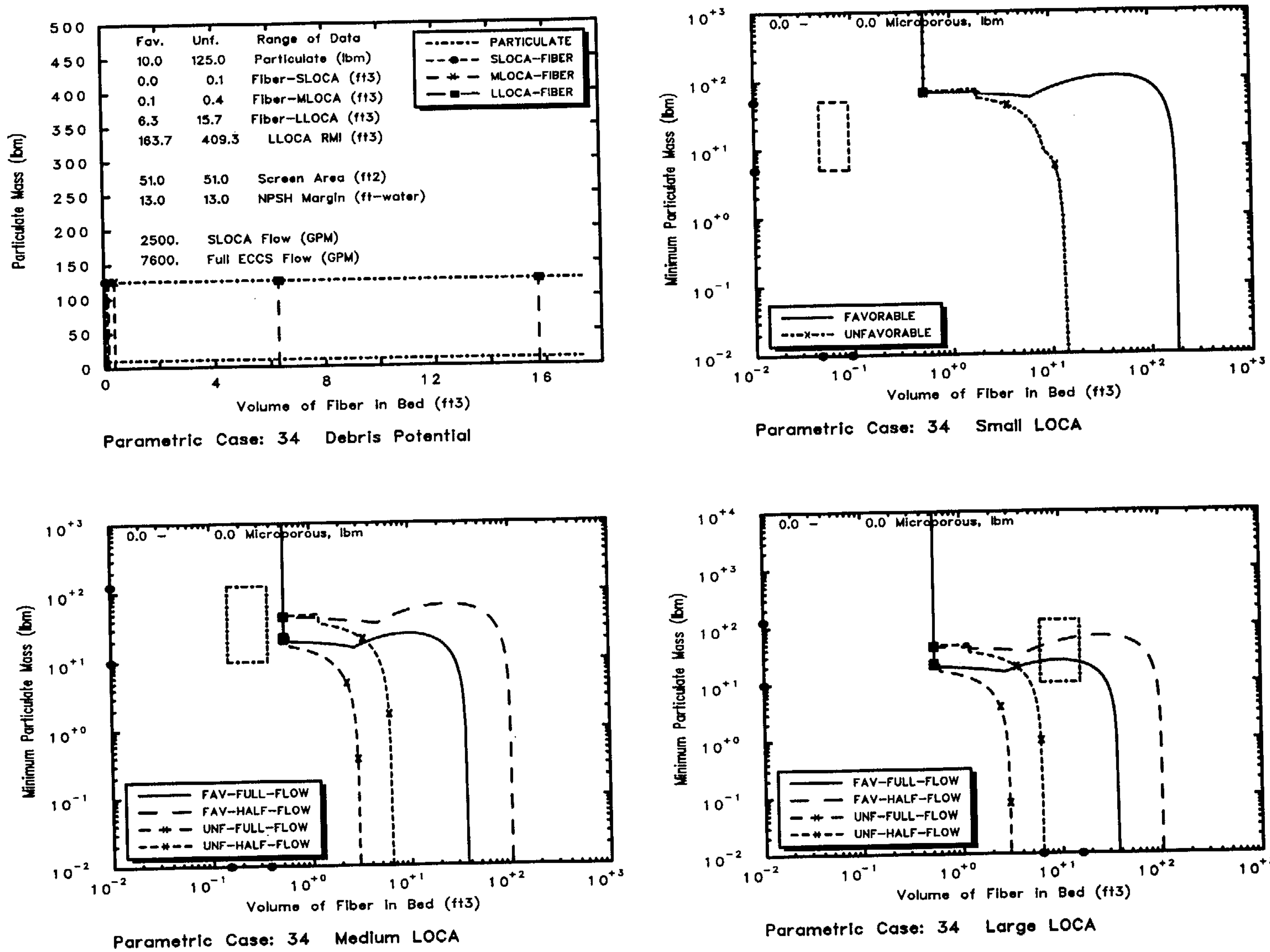


Fig. B-34. Parametric Case 34.

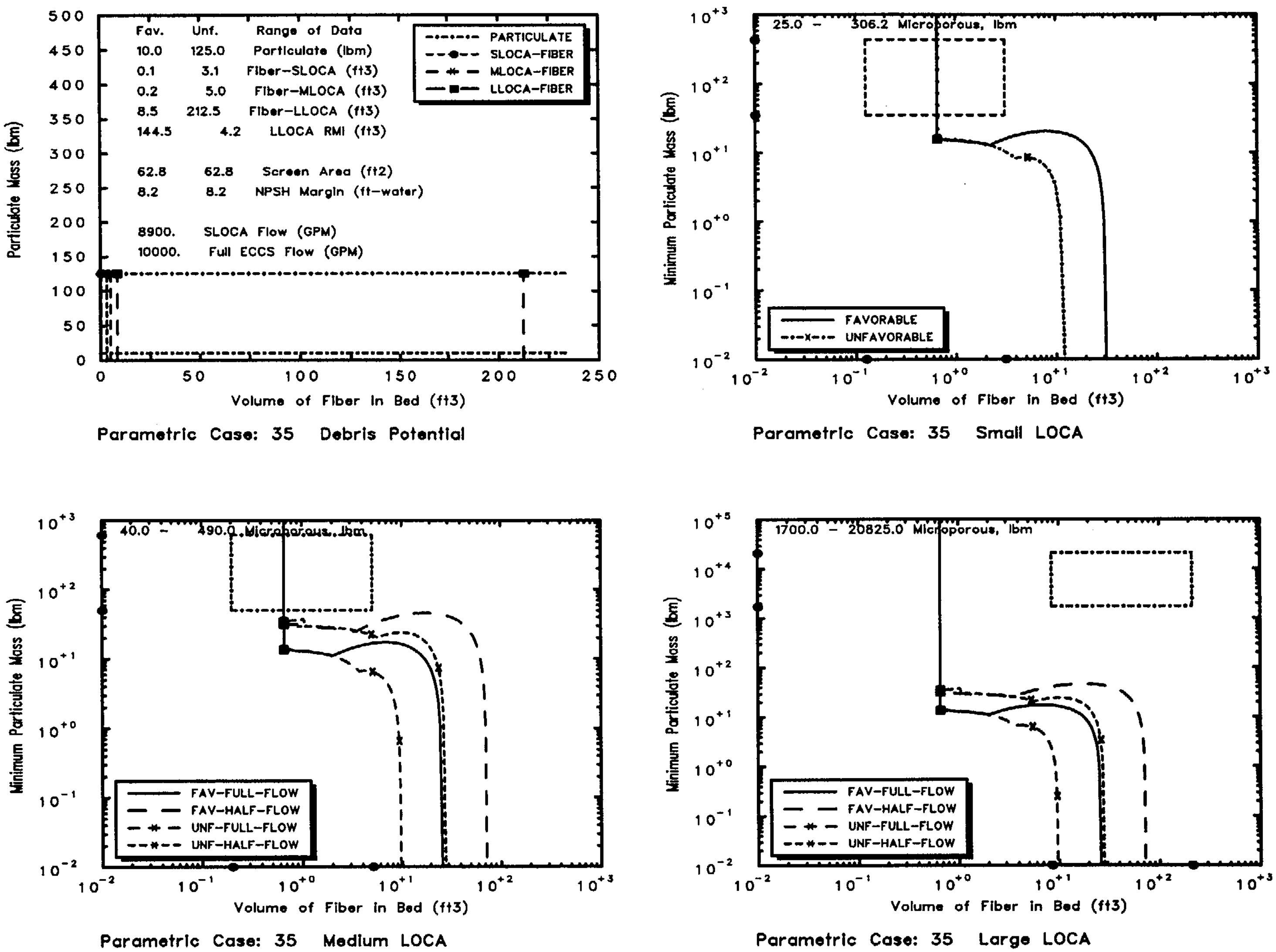


Fig. B-35. Parametric Case 35.

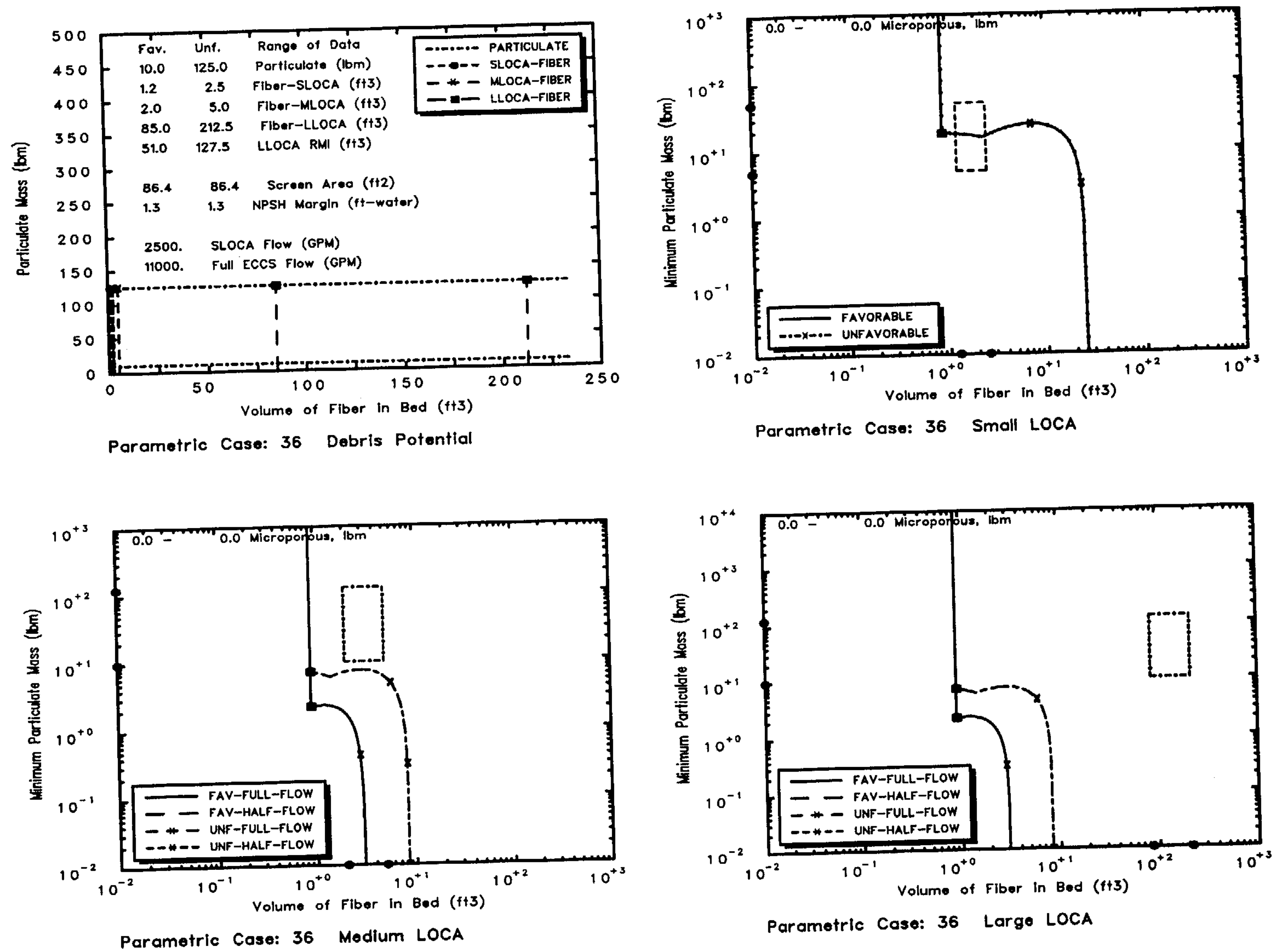


Fig. B-36. Parametric Case 36.

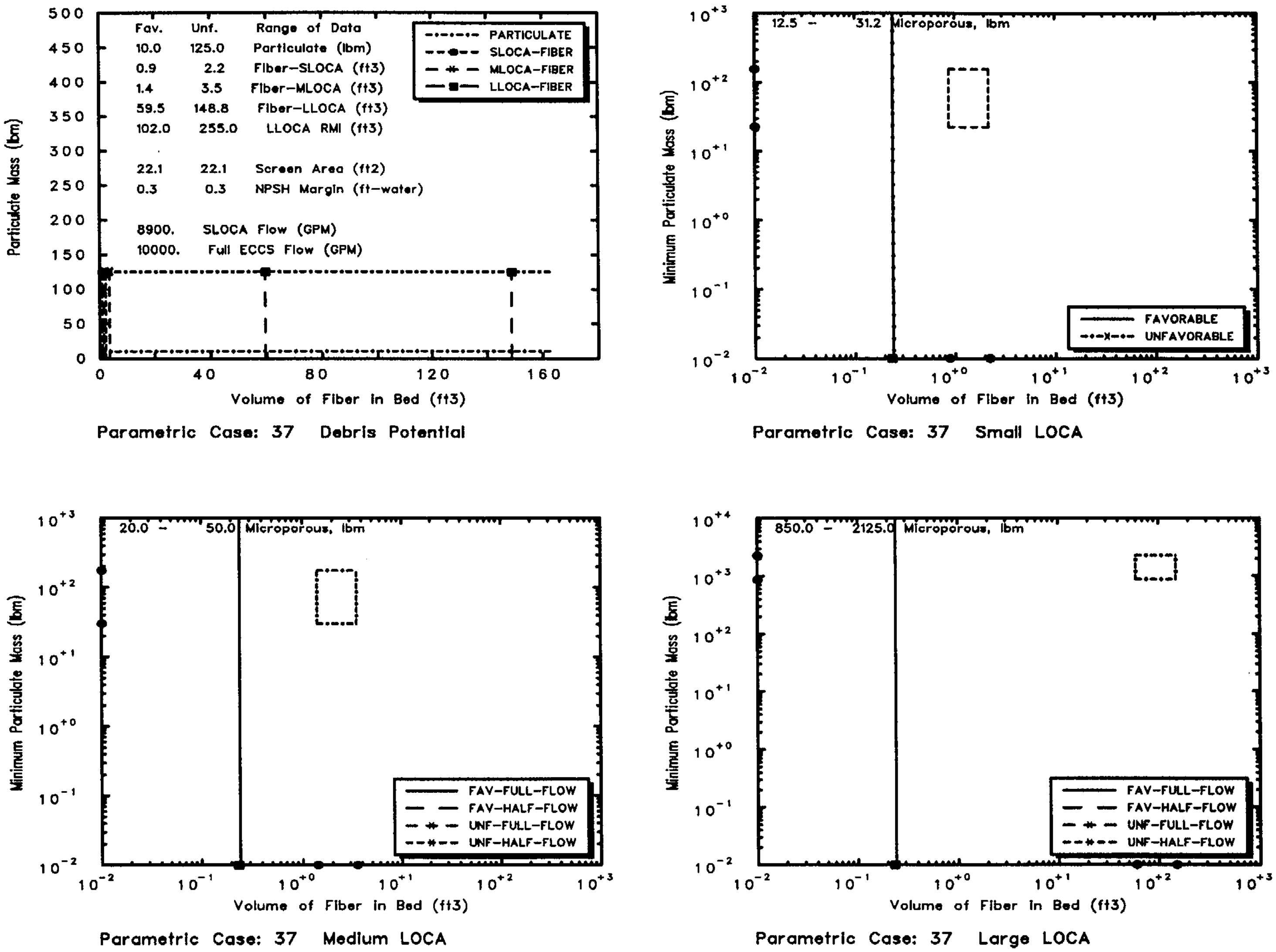
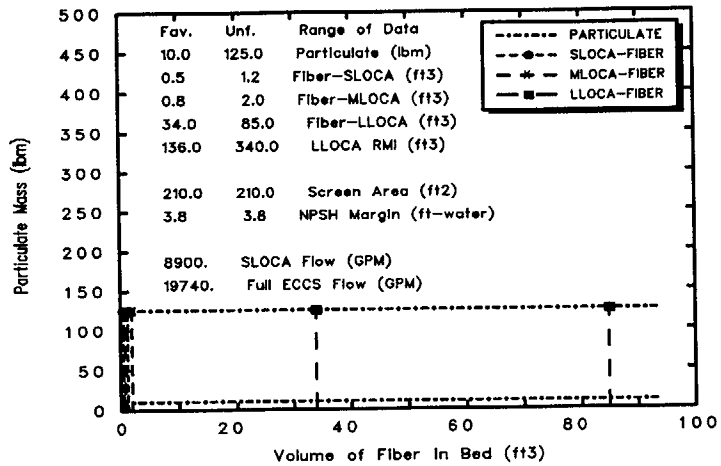
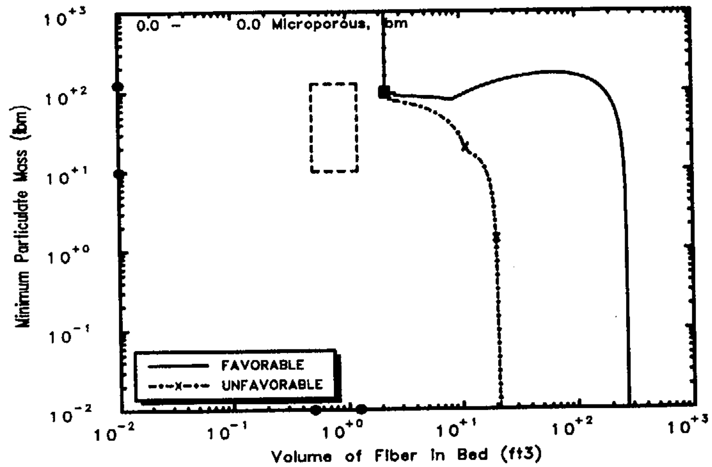


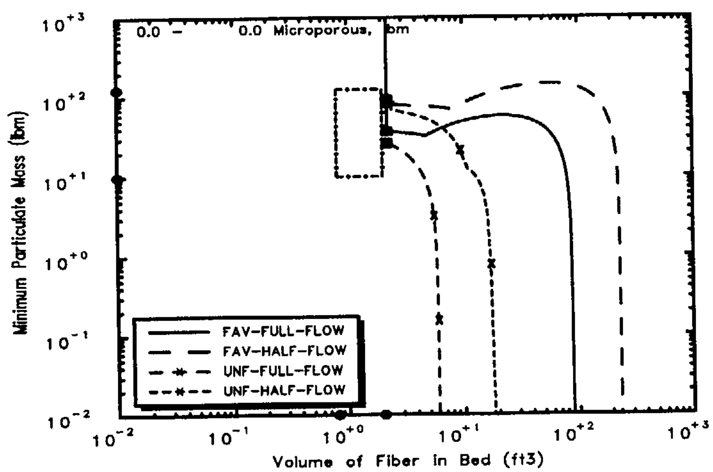
Fig. B-37. Parametric Case 37.



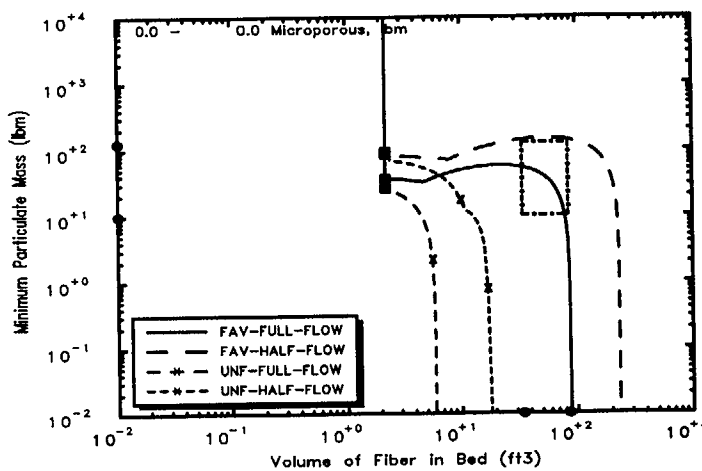
Parametric Case: 38 Debris Potential



Parametric Case: 38 Small LOCA



Parametric Case: 38 Medium LOCA



Parametric Case: 38 Large LOCA

Fig. B-38. Parametric Case 38.

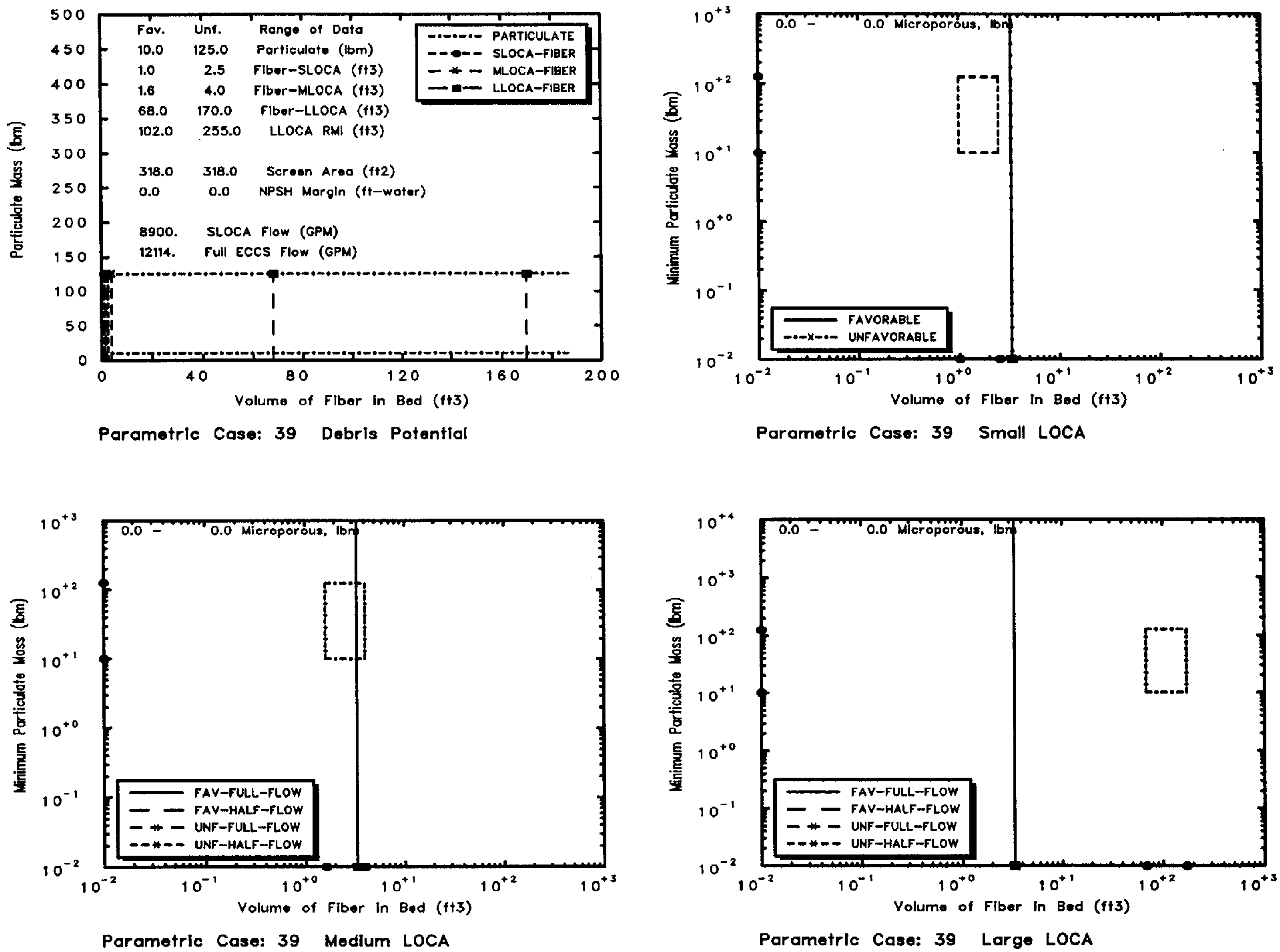


Fig. B-39. Parametric Case 39.

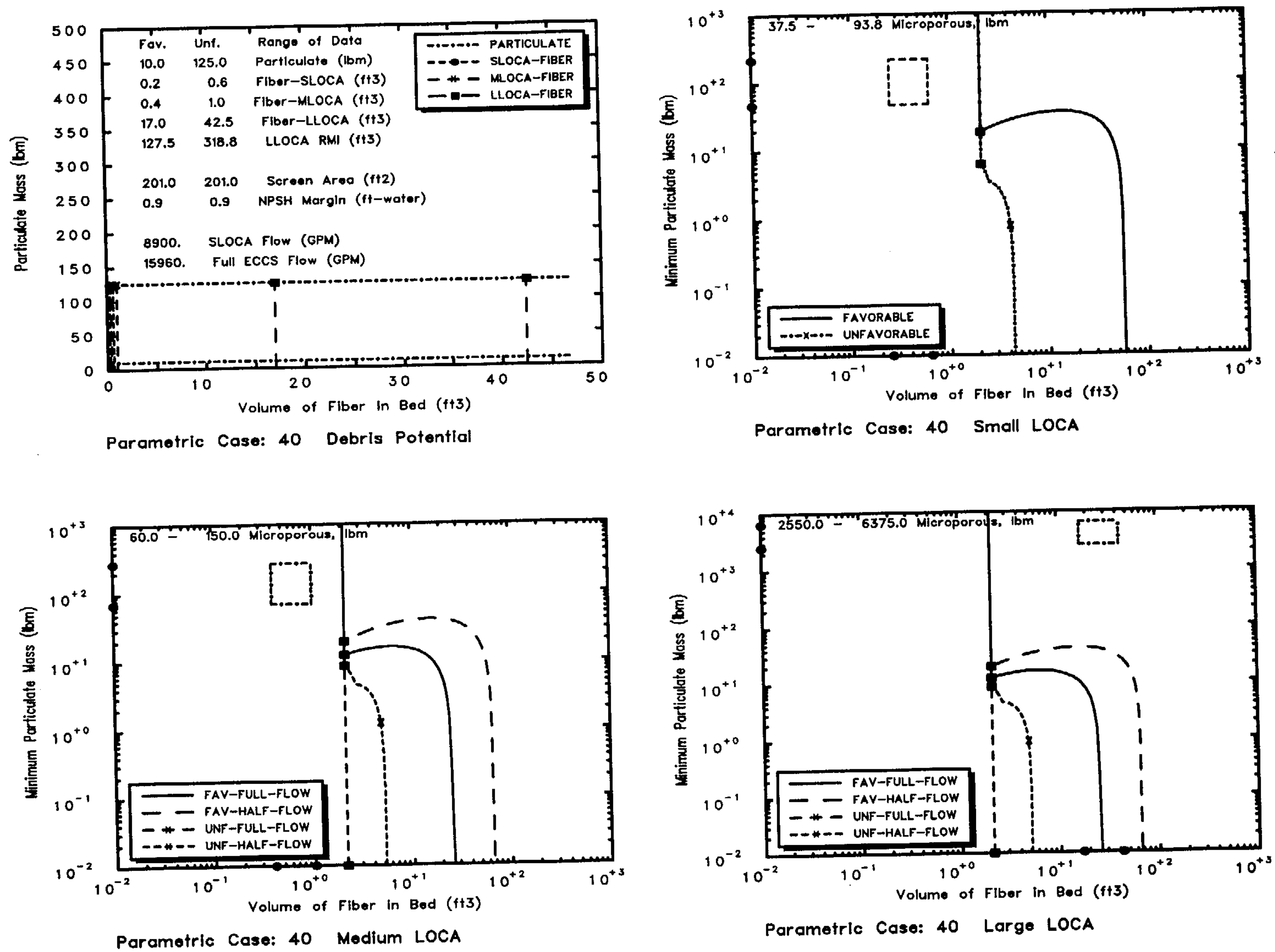


Fig. B-40. Parametric Case 40.

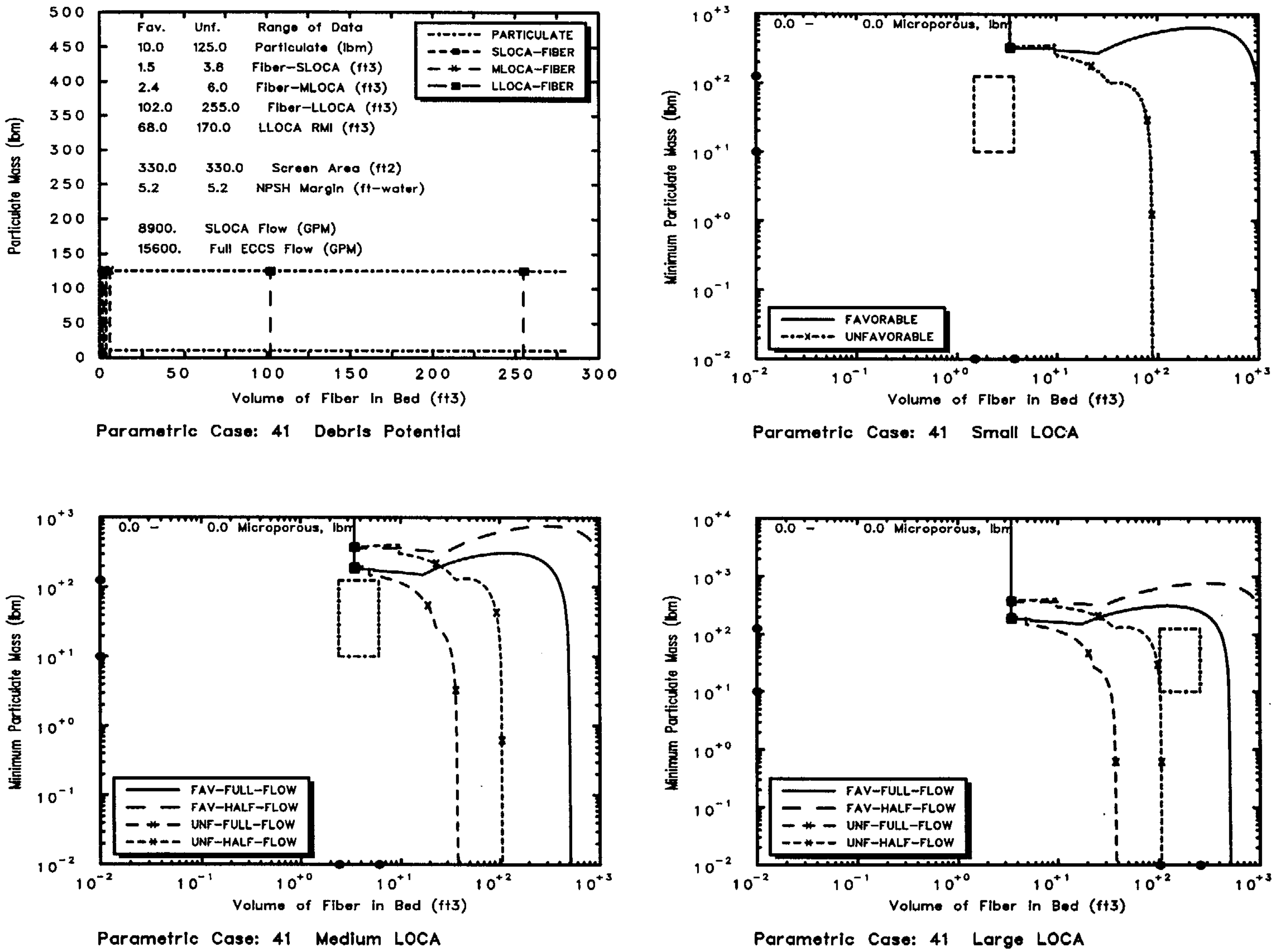


Fig. B-41. Parametric Case 41.

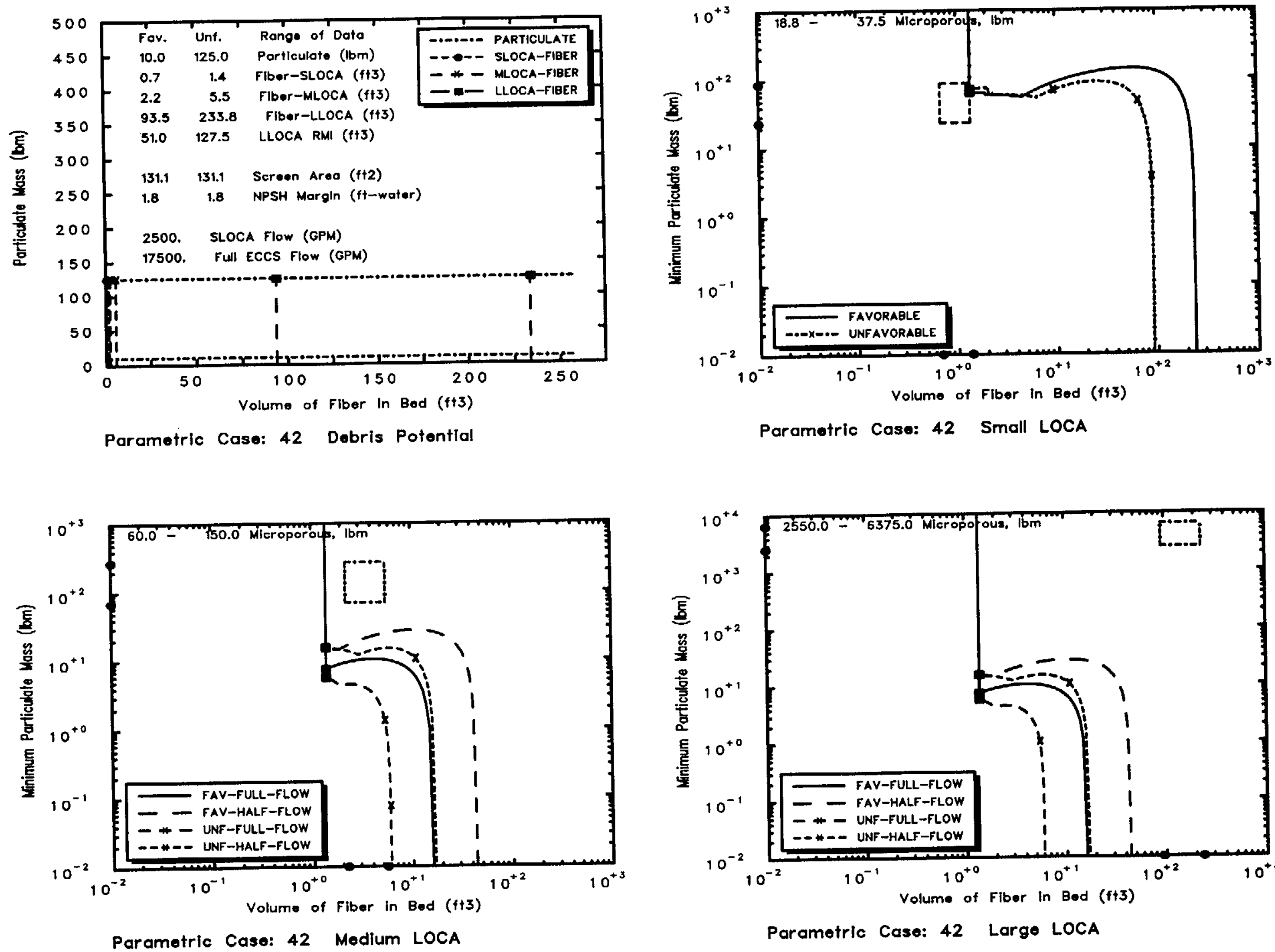


Fig. B-42. Parametric Case 42.

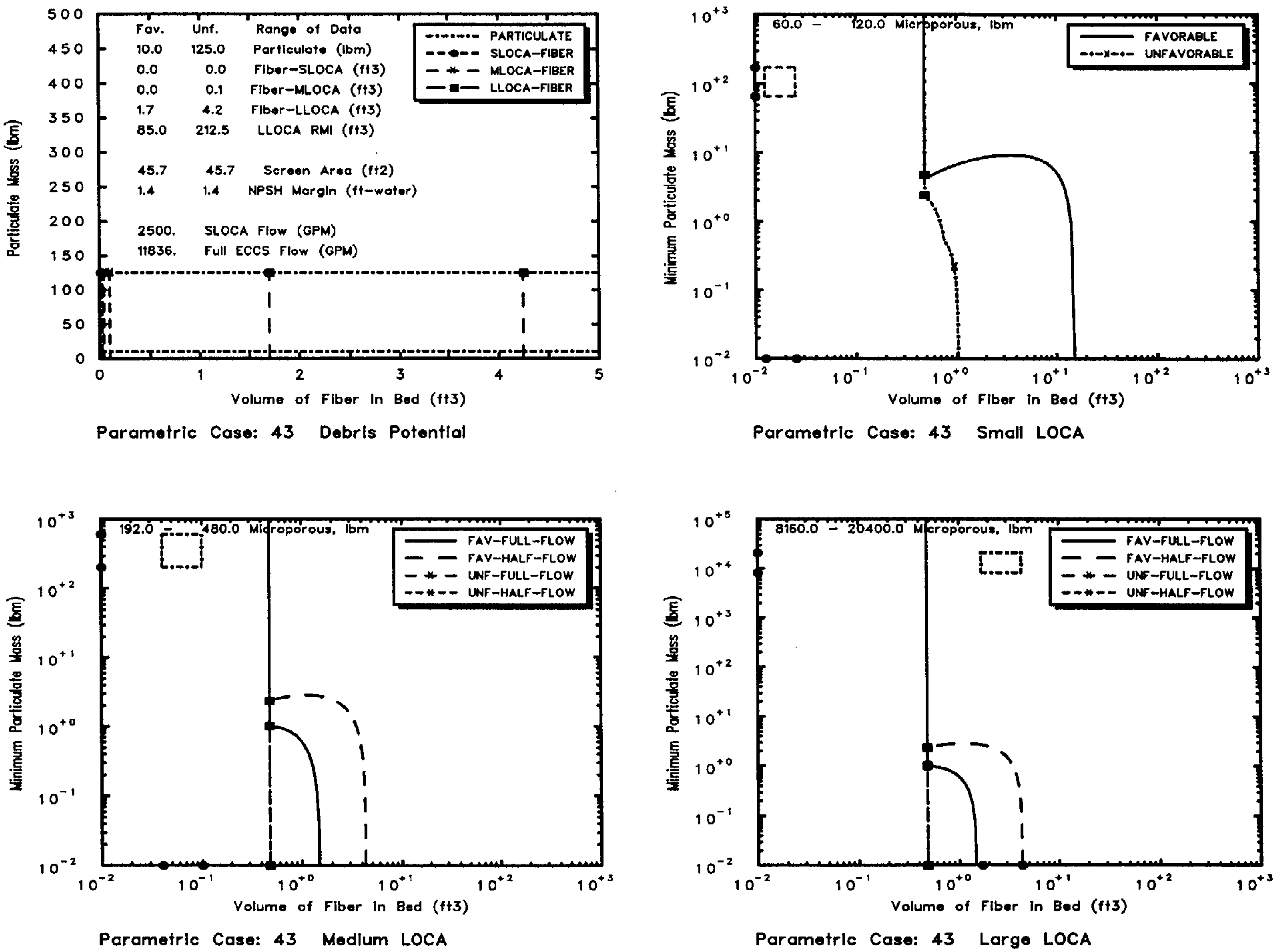


Fig. B-43. Parametric Case 43.

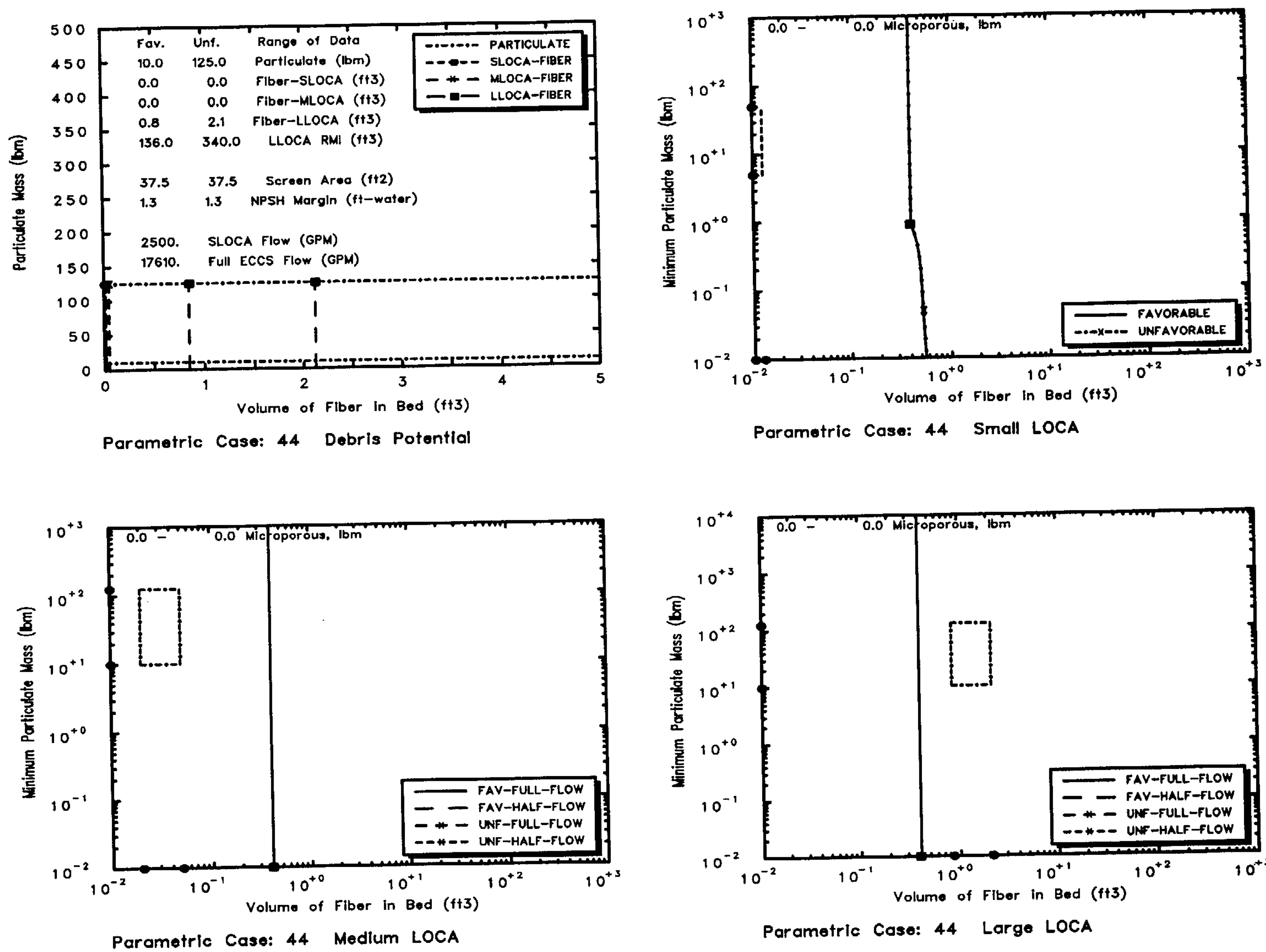


Fig. B-44. Parametric Case 44.

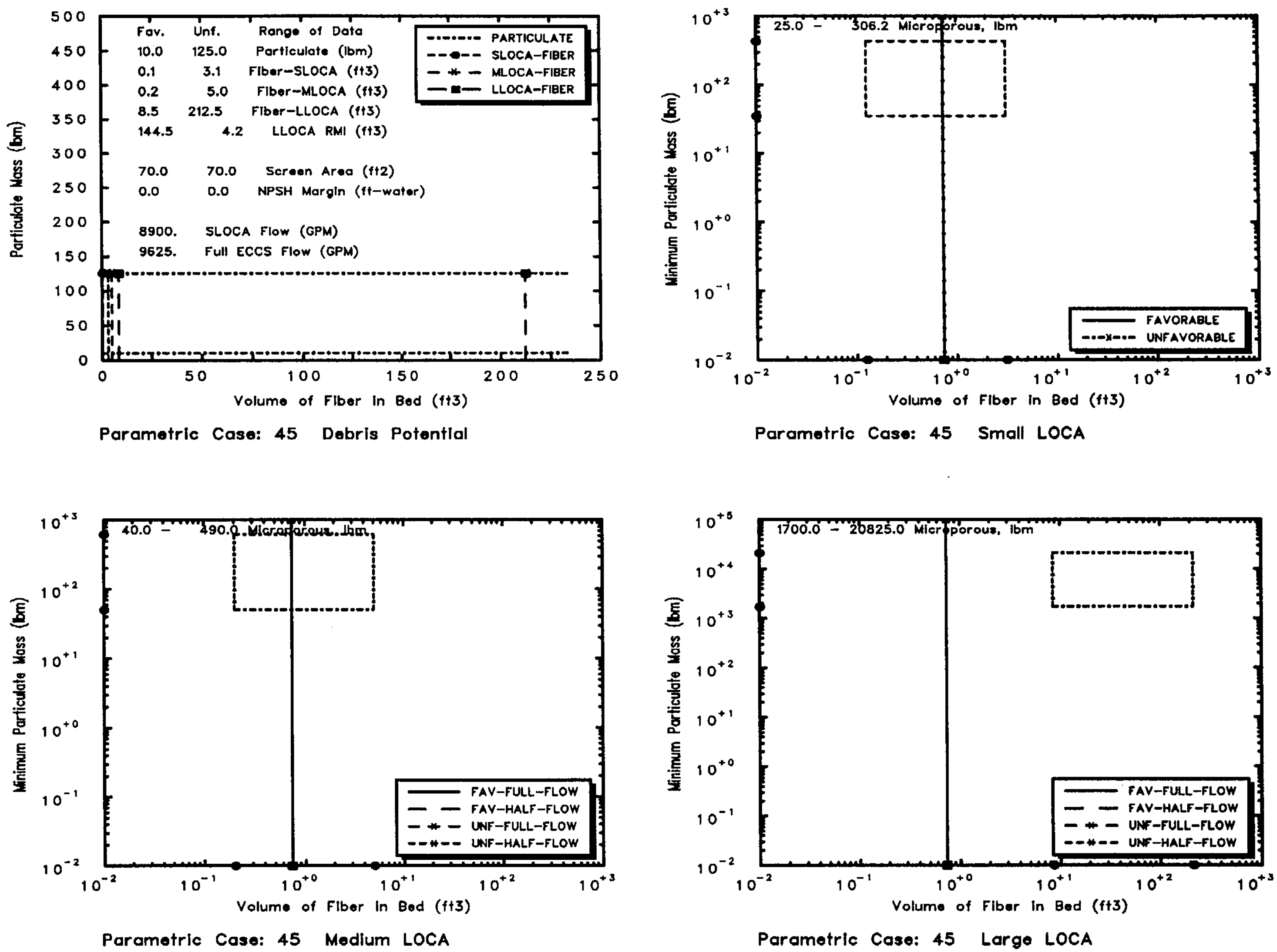


Fig. B-45. Parametric Case 45.

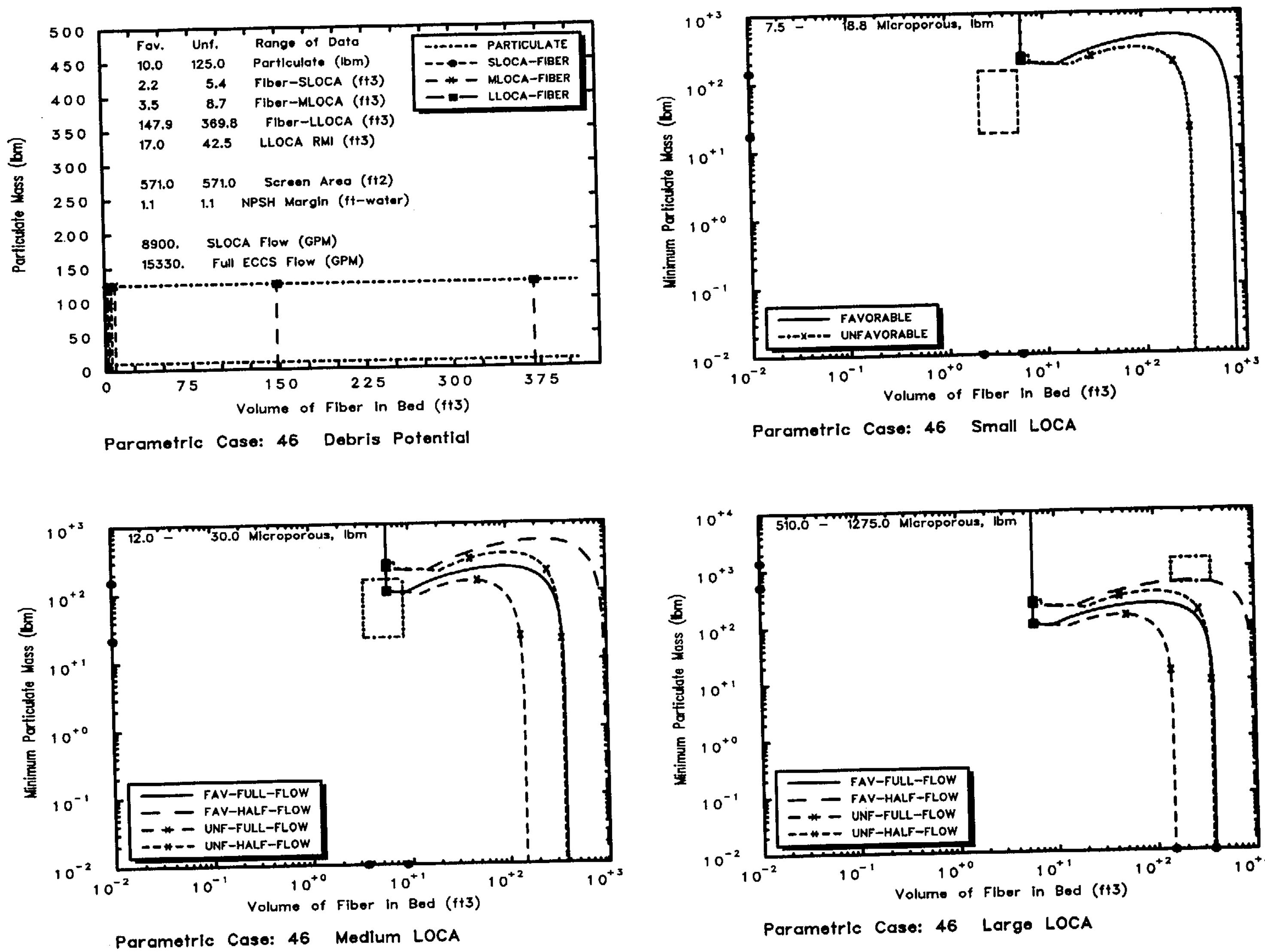


Fig. B-46. Parametric Case 46.

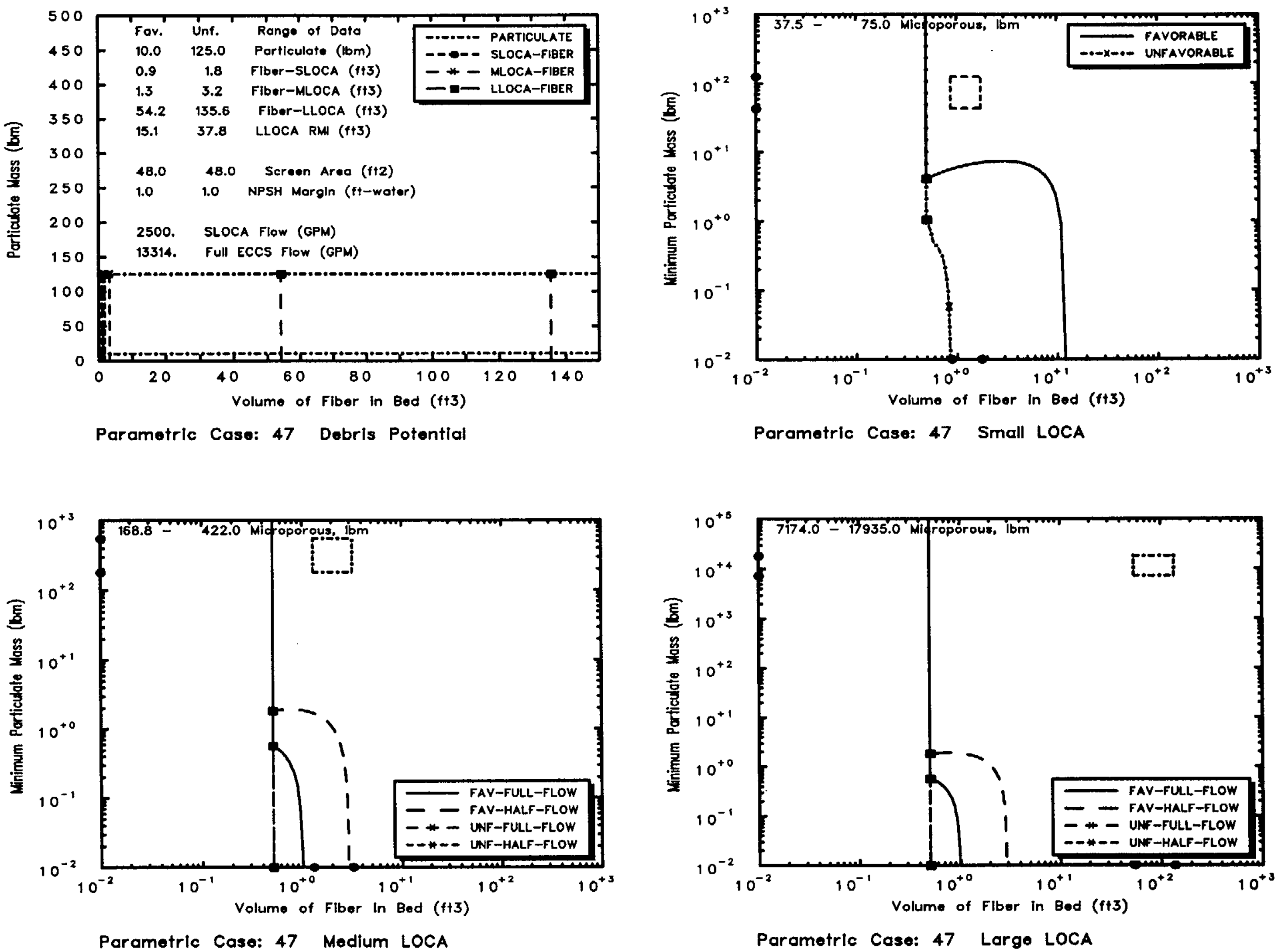


Fig. B-47. Parametric Case 47.

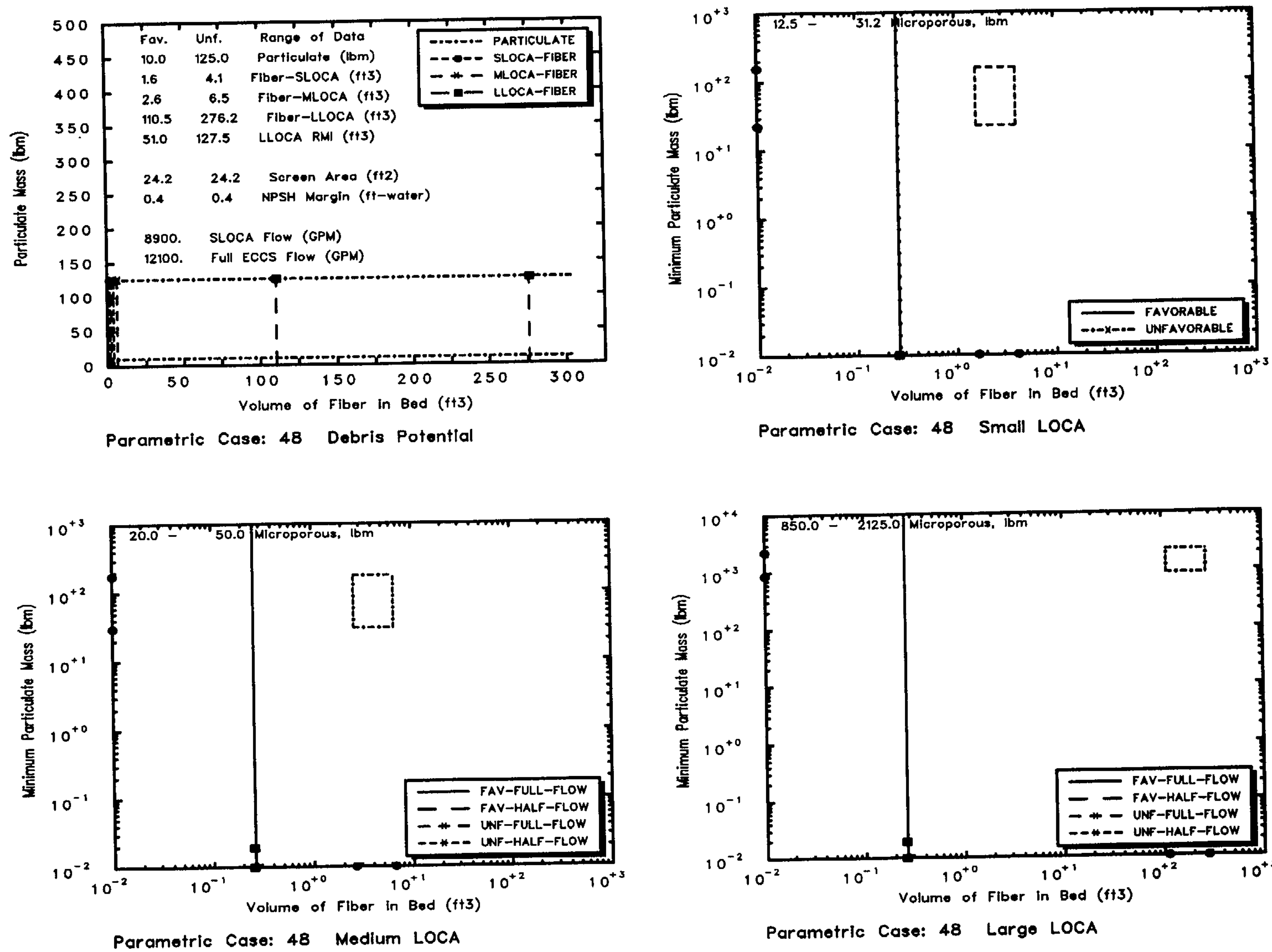


Fig. B-48. Parametric Case 48.

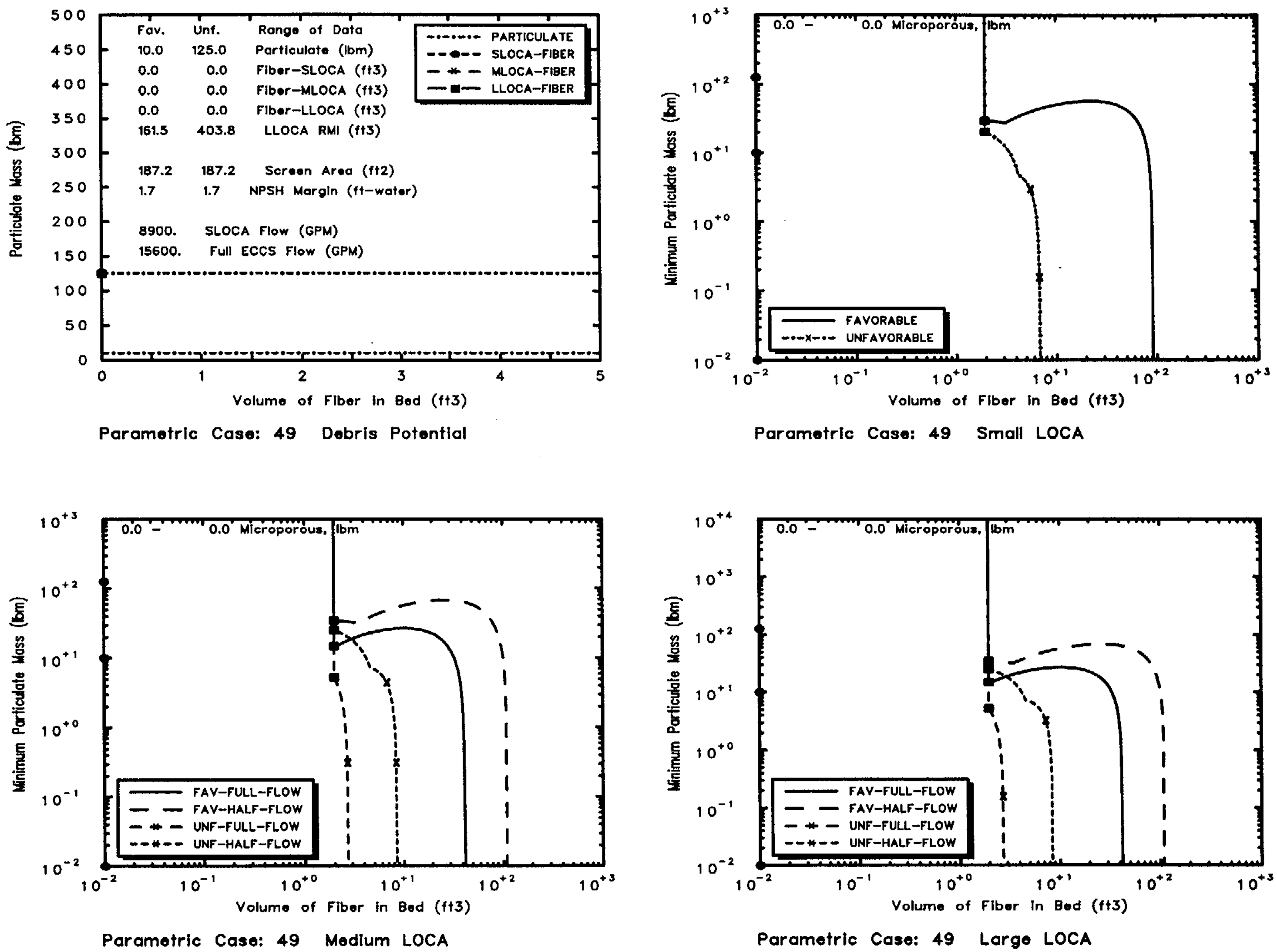


Fig. B-49. Parametric Case 49 (Note: No fiber in this case, so no debris boxes presented).

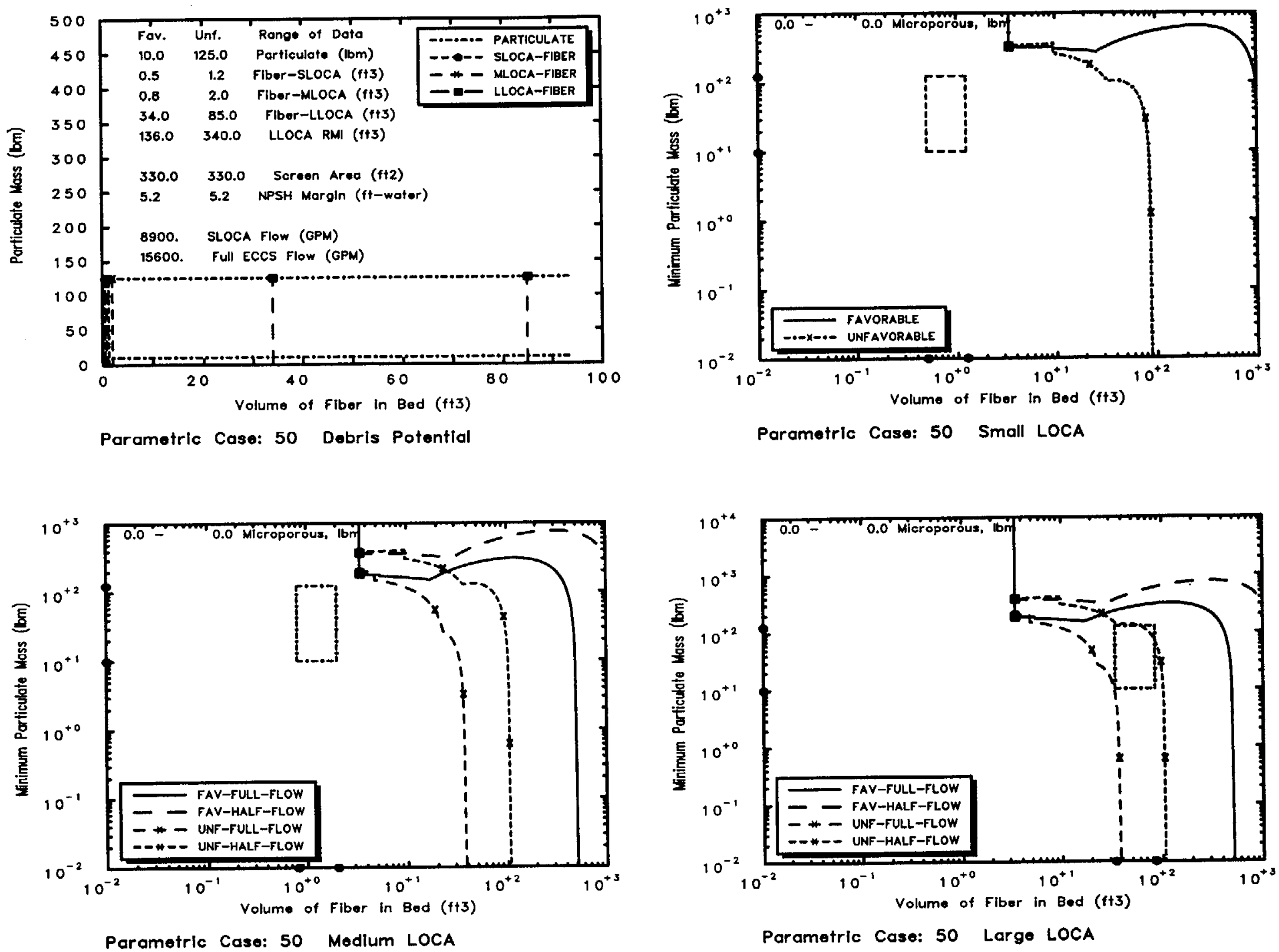


Fig. B-50. Parametric Case 50.

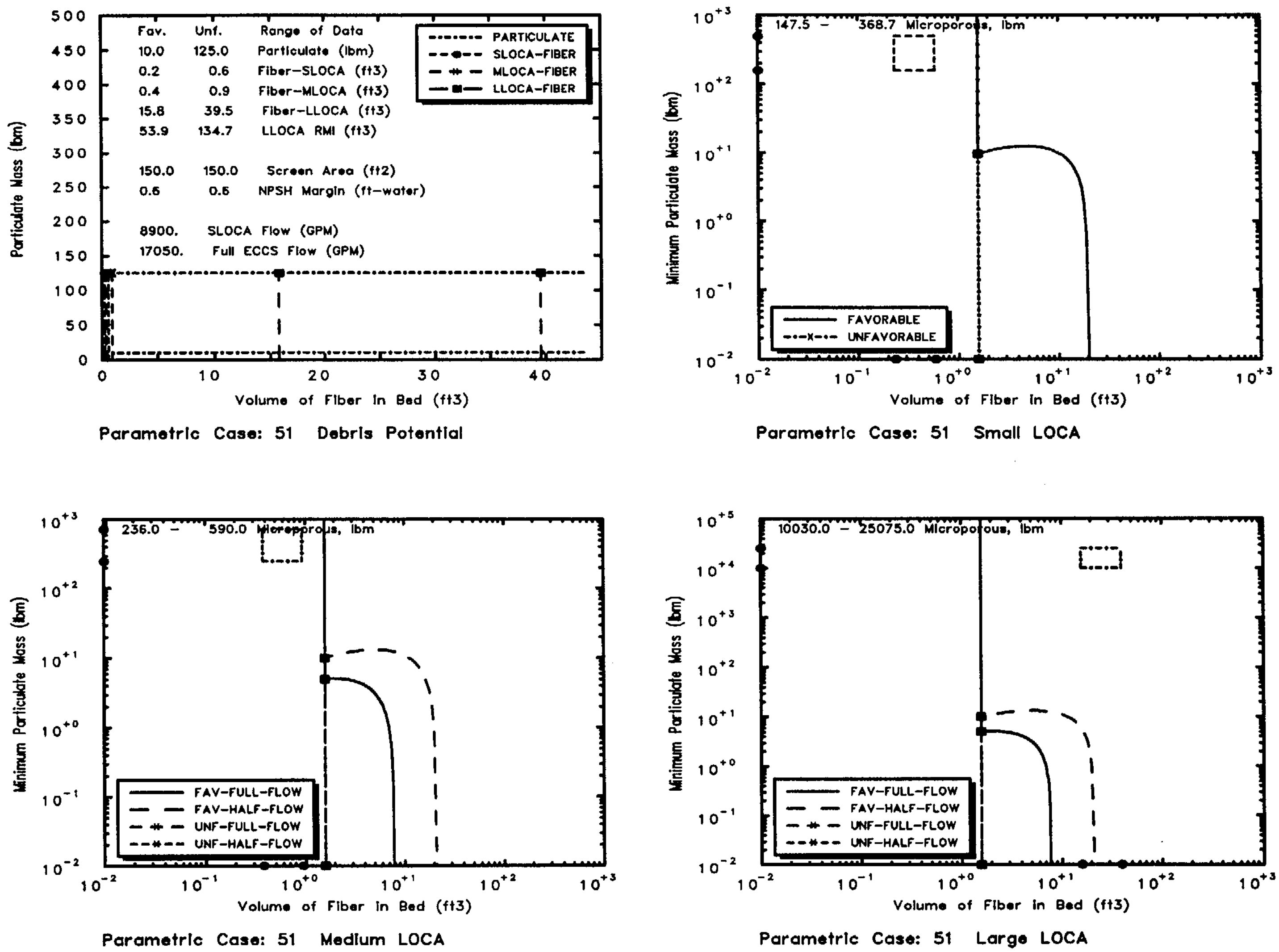


Fig. B-51. Parametric Case 51.

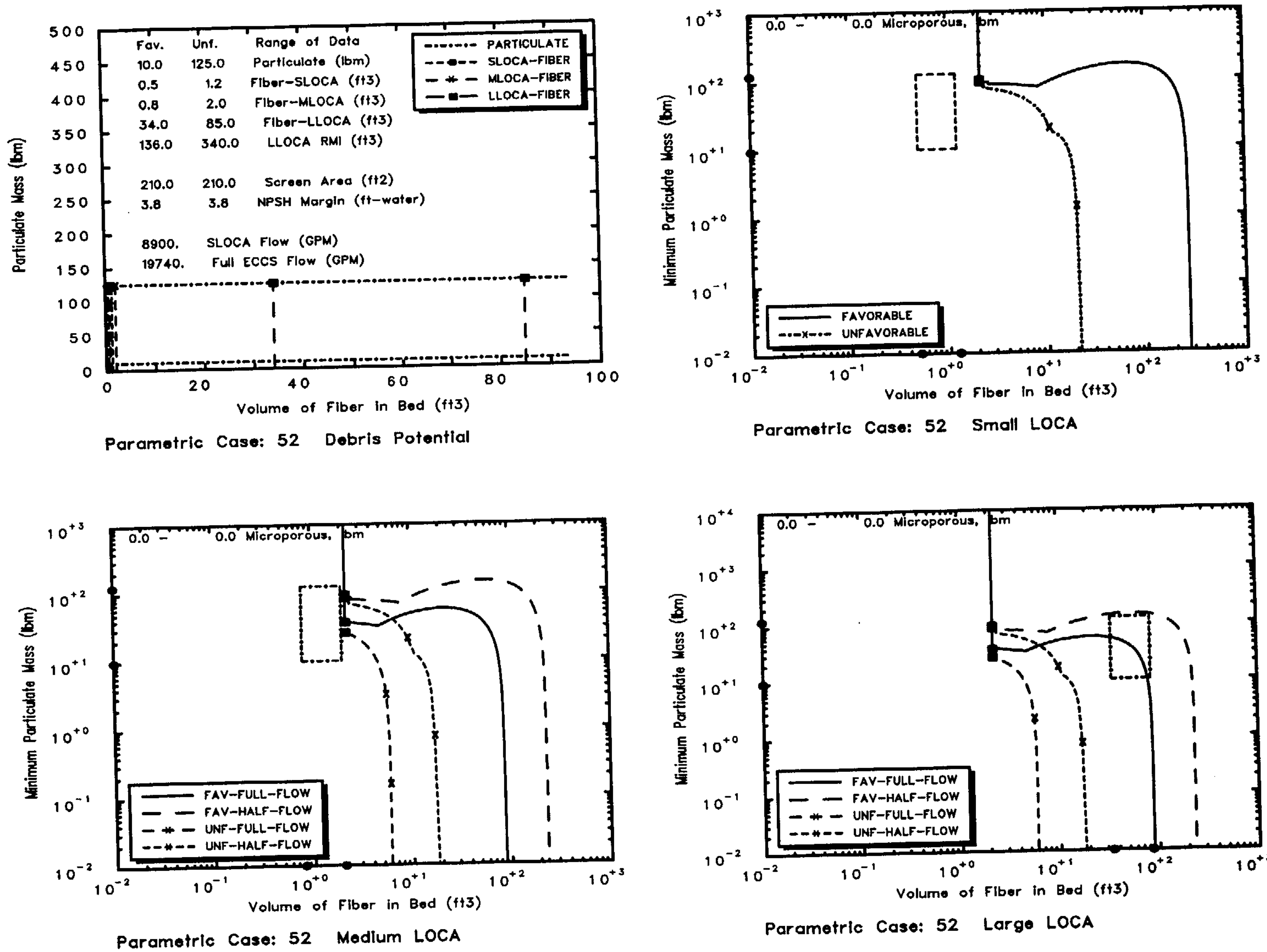
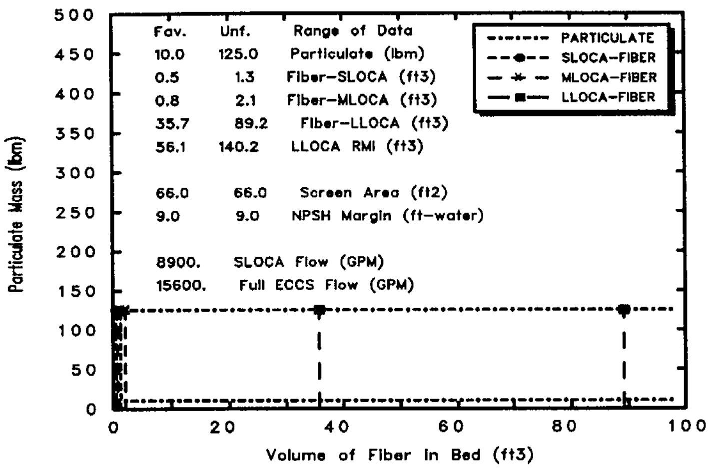
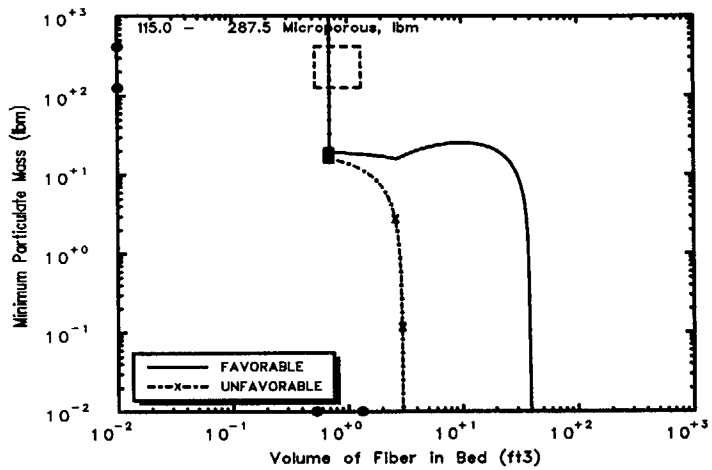


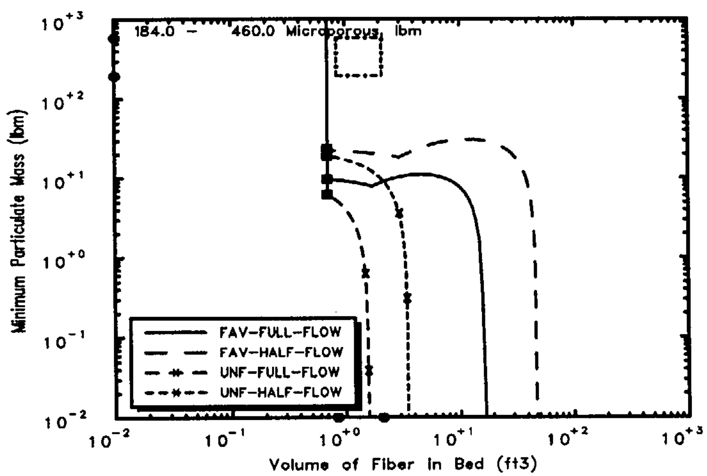
Fig. B-52. Parametric Case 52.



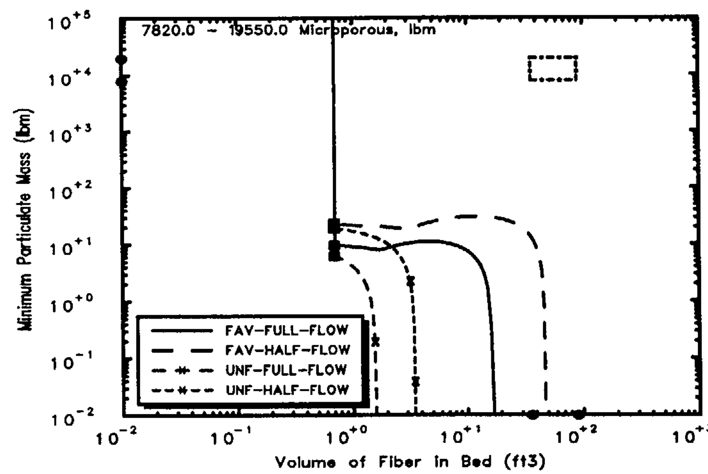
Parametric Case: 53 Debris Potential



Parametric Case: 53 Small LOCA



Parametric Case: 53 Medium LOCA



Parametric Case: 53 Large LOCA

Fig. B-53. Parametric Case 53.

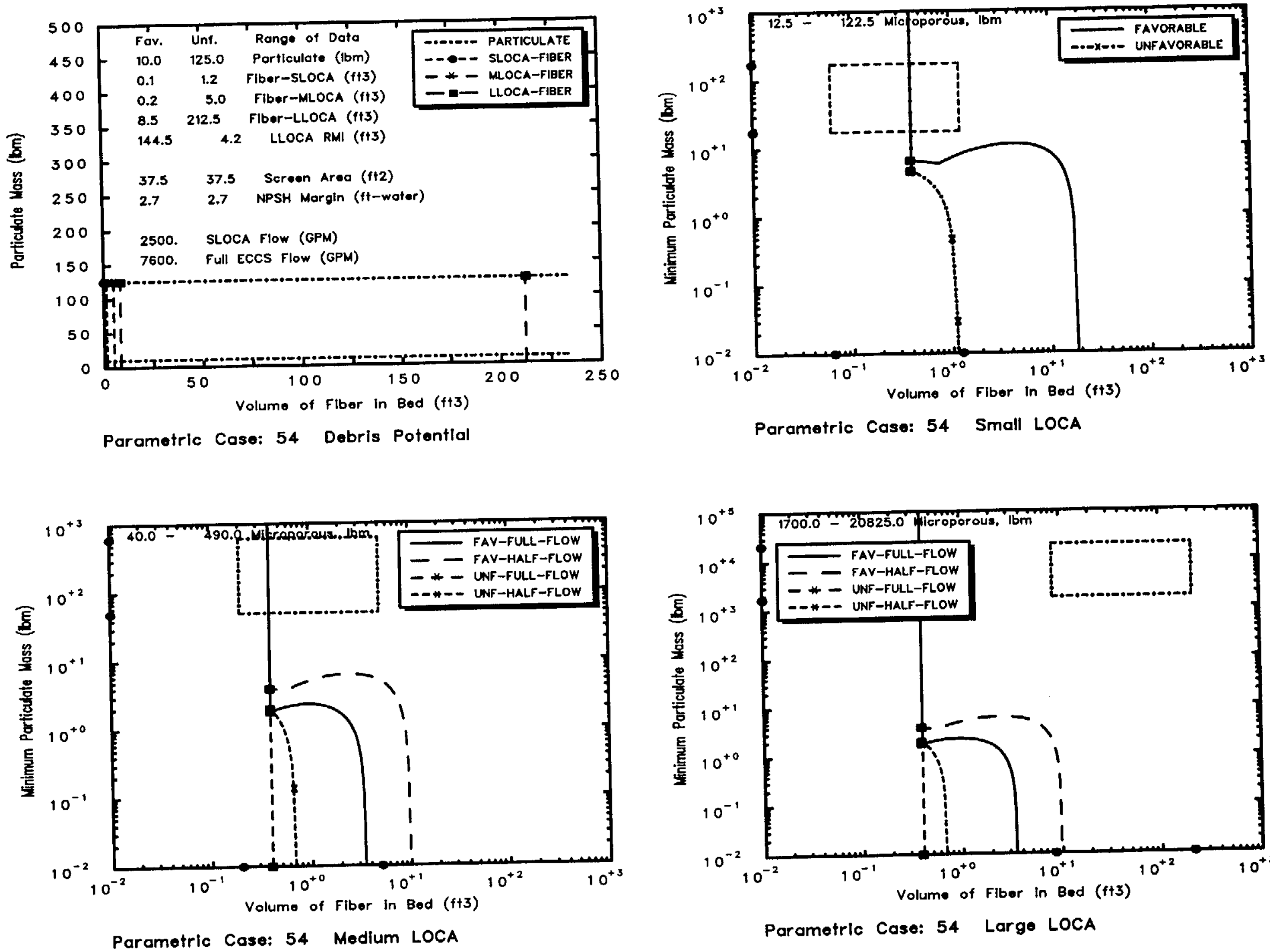


Fig. B-54. Parametric Case 54.

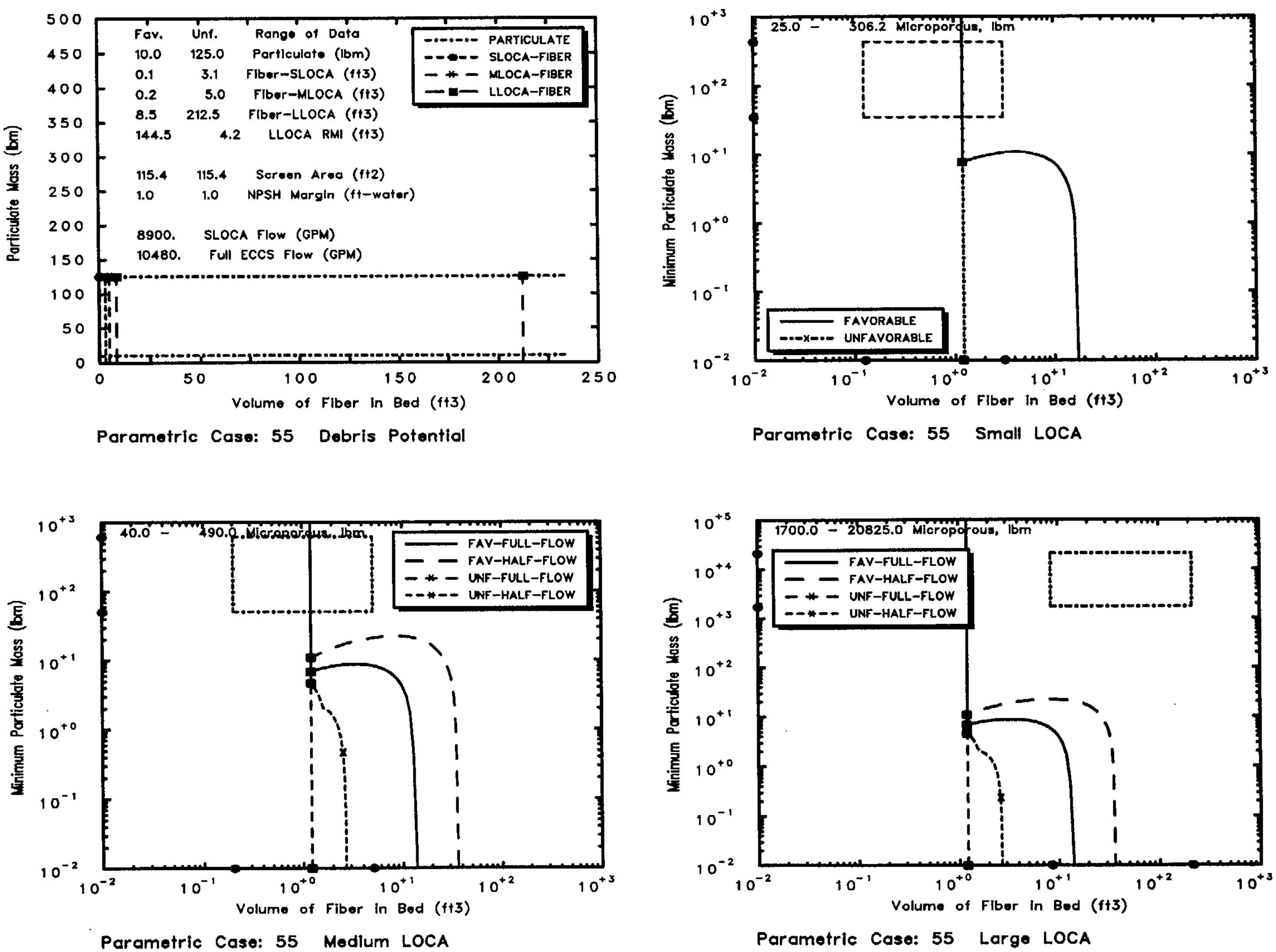


Fig. B-55. Parametric Case 55.

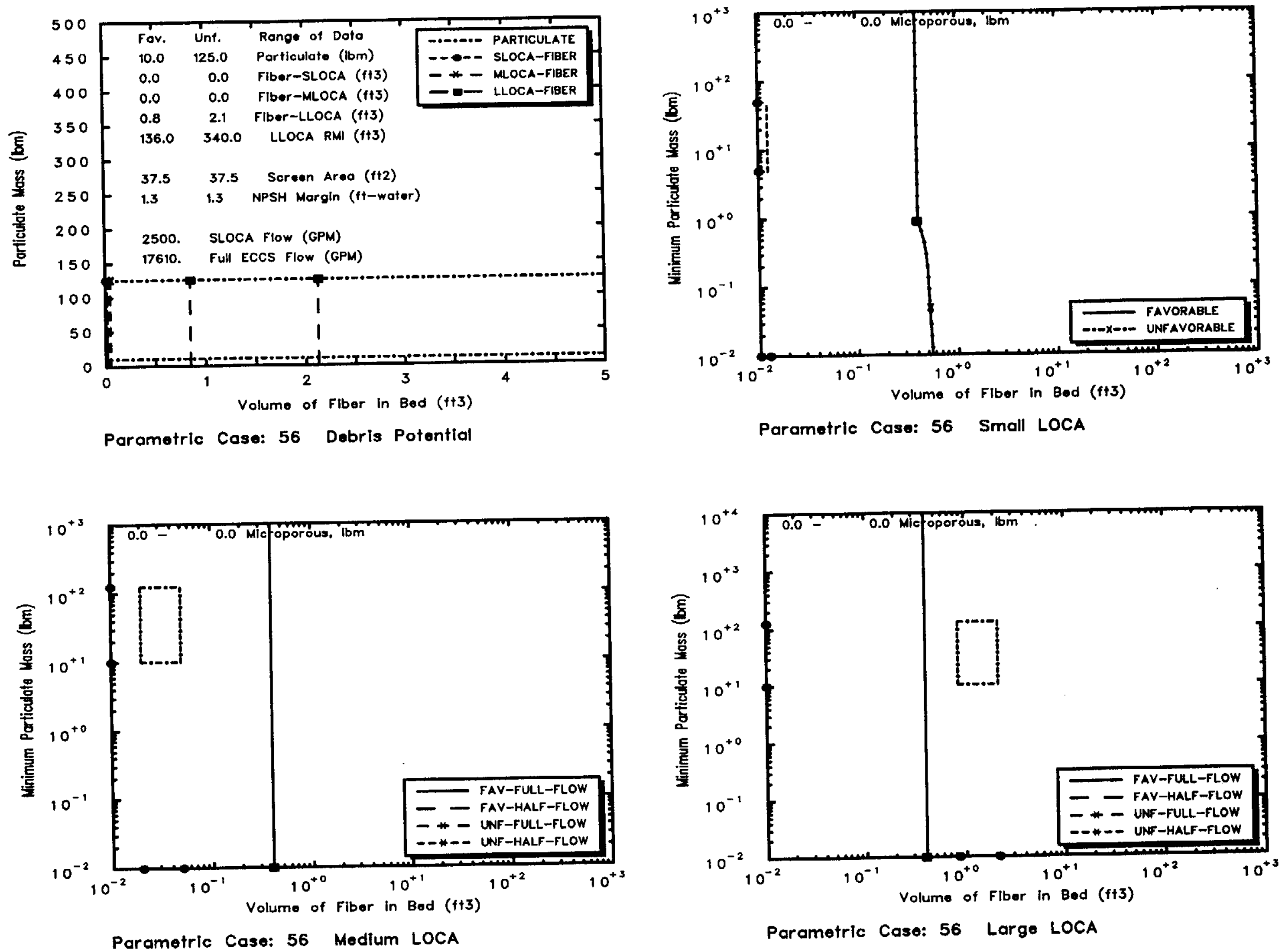


Fig. B-56. Parametric Case 56.

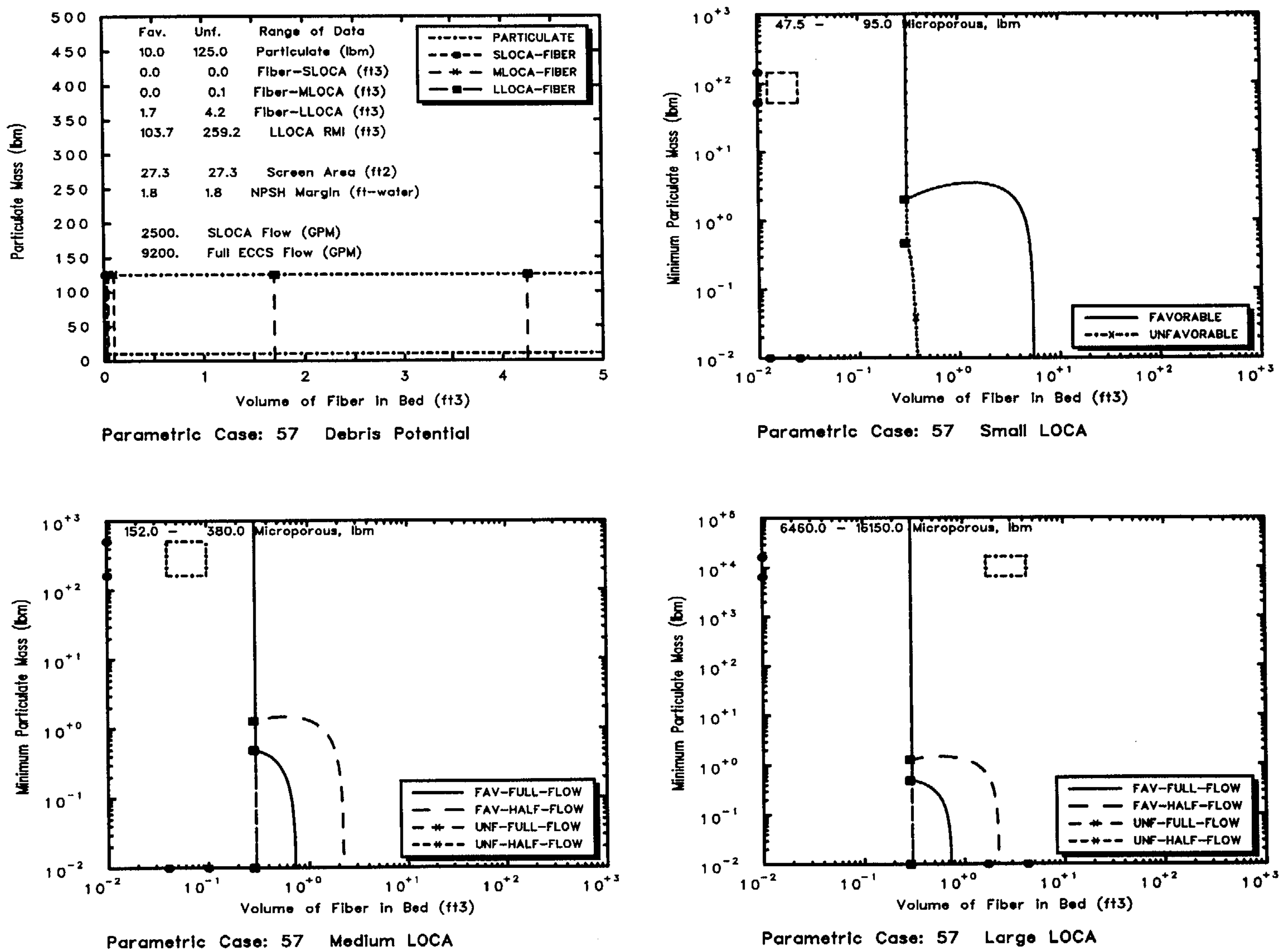


Fig. B-57. Parametric Case 57.

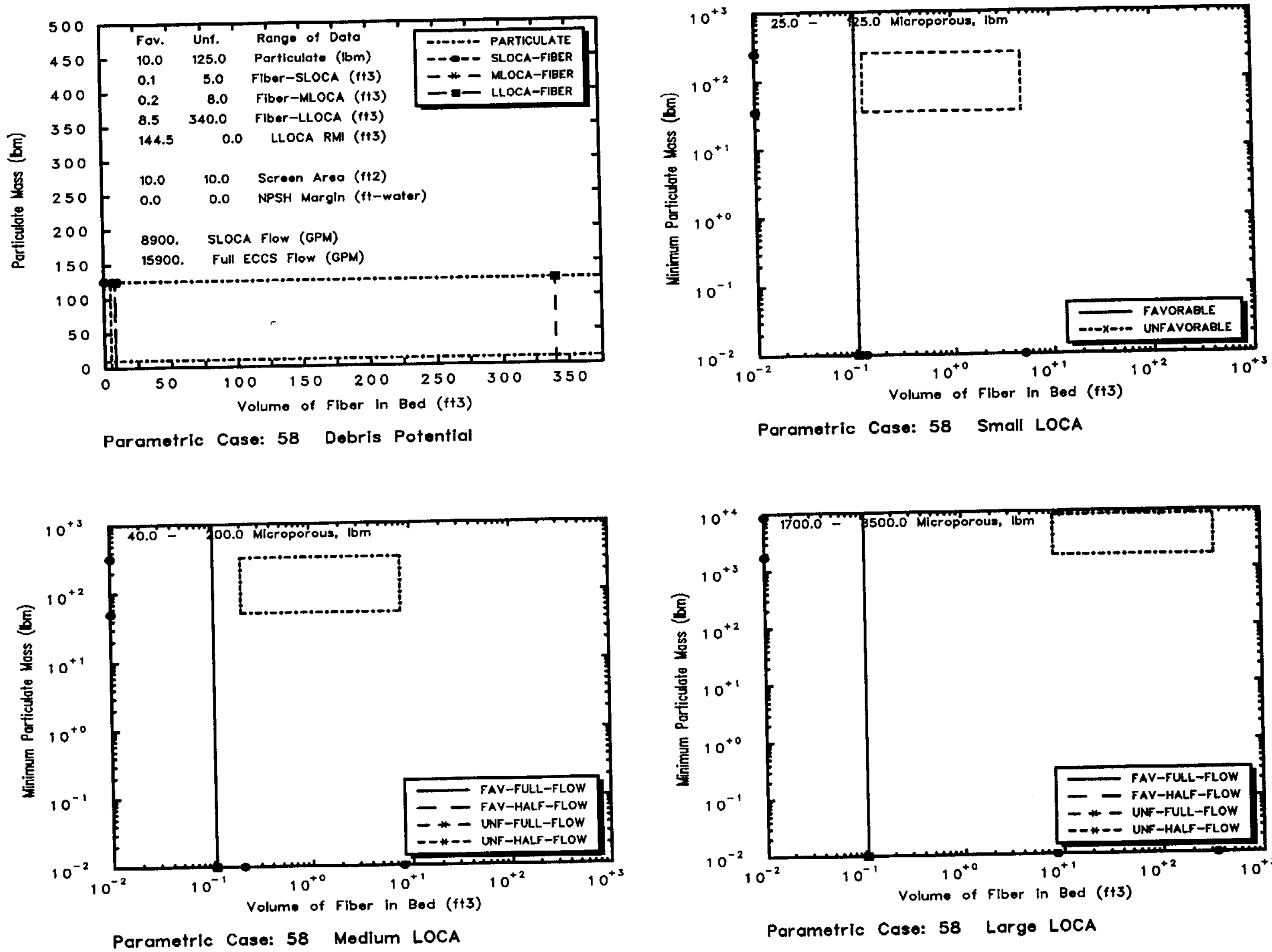


Fig. B-58. Parametric Case 58.

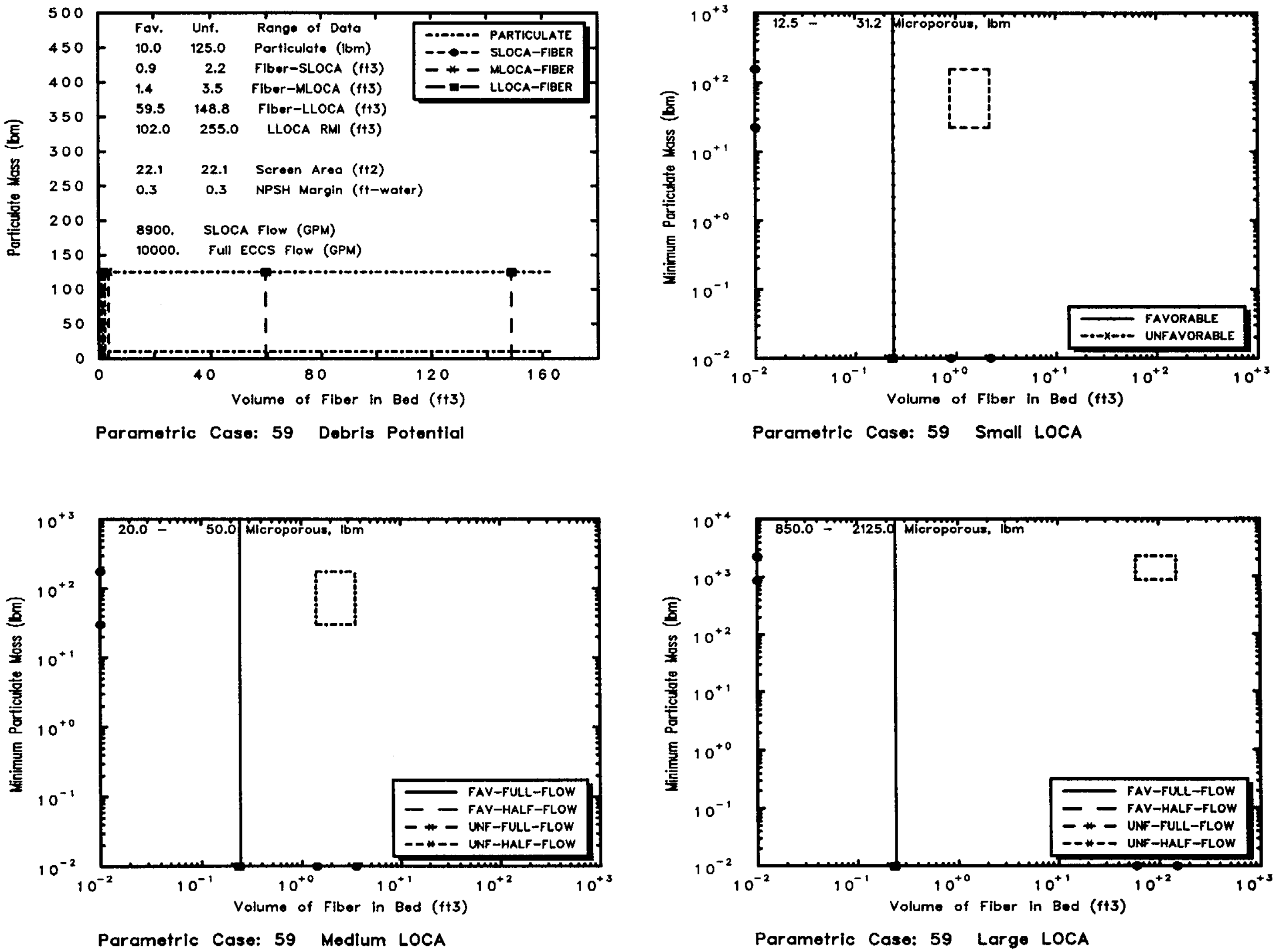


Fig. B-59. Parametric Case 59.

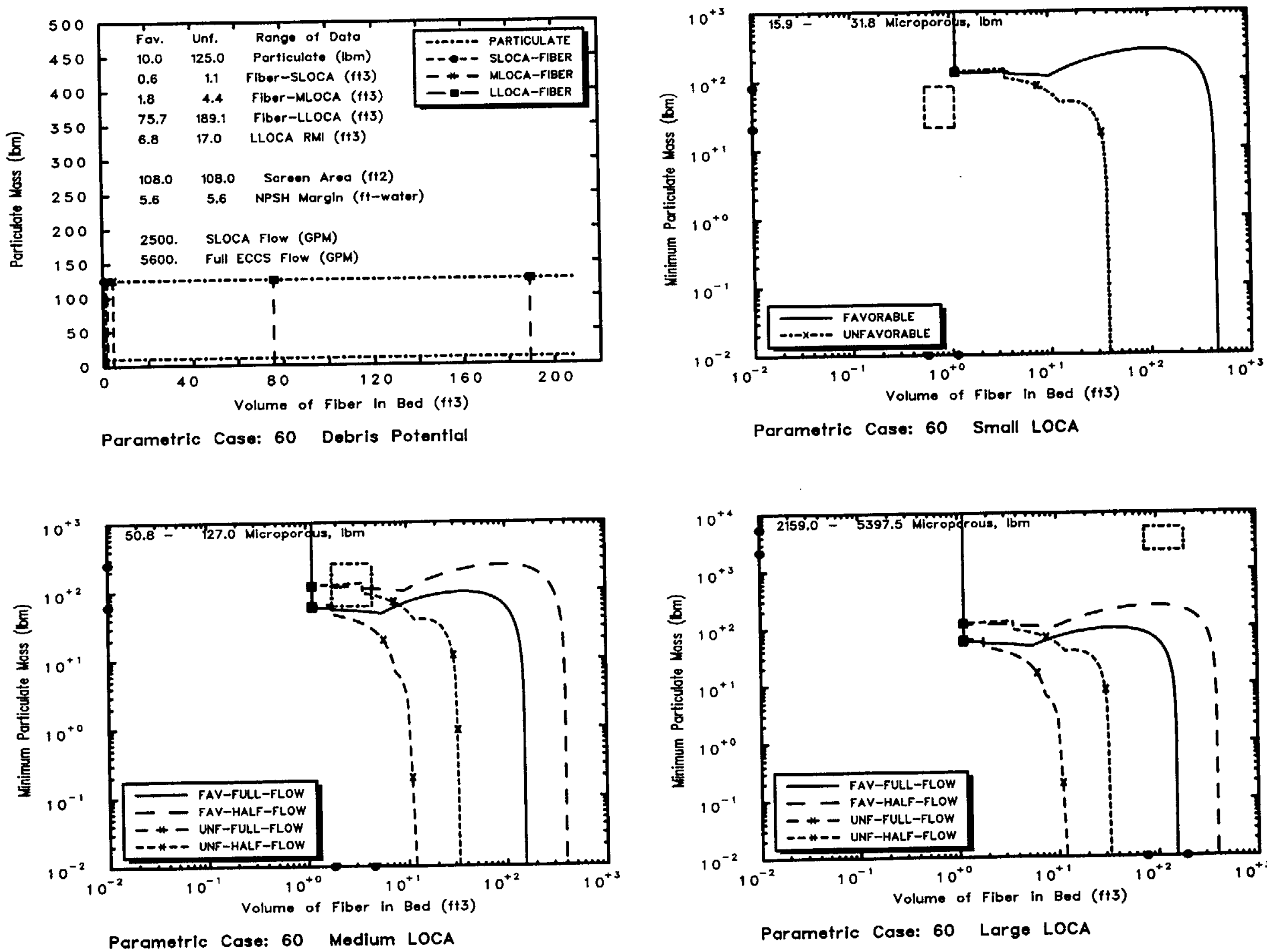


Fig. B-60. Parametric Case 60.

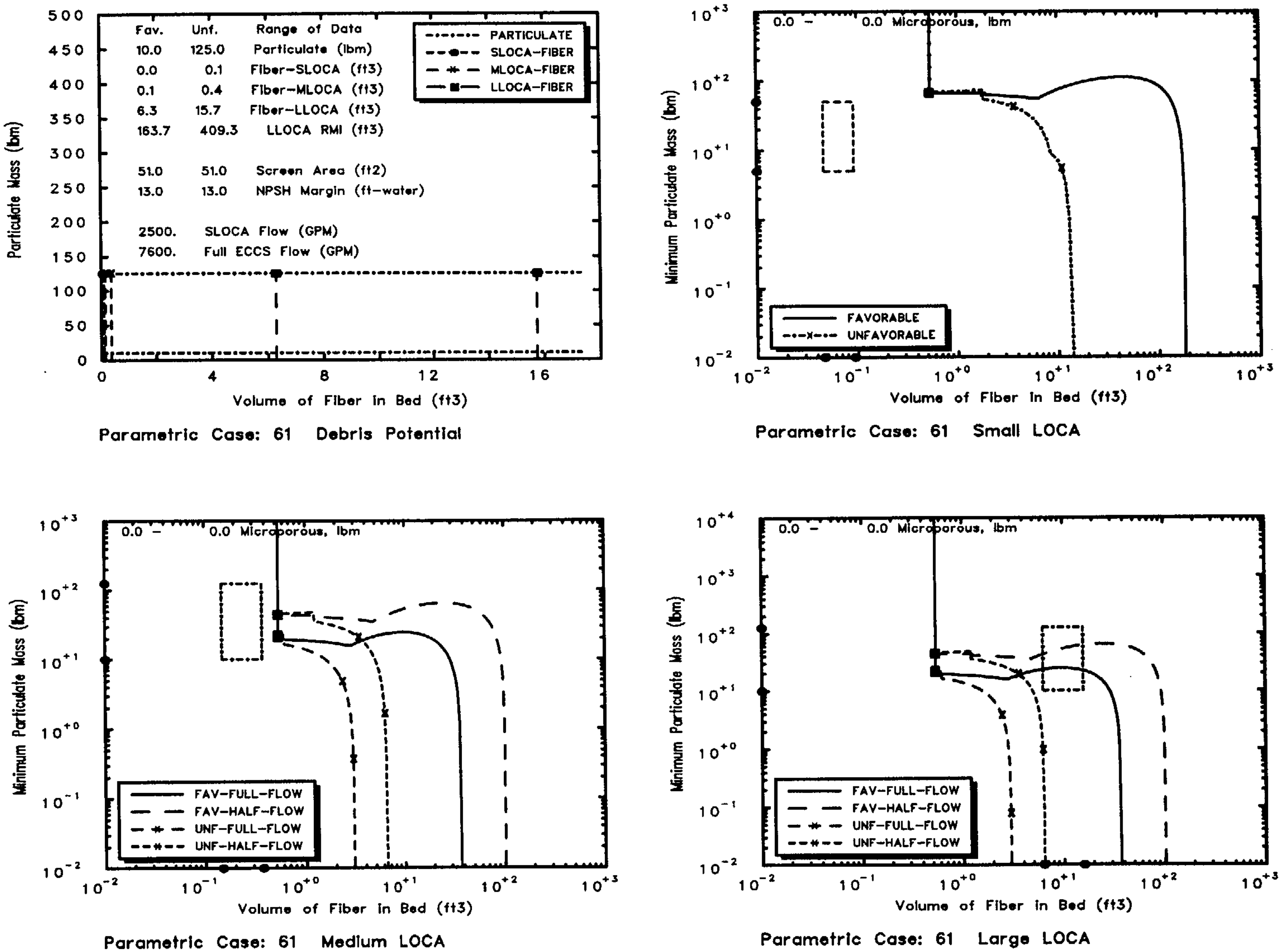


Fig. B-61. Parametric Case 61.

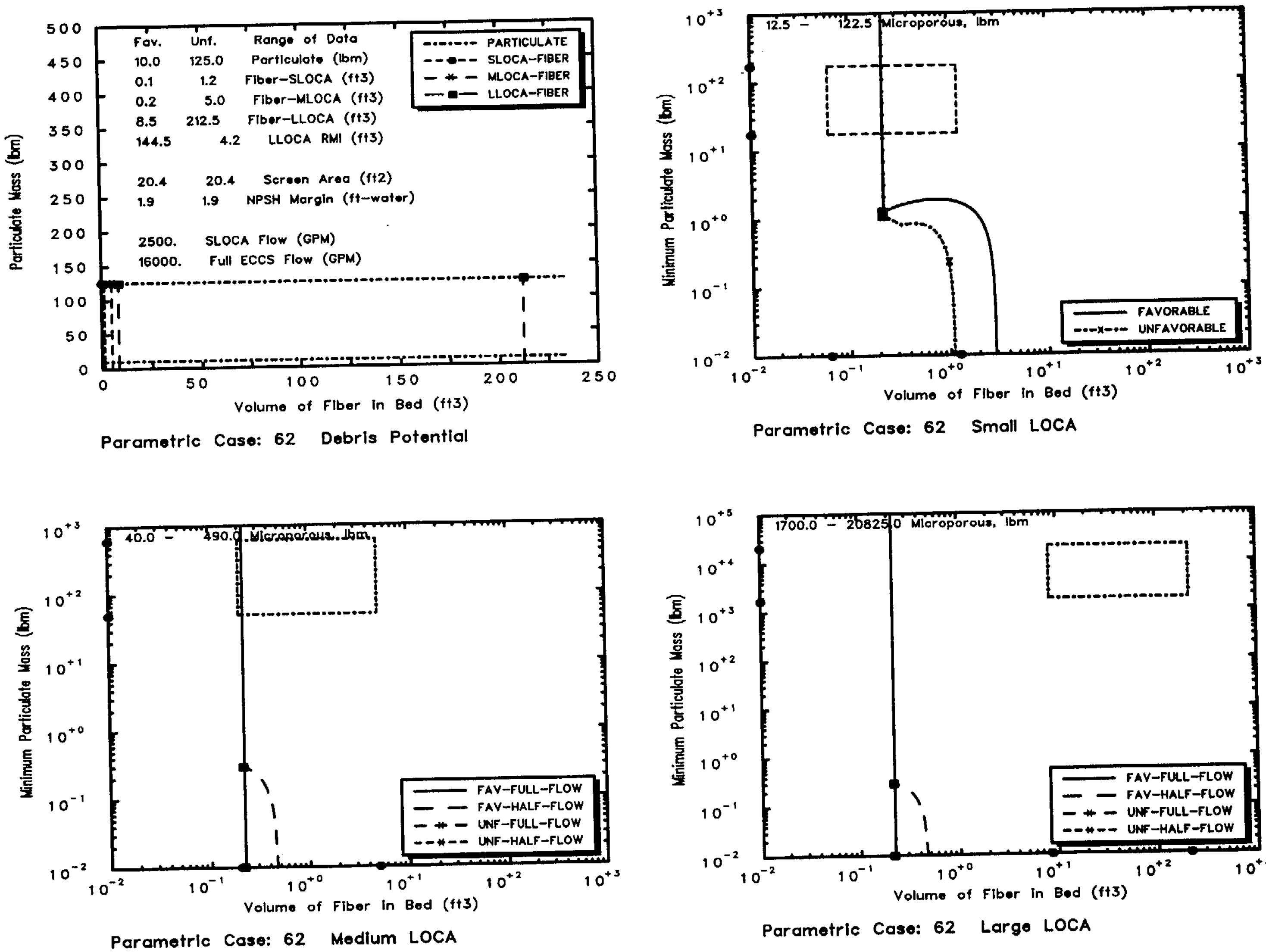
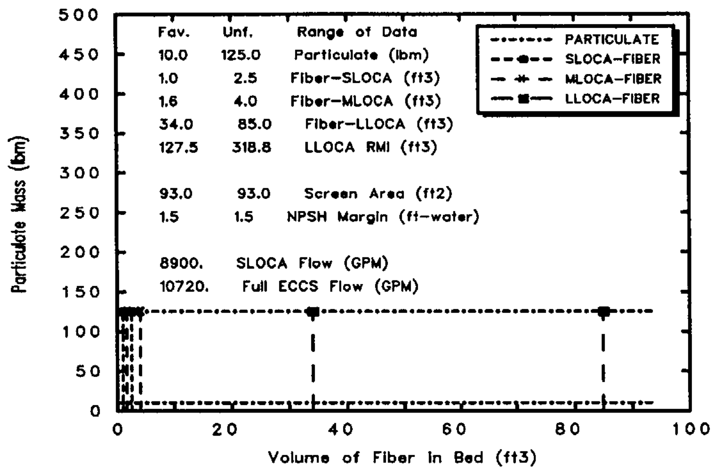
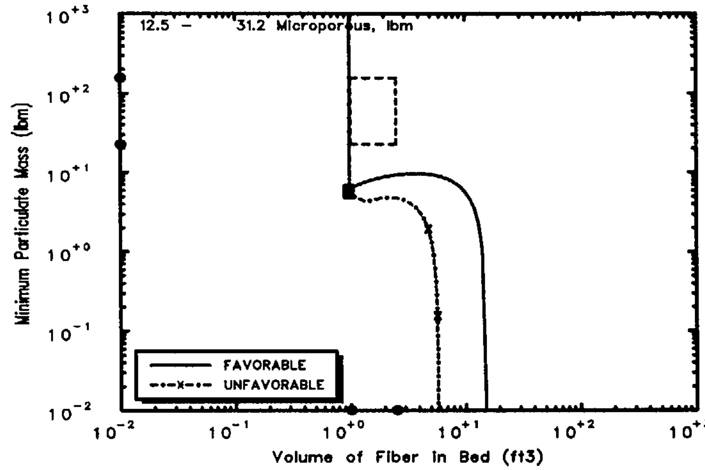


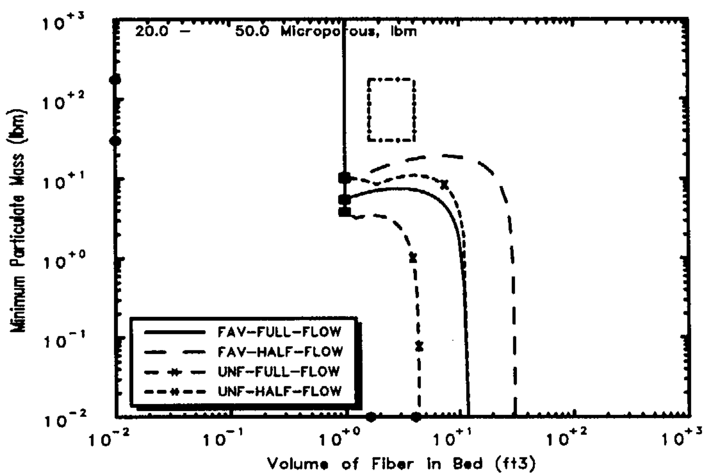
Fig. B-62. Parametric Case 62.



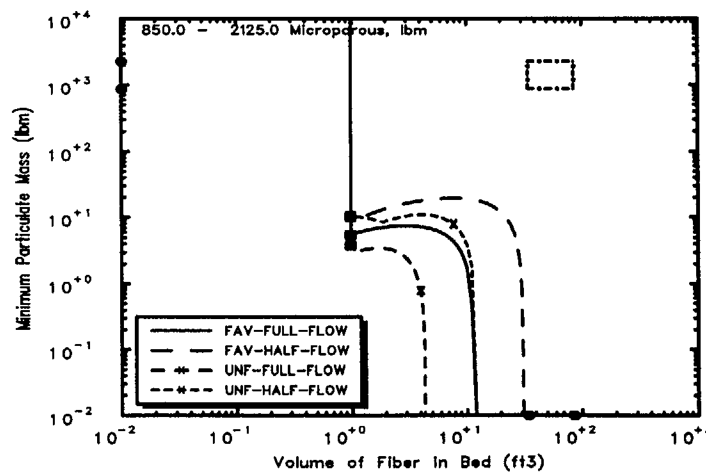
Parametric Case: 63 Debris Potential



Parametric Case: 63 Small LOCA



Parametric Case: 63 Medium LOCA



Parametric Case: 63 Large LOCA

Fig. B-63. Parametric Case 63.

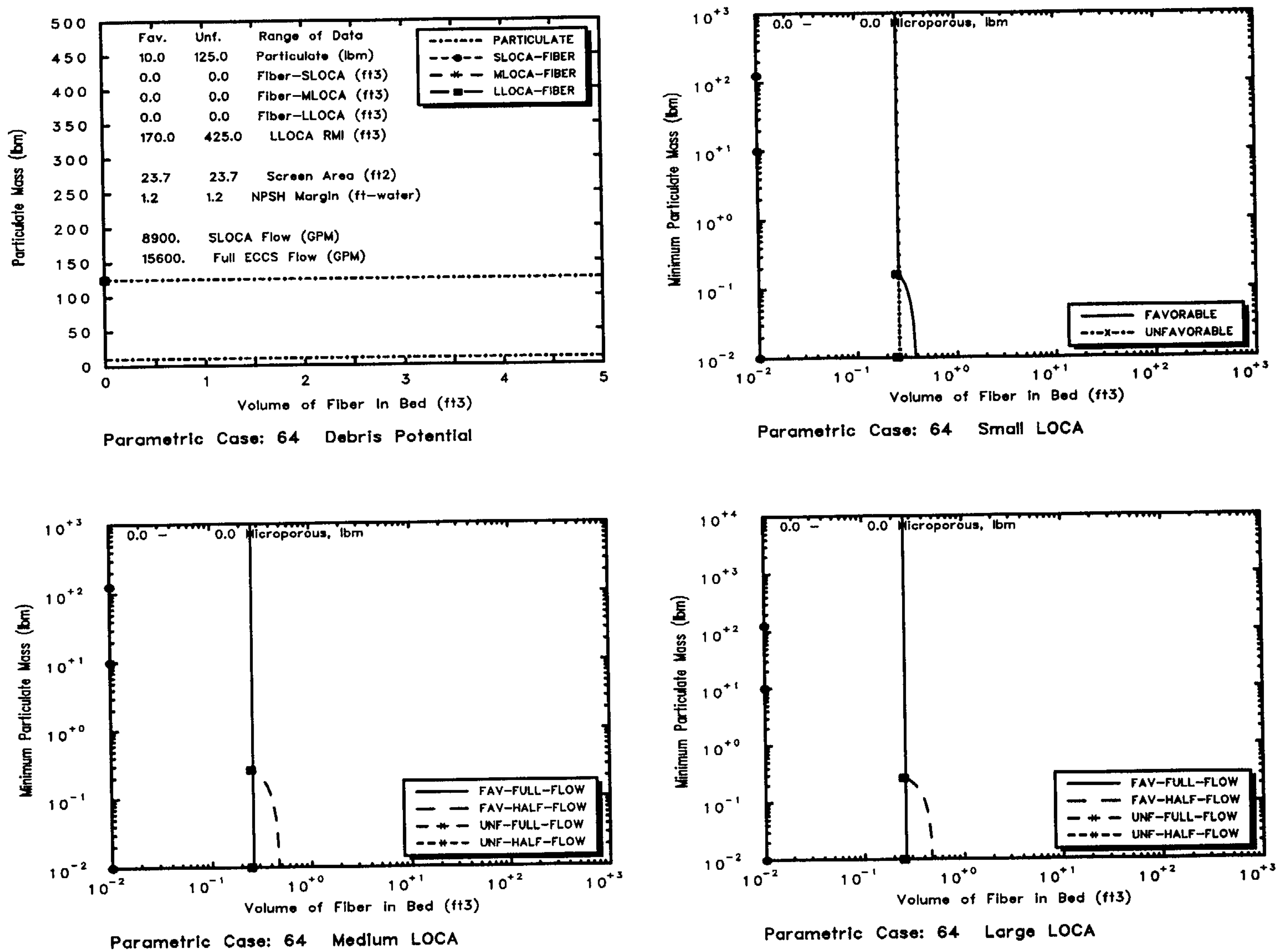


Fig. B-64. Parametric Case 64 (Note: No fiber in this case, so no debris boxes presented).

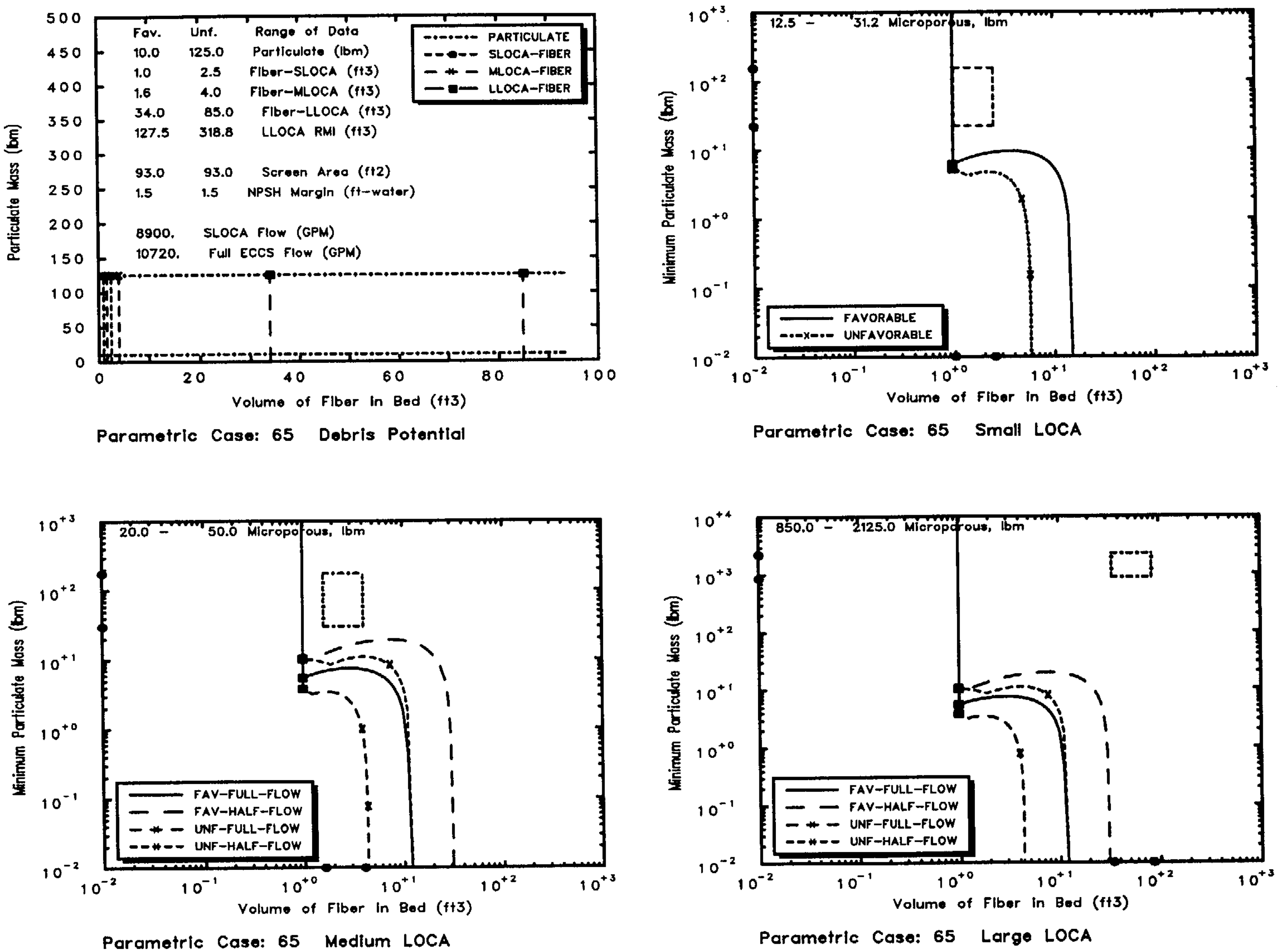


Fig. B-65. Parametric Case 65.

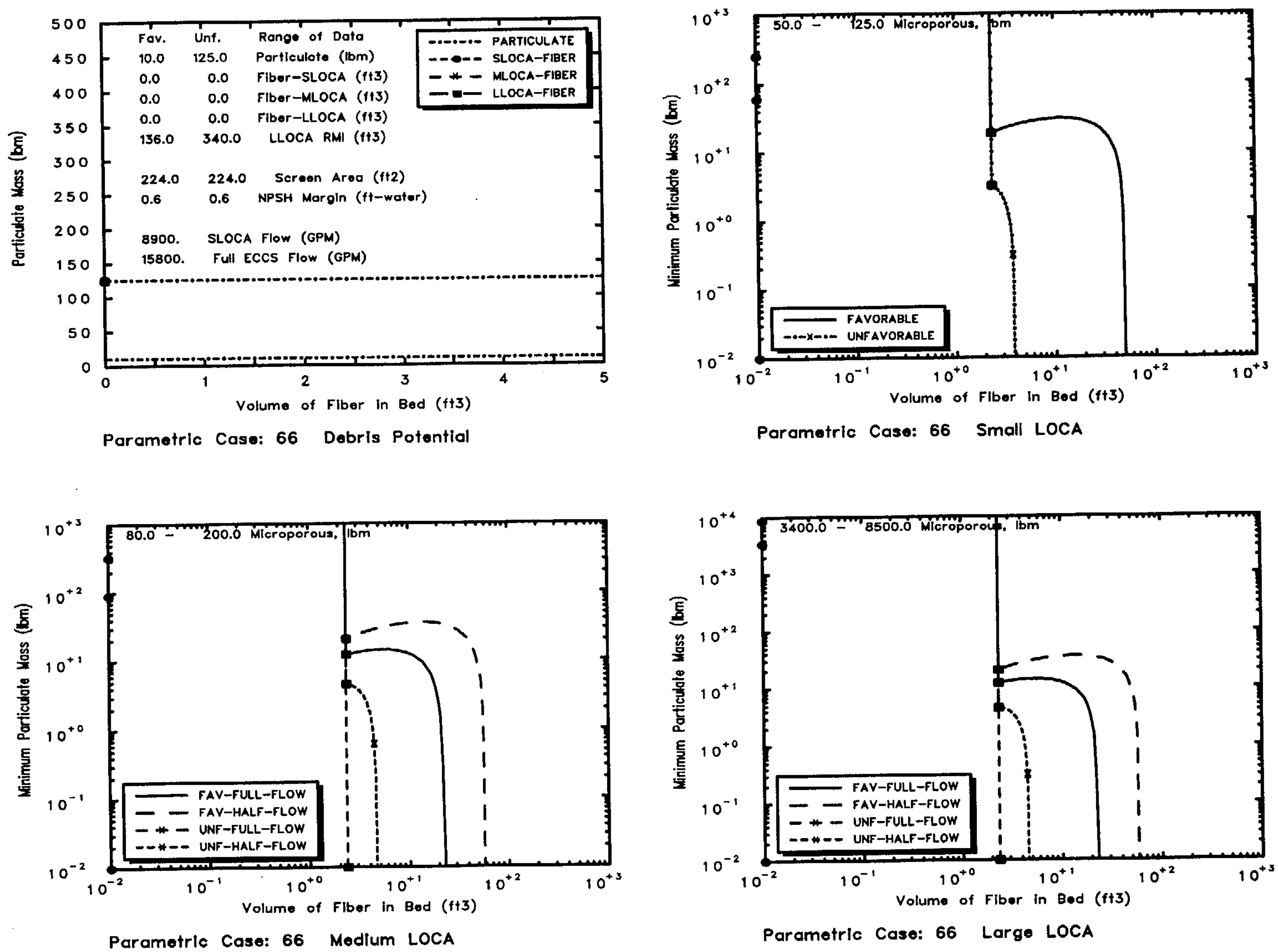


Fig. B-66. Parametric Case 66 (Note: No fiber in this case, so no debris boxes presented).

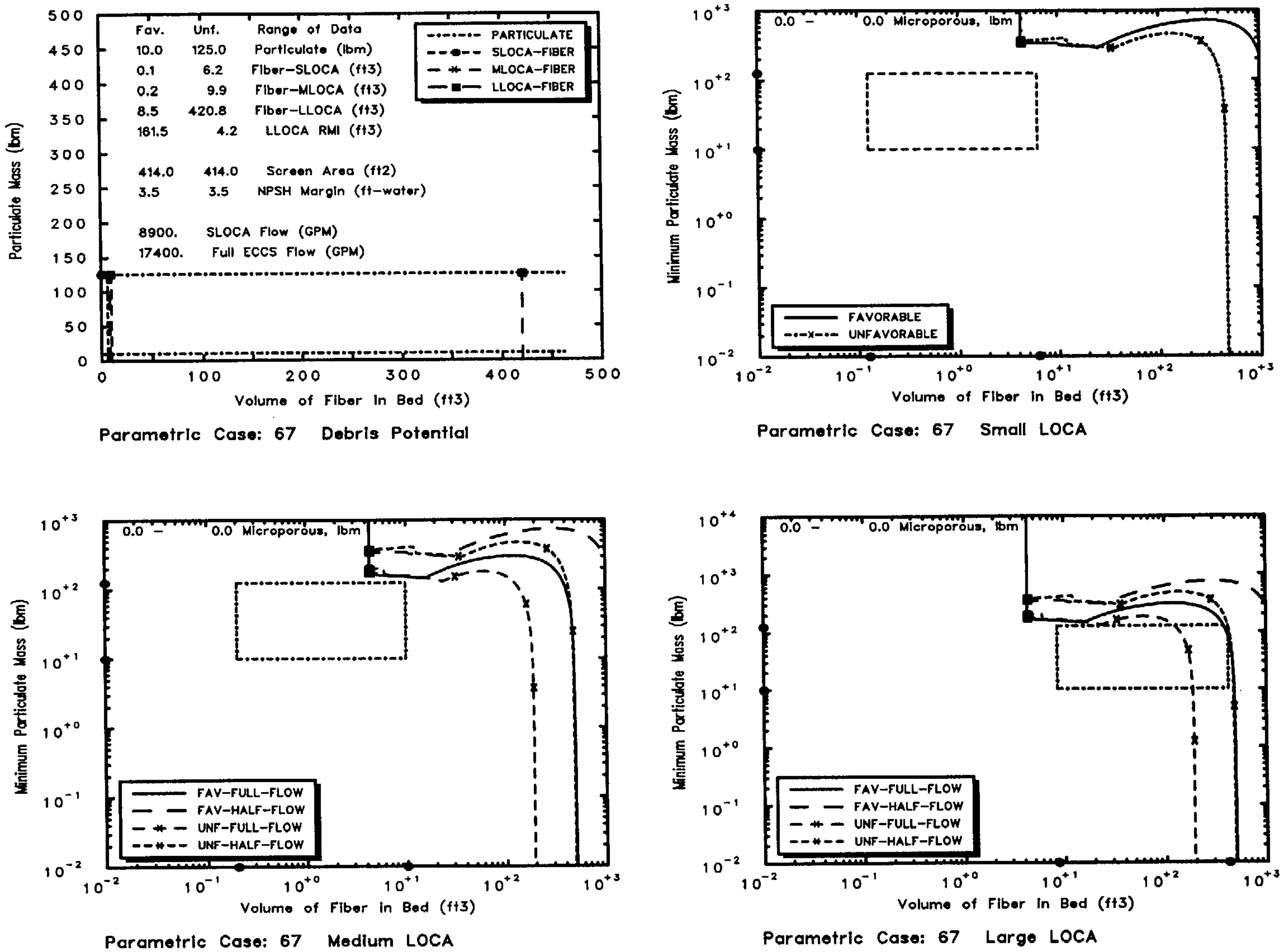


Fig. B-67. Parametric Case 67.

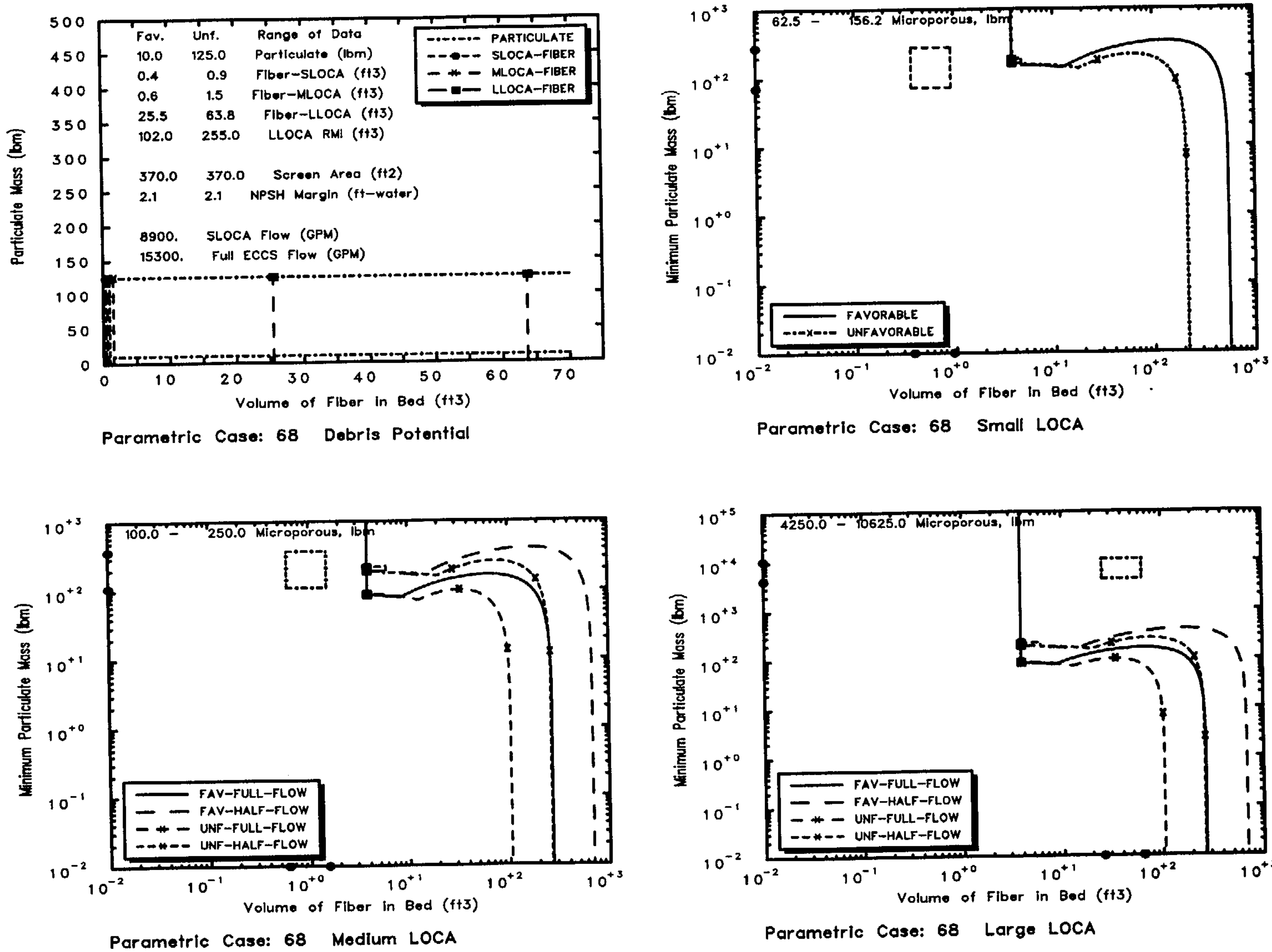
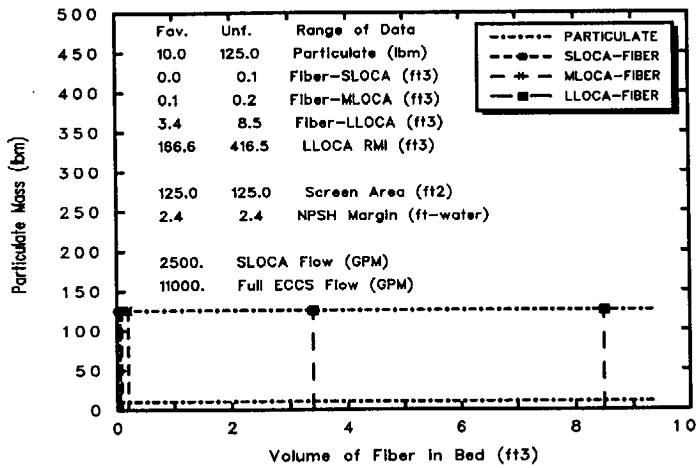
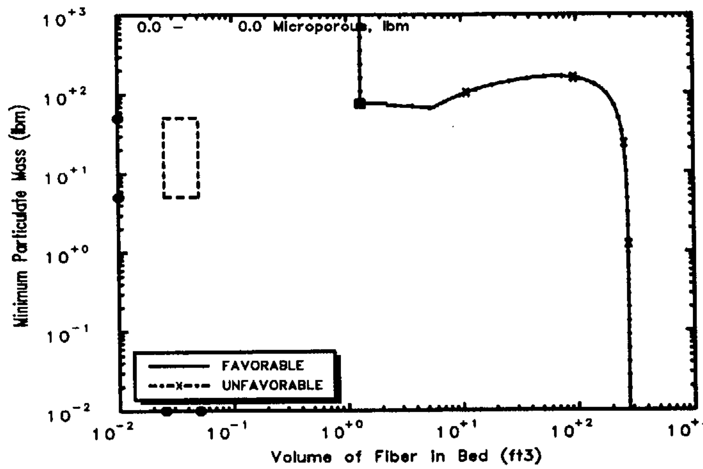


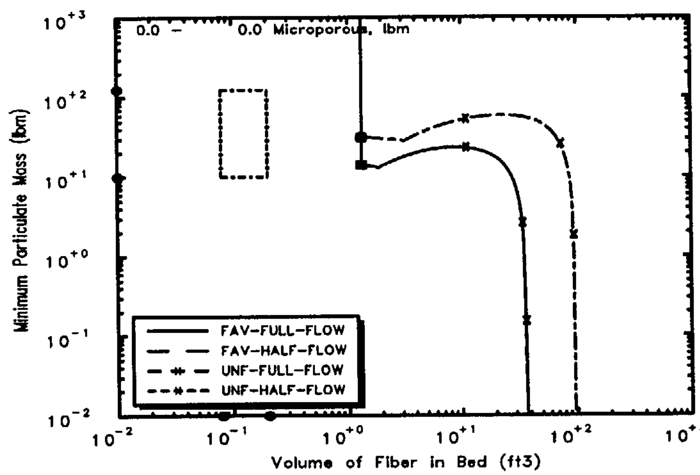
Fig. B-68. Parametric Case 68.



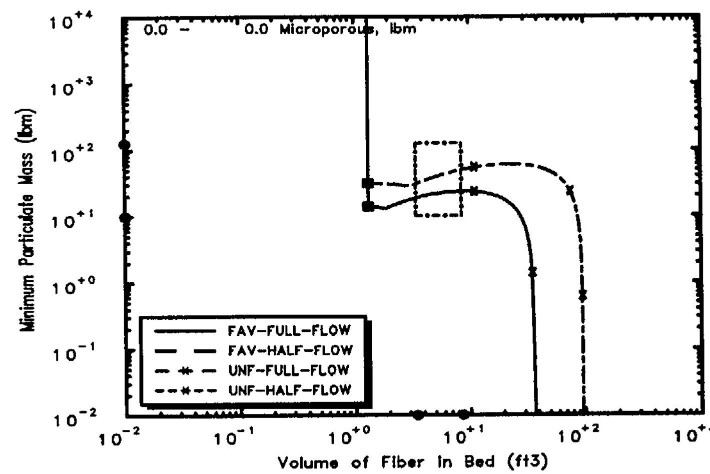
Parametric Case: 69 Debris Potential



Parametric Case: 69 Small LOCA



Parametric Case: 69 Medium LOCA



Parametric Case: 69 Large LOCA

Fig. B-69. Parametric Case 69.

Table B-1. Fraction of Debris-Transport Box Above FTDL Curve.

Case	SLOCA Single Flow Fav.	SLOCA Single Flow Unfav.	MLOCA Half Flow Fav.	MLOCA Half Flow Unfav.	MLOCA Full Flow Fav.	MLOCA Full Flow Unfav.	LLOCA Half Flow Fav.	LLOCA Half Flow Unfav.	LLOCA Full Flow Fav.	LLOCA Full Flow Unfav.
1	0.731	0.731	0.96	0.96	0.96	0.96	1	1	1	1
2	0	0	0.459	0.459	0.459	0.459	1	1	1	1
3	0	0	0	0	0	0	0	1	0.821	1
4	1	1	1	1	1	1	1	1	1	1
5	0.867	0.867	0.93	0.93	0.93	0.93	1	1	1	1
6	0.803	0.803	1	1	1	1	1	1	1	1
7	0	0	0	0	0	0	0	0	0	0
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	0.88	0.88	0.997	0.997	0.997	0.997	1	1	1	1
11	0.905	0.995	0.781	0.84	1	1	1	1	1	1
12	0.86	0.86	0.921	0.921	0.921	0.921	1	1	1	1
13	0	0	0	0	0	0	1	1	1	1
14	0	0	0	0	0	0	1	1	1	1
15	0	0	0.509	0.509	0.751	0.751	0.997	0.997	1	1
16	0.905	0.995	0.781	0.84	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	0	0	0	0	0	0	0	0	0	0
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	0	0	0	0	0.204	0.438	0	1	0.697	1
22	0.568	0.525	1	1	1	1	1	1	1	1
23	0	0	0.459	0.459	0.459	0.459	1	1	1	1
24	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0.019	0.644
26	1	1	1	1	1	1	1	1	1	1
27	0.443	0.443	0.918	0.918	0.918	0.918	1	1	1	1
28	0.014	0.013	1	1	1	1	1	1	1	1
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	1	1	1	1
31	0	0	0	0	0	0	0	0	0	0
32	1	1	1	1	1	1	1	1	1	1
33	0	0	0.634	0.634	0.634	0.634	1	1	1	1

Table B-1. Fraction of Debris-Transport Box Above FTDL Curve (cont).

	SLOCA Single Flow		MLOCA Half Flow		MLOCA Full Flow		LLOCA Half Flow		LLOCA Full Flow	
Case	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.	Fav.	Unfav.
34	0	0	0	0	0	0	0.598	1	0.878	1
35	0.828	0.828	0.906	0.906	0.906	0.906	1	1	1	1
36	0.742	0.742	1	1	1	1	1	1	1	1
37	1	1	1	1	1	1	1	1	1	1
38	0	0	0	0	0	0	0	1	0.821	1
39	0	0	0.286	0.286	0.286	0.286	1	1	1	1
40	0	0	0	0	0	0	1	1	1	1
41	0	0	0	0	0	0	0	1	0	1
42	0.005	0.002	1	1	1	1	1	1	1	1
43	0	0	0	0	0	0	1	1	1	1
44	0	0	0	0	0	0	1	1	1	1
45	0.802	0.802	0.89	0.89	0.89	0.89	1	1	1	1
46	0	0	0	0	0.217	0.203	0.973	1	1	1
47	1	1	1	1	1	1	1	1	1	1
48	1	1	1	1	1	1	1	1	1	1
49	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0.119	0	1
51	0	0	0	0	0	0	1	1	1	1
52	0	0	0	0	0	0	0	1	0.821	1
53	0.803	0.803	1	1	1	1	1	1	1	1
54	0.731	0.731	0.96	0.96	0.96	0.96	1	1	1	1
55	0.645	0.645	0.791	0.791	0.791	0.791	1	1	1	1
56	0	0	0	0	0	0	1	1	1	1
57	0	0	0	0	0	0	1	1	1	1
58	1	1	1	1	1	1	1	1	1	1
59	1	1	1	1	1	1	1	1	1	1
60	0	0	0.725	0.714	1	1	1	1	1	1
61	0	0	0	0	0	0	0.598	1	0.878	1
62	0.88	0.88	0.997	0.997	0.997	0.997	1	1	1	1
63	1	1	1	1	1	1	1	1	1	1
64	0	0	0	0	0	0	0	0	0	0
65	1	1	1	1	1	1	1	1	1	1
66	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0.019	0.644
68	0	0	0	0	0	0	1	1	1	1
69	0	0	0	0	0	0	0.729	0.729	0.897	0.897

Attachment 3

September 21, 2001

RISK AND COST-BENEFIT CONSIDERATIONS ASSOCIATED WITH GSI-191, "ASSESSMENT OF DEBRIS ACCUMULATION ON PWR SUMP PERFORMANCE" (Rev. 1)

Arthur Buslik

1.0 Introduction

In this report, the risk associated with sequences involving sump screen clogging (in PWRs) will be addressed. Because there are many plant specific considerations which enter, and because there were insufficient resources to treat each plant individually, these estimates will necessarily be rather crude; nevertheless, especially for the results summed over various populations of plants, they are adequate for the purpose of determining the risk and whether the fixes under consideration are cost-beneficial. Estimates of the core damage frequency contribution, of the associated offsite risk, and of the associated onsite expected costs, from the accidents associated with sump screen clogging, will be given. (The onsite costs considered here are the costs that would be averted if the sump screen clogging problem were fixed.) The core damage frequency estimates will all depend on the probability of sump screen clogging. This will be initially treated as a parameter. Our LANL contractors have classified the likelihood of sump screen clogging as "very likely", "likely", "possible", or "unlikely". Mike Marshall (private communication) has indicated that "very likely" corresponds to a probability of unity, "likely" corresponds to a probability of 60%, "possible" corresponds to a probability of 40%, and "unlikely" corresponds to a negligible probability. These probabilities are best interpreted in the Bayesian sense. They represent subjective probabilities, not an estimate of the frequency of sump blockage in a large number of trials. This revision differs from an earlier version (dated August 22, 2001) in that (1) the revised likelihoods of sump screen clogging presented in rev. 1 of the LANL report, LA-UR-01-4083, August 2001 are used; (2) the percentage of plants which will obtain license renewal was assumed to be 85% instead of 50%; (3) in the base case, the probability of sump screen clogging for a RCP seal LOCA is taken as zero, and, in a sensitivity study, the probability of sump clogging on a RCP seal LOCA is taken as equal to that for a small break LOCA; and (4) additional uncertainty analysis is presented. In the August 22, 2001, version of this report, only the case where the probability of sump screen clogging (to the point of ECCS recirculation failure) was the same for RCP seal LOCAs as for small pipe break LOCAs was considered. In the earlier version of the report, "possible" corresponded to a 30% probability of sump blockage.

Of course, sump screen clogging is only relevant for LOCAs where it is necessary to go to sump recirculation. Some LOCAs can be handled by cooldown and depressurization of the primary without the necessity of going to sump recirculation. First the various size LOCAs used in this study will be given, together with their frequencies. Then the accident sequence delineation will be given, together with the quantification of the sequence core damage frequencies. Next, the offsite risk and expected onsite costs associated with the core damage events caused by sump screen clogging will be considered, on a per plant basis, using a range of possible values for the probability of sump screen clogging. Finally, estimates of aggregate benefits (expected averted costs) will be presented for sets of plants which may implement the fix.

LANL has supplied us with a technical letter report (D.V. Rao et al., "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance", LA-UR-01-4083, August 2001, Rev. 1) in which for 69 "parametric cases" the subjective likelihood of sump screen clogging is given. This LANL report will be referred to as "the LANL GSI-191 parametric study." Each case corresponds to a PWR plant. The word "case" was used because the case corresponding to a plant approximated individual plant features and therefore each individual case did not represent a complete perspective of sump screen clogging at its corresponding plant. However, for the purposes of estimating aggregate benefits it is considered adequate to equate the "cases" with plants.

2.0 **LOCA Types and Their Frequencies**

The various LOCA types used in this study will correspond to those given in NUREG/CR-5750, ("Rates of Initiating Events at U.S. Nuclear Power Plants: 1987-1995", February 1999). Then the frequencies of various LOCA types can be taken directly from this document. The LOCA types, and their frequencies are:

Large LOCA (> 6 inches)	7E-6/yr
Medium LOCA (2 to 6 inches)	4E-5/yr
Small LOCA (0.5 to 2 inches)	5E-4/yr
Very Small LOCA	6.2E-3/yr
Stuck-Open Safety Relief Valve	5E-3/yr
Reactor Coolant Pump Seal LOCA	2.5E-3/yr

Except for the Large LOCA, the frequencies are taken from Table 3-1 of NUREG/CR-5750. The Large LOCA frequency was updated (private communication from Sunil Weekakkody) to take into account the V.C. Summer event of 10/12/2000, LER 39500008. The numbers in parentheses after the LOCA types refer to the inside pipe diameter, and are taken from Table J-1 of NUREG/CR-5750.

Seismically-induced LOCAs

One should also consider LOCAs caused by external events. The Surry seismic analysis done for the NUREG-1150 studies was used to determine the fragility curves for the various size LOCAs. The conditional probabilities of core damage for a given peak ground acceleration, from Table 4.19 of NUREG/CR-4550, Vol. 3, Rev. 1, Part 3, were fitted to lognormal distributions. The lognormal parameters were:

Small LOCA:	a_{median}=1.33, β=0.81
Medium LOCA:	a_{median}=1.88, β=0.70
Large LOCA:	a_{median}=1.14, β=0.61

The revised LLNL hazard functions (see NUREG-1488) for the Surry site were approximated by the expression (see R.P. Kennedy, Nucl. Eng. Design **192**, 117 (1999))

$$H(a)=K_1 a^{-K_H},$$

with K_1 = 1.29E-6 and K_H = 2.23; these values were obtained by a least squares fit to log(H(a)). Here H(*a*) is the exceedance frequency for the peak ground acceleration *a*.

With the lognormal fragility curves, and the approximation to the hazard function given above, the integration of the fragility over the hazard function can be done analytically. The results are:

Seismically-induced large LOCA	2E-6/yr
Seismically-induced medium LOCA	1E-6/yr
Seismically-induced small LOCA	3E-6/yr

Comparing these frequencies to the internal events LOCA frequencies (7E-6/yr for large LOCA, 4E-5/yr for medium LOCA, and 5E-4/yr for small LOCAs), one sees that the seismic contributions can be neglected, except possibly for large LOCAs. For seismic events, at the higher peak ground accelerations, there is an appreciable probability of core damage even without sump screen clogging, so the absence of sump screen clogging may not affect the seismic core damage frequency appreciably. The fragility curves used are considered to be typical for all PWRs; they were generated originally for the SSMRP Zion analysis (see p. 4-71 of NUREG/CR-4550, Vol. 3, Rev. 1, Part 3). Newer plants may have higher seismic capacities, with respect to LOCAs. The seismic hazard curves were unique for Surry. Nevertheless, it was assumed that the seismic contributions to the LOCA frequencies can be neglected, for the purposes of this study.

3.0 **Accident Sequence Delineation and Quantification**

The core damage sequence which is of interest is the following:

LOCA(n)*RECIRC*SUMP-CLOGS*NON-RECOVERY

Here the n indexes the various size LOCAs.

LOCA(1)= Large LOCA=A

LOCA(2)=Medium LOCA=S1

LOCA(3)=Small LOCA=S2

LOCA(4)=RCP Seal LOCA

RECIRC= Event that ECCS recirculation is required

SUMP-CLOGS= Event that the sump screen clogs to the point that ECCS recirculation fails

NON-RECOVERY= Event that recovery actions fails

For other LOCAs (very small LOCAs, stuck-open pressurizer safety valves), the discussion below will show that the contribution of sump screen clogging to the core damage frequency is negligible.

Very-small LOCA

For very small LOCAs, the likelihood of having to go to recirculation is very small. Very small LOCAs are defined on p. 45 of NUREG/CR-5750 as pipe breaks or component failure resulting in a reactor coolant system leak rate between 10 to 100 gpm. These leaks would be controllable by the charging system. There does appear to be a gap in the range of LOCA sizes: a 3/8" diameter pipe may, at system pressure, exceed 100 gpm leak, and yet is too small to be considered a small LOCA. However, the frequency of all LOCAs controllable by the charging system is dominated by LOCAs less than 100 gpm. These are the only very small LOCAs that have occurred. We note that if the charging pumps are unavailable, then it would be necessary to go to sump recirculation. However, the likelihood of this is negligible for the purposes of this study, especially since one charging pump is normally running; for very small LOCAs, the injection path is through the normal charging path, so failures of valves associated with changing the injection path to the emergency injection path are not relevant.

Stuck-open pressurizer safety valve

For stuck-open pressurizer safety valves, the likelihood of having to go to recirculation may not be small, in some plants. However, such LOCAs are considered to be relatively benign from a sump-screen clogging point of view. The discharge from the safety valves is routed to a quench tank, and is released at relatively low pressure from the quench tank rupture valve. Therefore, the opportunity for the stuck-open pressurizer safety valve to generate much debris is minimal. If this were not the case, the stuck-open pressurizer safety valves would have to be treated together with the small break LOCAs.

Large and medium LOCAs

For large LOCAs and medium LOCAs, the chance of not having to go to sump recirculation is very low. Westinghouse emergency response guidelines for post-LOCA cooldown and depressurization (guideline ES-1.2) indicate that this procedure should only be entered for those cases where (within the first twenty-five minutes or so) the low pressure injection (LPI) pumps do not inject because the reactor coolant system pressure exceeds the LPI shutoff head (or in the low probability case that the LPI system is failed). Even if, for some plants, some medium LOCAs as we have defined them (2 to 6 inch breaks) could be handled with the high pressure pumps alone, there would be questions of whether there is sufficient water in the refueling water storage tank to control the LOCA without having to go to sump recirculation. Westinghouse emergency contingency action guidelines (in particular, ECA-1.1) address actions which can be taken in case sump recirculation fails. However, given the timing for large and medium LOCAs, it is unlikely that much credit can be given for these procedures for large and medium LOCAs. It may be that although there is insufficient net positive suction head

(NPSH) for the ECCS pumps drawing suction from the sump when both low pressure ECCS pumps are operating, there is sufficient NPSH for the operation of one pump. This is assumed to be incorporated into the probability of sump clogging, since the overall estimate of sump clogging takes into account both favorable cases where one pump is operating and unfavorable cases where both pumps are operating. Accordingly, for large and medium LOCAs the contribution to the core damage frequency is simply the product of the initiating event frequency and the probability of sump screen clogging, given the initiating event. Thus:

	Contribution to CDF From Sump-Clogging
Large LOCA	(7E-6/yr)*P(sump-clogs|large LOCA)
Medium LOCA	(4E-5/yr)*P(sump-clogs|medium LOCA)

RCP seal LOCAs

Reactor coolant pump seal LOCAs from Westinghouse pumps can be about 480 gpm maximum, for the case where all three seal stages are failed. For other types of RCP seals, the maximum leak rates are probably less. In a Westinghouse pump, the primary leakage path will be along the pump shaft out of the top of the pump. The dominant resistance, for the case of all three seal stages failed, is the labyrinth seal, and the pressure drop across this seal is about 1235 psi, according to p. 36 of NUREG/CR-4294 (T. Boardman et al., "Leak Rate Analysis of the Westinghouse Reactor Coolant Pump", July 1985). Thus the pressure of the fluid exiting the pump is about 1015 psia, initially, when the reactor coolant system is at 2250 psia. The direct line of sight path for the fluid would be towards the flanges coupling the motor and pump shafts. Because the LOCA size is towards the low end of the small break LOCA sizes, the zone of influence will be less than that assumed for the 2-inch small break LOCA used in the LANL parametric report to assess the probability of sump clogging. It is uncertain to what extent there will be sump clogging on an RCP seal LOCA. For the purposes of this study, a base case where the probability of sump clogging on an RCP seal LOCA is taken equal to zero will be used, and a sensitivity study where the probability of sump clogging on an RCP seal LOCA is taken equal to that for a small break LOCA will also be presented. It will be seen that the decision is not affected by this variable.

- Non-Ice-Condenser Plants

Let us now consider RCP seal LOCAs. These correspond to LOCAs in the small break range (perhaps 400 gpm). They are however towards the small end of the range, and it seems very likely that the operator can cool down and depressurize the plant before needing to go to recirculation. Ice condenser plants may be an exception here. For plants other than ice condensers, even if the containment spray comes on initially, it can be shut off later. Assuming an operator error of 5% (partly diagnosis error and partly action error, somewhat similar to the operator error in the Sequoyah NUREG-1150 study (ref: p. D-70 of NUREG/CR-4550, vol. 5, Rev. 1, Part 2), and a probability of failing to recover from loss of sump recirculation of 0.1(estimate from the Comanche Peak IPE, on p. 3-198), one obtains:

	PROBABILITY/ FREQUENCY
I.E. freq, RCP seal LOCA:	2.5E-3/yr
RECIRC	.05
NON-RECOVERY	0.1
SUMP-CLOGS	P(SUMP-CLOGS|RCP seal LOCA)

Thus, for non-ice-condenser plants, one estimates about 1.25E-5/yr*P(sump-clogs) for the contribution of RCP seal LOCA sequences involving sump screen clogging to the core damage frequency.

- Ice-Condenser Plants

For ice condenser plants, the NUREG-1150 study for Sequoyah estimates (see p. D-70, NUREG/CR-4550, vol. 5, rev. 1, part 2) that 40% of RCP seal LOCAs were so large as to result in spray actuation. For such cases, the NUREG-1150 study assumed that it would be necessary to go to recirculation. This may not be the case, with cooldown and depressurization of the primary system. Nevertheless, in the absence of calculations showing the contrary, we will assume this is the case. For the other 60% of the RCP seal LOCAs, we can assume a 5% chance of failing to cooldown and depressurize before it is necessary to go to sump recirculation, as we did above for non-ice-condenser plants. This means that the fraction of RCP seal LOCAs where it is necessary to go to recirculation is 0.40+0.60*(0.05), or 0.43. The Sequoyah IPE estimated that the probability of non-recovery from small break LOCA sequences with failure of sump recirculation was 0.3 (Event HAMU3, given in Table 3.3.3.-4 on p. 3.3.3-29 of the IPE). Then the contribution to the core damage frequency in an ice condenser plant, from RCP seal LOCA sequences involving sump screen clogging is:

	Probability/ Frequency
RCP seal LOCA	2.5E-3/yr
RECIRC	0.43
NON-RECOVERY	0.3
SUMP-CLOGS	P(SUMP-CLOGS|RCP seal LOCA)

One obtains for the contribution to the core damage frequency, for the ice condenser plants, an estimate of 3.2E-4*P(sump-clogs), from the RCP seal LOCA sequences involving the clogging of the sump.

<u>Small-Break LOCA</u>

There are several plant specific considerations here, which affect the likelihood that the plant can be depressurized and cooled down without having to go to recirculation. These include:

-- The size of the RWST

-- The containment pressure at which the containment sprays are actuated
-- Whether or not there are emergency fan coolers

- Plants with Large Dry Containments, Emergency Fan Coolers, and Large RWSTs

At one extreme, there are plants like Callaway and Comanche Peak which have large RWST tanks (420,000 gallons or larger) and emergency fan coolers. These plants can with high probability cooldown and depressurize to RHR conditions for all small break LOCAs. In fact, the background information for Westinghouse emergency response guideline ES-1.2 states that such LOCAs can be handled without going to sump recirculation, for the reference plant, which appears similar to Callaway and Comanche Peak. A probability of failing to go to recirculation of 0.1 seems to be a reasonable estimate; some small fraction of small break LOCAs cannot be mitigated without going to sump recirculation, since the break location is below the midplane of the hot legs, and it would not be possible to use the residual heat removal pumps, drawing suction from the hot legs, as is done in a normal hot shutdown. The human error probability for failing to cooldown and depressurize may also be somewhat larger, for the larger small breaks, than it is for a RCP seal LOCA. A non-recovery probability (following, for example, for Westinghouse plants, the plant specific procedures corresponding to ECA-1.1) of 0.1 is chosen (from the Comanche Peak IPE, p. 3-198). For such plants:

	Probability/ Frequency
Small-Break LOCA	5E-4/yr
RECIRC	0.1
NON-RECOVERY	0.1
SUMP-CLOGS	P(sump-clogs|small LOCA)

One obtains, for these plants, 5E-6/yr*P(sump-clogs) as the contribution to the core damage frequency from small break LOCAs involving clogging of the recirculation sump.

- Ice-Condenser Plants

At the other extreme, one can consider ice-condenser plants. For such plants, the containment spray will actuate on nearly every small break LOCA. The NUREG-1150 study for Sequoyah, and the IPE for Sequoyah, conclude that it will be necessary to go to sump recirculation on small break LOCAs. The IPE for Sequoyah assumes that recovery procedures will have a 30% chance of failure. Accordingly, considering Sequoyah as typical of ice-condenser plants, we have:

	Probability/ Frequency
Small-Break LOCA	5E-4/yr
RECIRC	1.0
NON-RECOVERY	0.3
SUMP-CLOGS	P(sump-clogs|small LOCA)

One obtains, for the ice-condenser plants, 1.5E-4/yr*P(sump-clogs|small LOCA), as the contribution to the core damage frequency from small break LOCAs involving clogging of the recirculation sump.

- Sub-Atmospheric Containments

The analysis performed was for Surry, which was assumed typical of these plants. Surry has containment fan coolers which are normally operating and not isolated until a containment hi-hi pressure is reached. No calculations were performed as to what size small break LOCAs can be mitigated by cooling down and depressurizing and using the RHR before needing to go to sump recirculation. The RHR pumps are inside containment, are not safety-grade, and are not environmentally qualified. Nevertheless, it was judged that for small break LOCAs of one inch in diameter or less the RHR system will very likely operate. It was judged that about 30% of small break LOCAs could be mitigated without going to sump recirculation, and that of the small break LOCAs where it was necessary to go to sump recirculation, the probability of non-recovery was 0.3. A relatively high probability of non-recovery was chosen because, for the larger small break LOCAs where it was necessary to go to sump recirculation, it was not clear what the reliability of the RHR system would be, and recovery without the RHR system appeared more difficult.

Accordingly, for sub-atmospheric containments one obtains:

	Probability/ Frequency
Small-Break LOCA	5E-4/yr
RECIRC	0.7
NON-RECOVERY	0.3
SUMP-CLOGS	P(sump-clogs|small LOCA)

Thus, for sub-atmospheric containments, 1E-4/yr*P(sump-clogs|small LOCA) is the contribution to the core damage frequency from small break LOCAs involving clogging of the recirculation sump.

4.0 Benefits from Averting Accidents Associated with Sump Screen Clogging (per plant basis)

This section will consider the monetized benefits associated with eliminating completely the accidents associated with sump screen clogging. These benefits will be considered here on a per plant basis, and the probability of sump screen clogging for the various size LOCAs will be treated parametrically. The benefits to be considered are:

-- expected averted population dose to 50 miles, monetized at $2000/p-rem (Year 2001 dollars)

-- expected averted offsite financial costs

-- expected averted onsite financial costs (cleanup and decontamination; replacement power)

-- expected averted onsite occupational dose

The benefits of course depend on the years of remaining life of the plant, for which the fix to the sump has been made. The assumption was made that the fix would be in place in three years. The average remaining years for a PWR, without license renewal, would be 14 years in 2004. The years of remaining life was taken as a free parameter, ranging from 14 years to 34 years.

For the population dose, the data given for Zion in Table 5.3 of NUREG/BR-0184 (Regulatory Analysis Technical Evaluation Handbook, January 1997) was used. The data for Zion in this table does not use the actual population density around the Zion site, but rather that for a site which had an 80th percentile population density. The particular values taken from Table 5.3 of NUREG/BR-0184 for Zion were for a LOCA. The calculations done for Table 5.3 of NUREG/BR-0184 were based on NUREG-1150 models. The dominant LOCA in the NUREG-1150 calculation for Zion was that which arose from a loss of component cooling water with consequential reactor coolant pump seal LOCA and loss of high pressure injection. In such a sequence, the reactor cavity is not filled at the time of vessel breach, and the radioactive source term may be larger (because of less scrubbing of the radioactive releases by the reactor cavity water) than if the failure occurred during recirculation, with more water in the reactor cavity. This is a conservative approximation, for our case. We assumed that the probability of early containment failure was 0.02. This value was obtained by estimating the probability of early containment failure as 0.05 for a sequence where vessel breach occurs with the reactor vessel internal pressure high (> 200 psi), and as 0.01 for a sequence where the reactor vessel pressure at vessel breach was low (< 200 psi). A 20% chance of vessel breach at high pressure was assumed. This corresponds to the NUREG-1150 estimate for a small break LOCA. Since there are substantial contributions of large and medium LOCAs to the core damage frequency associated with sump screen clogging, this is again a conservative approximation.

The discount rate used to convert costs in the future to present value was 7%.

For averted offsite financial consequences the Sequoyah NUREG-1150 study was used, with modifications to correct errors in the calculation of offsite financial consequences which were found by Mubayi (see NUREG/CR-4695). The CRIC-ET code (see: Letter report for FIN L1672, "NUREG-1150 Data Base Assessment Program: A Description of the Computational Risk Integration and Conditional Evaluation Tool (CRIC-ET) Software and the NUREG-1150 Data Base, prepared by T.D. Brown, J.D. Johnson, S.L. Humphreys, and J.J. Gregory, Sandia National Laboratories, March 1995) was used, with the offsite financial consequences data modified to correct for the errors in the NUREG-1150 calculation. One reason Sequoyah was used was that it was less time consuming to make the changes to the consequence data for Sequoyah than it would have been for Zion. Also, the Zion site may be atypical, if only one calculation is being performed. Again a 2% chance of early containment failure was assumed, which is conservative because of the contribution of large and medium LOCAs where the probability of early containment failure is less. The sequences chosen were LOCA sequences with failure of containment sprays, which matches our case.

For onsite financial costs, cleanup and decontamination is given on p. 5.42 of NUREG/BR-0184 as $1.5E9 per accident, in 1993 dollars. From http://www.jsc.nasa.gov/bu2/inflateGDP.html the conversion factor to year 2001 dollars is 1.15. The costs were assumed to be spread over 10 years after the accident, and were discounted accordingly, using a 7% discount rate. For replacement power costs, formulae for a generic reactor are given on p. 5.44 of NUREG/BR-0184. These formulae are empirical, and the error in their use has not been determined. The generic reactor is a 910 MWe reactor.

The averted onsite occupational dose was calculated following the guidelines in NUREG/BR-0184. The best estimate immediate dose (per accident) is 3300 person-rem, and the best estimate long-term dose (per accident) is 20000 person-rem. The long-term dose is spread over a 10 year period after the accident.

Tables 1 through 7 on the following pages give the expected averted monetized costs, for various combinations of probabilities of sump screen clogging, for the various size LOCAs, and for the different containment types considered (large dry, subatmospheric, and ice condenser). The probability of sump screen clogging for a RCP seal LOCA was assumed equal to the probability for a small LOCA, in these tables.

The following observations can be made, from the tables.

- For a plant with a large dry containment, medium LOCAs are the most important for a plant which is "very likely" to have clogged screen sumps, for all size LOCAs. For a plant with a large dry containment, the results are not sensitive to the probability of sump screen clogging for a small LOCA, because of the high likelihood of being able to mitigate a small LOCA without going to sump recirculation, in a plant with a large dry containment. Large LOCAs contribute less because of a low initiating event frequency.

- For ice condenser plants, and plants with subatmospheric containments, small LOCAs can be important contributors to core damage sequences involving sump screen clogging, if the probability of sump screen clogging is sufficiently high.

- The expected averted onsite costs (replacement power and cleanup) dominate the benefits; however, expected offsite health costs are appreciable. It is to be remembered that for the purpose of calculating offsite consequences it was assumed that all LOCAs were small LOCAs, which is conservative, since the chances of early containment failure are greater for small LOCAs than for medium or large LOCAs.

- From Table 1, if a plant with a large dry containment is very likely (probability unity) to have sump screen clogging on all size LOCAs, then, if the plant has 24 years of remaining life with the fix in place, the total benefit (i.e., total expected averted costs) from completely fixing the sump is 1.8 million dollars. For an ice condenser, from Table 1, the total expected benefit for a reactor with 24 years of remaining life is about 14 million dollars, if sump screen clogging is very likely for all size LOCAs. The other results are to be interpreted similarly.

Tables 5,6, and 7 can be used to generate the results for other cases not given, since the expected monetized averted costs depend linearly on the probabilities of sump screen clogging for the various size LOCAs. If $C(p_1,p_2,p_3)$ denotes an expected averted cost, and p_1,p_2,p_3 represents the probabilities of sump screen clogging for small, medium, and large LOCAs respectively, then

$$C(p_1,p_2,p_3)=p_1*C(1,0,0)+p_2*C(0,1,0)+p_3*C(0,0,1)$$

The quantities C(0,0,1), C(0,1,0), and C(1,0,0) are given in Tables 5, 6, and 7, respectively. For example, the expected total averted costs (total expected benefit) for a plant with a subatmospheric containment with 34 years of remaining life (including license renewal) with the fix in place, and with a probability of sump screen clogging of 0.3 for a small LOCA, and unity for medium and large LOCAs, is given by

C(0.3,1,1)= (0.3)*(3.91E6)+(1)*(1.39E6)+(1)(2.43E5)=$2.80E6 (year 2001 dollars)

(Note that cases 6 and 7 given in Tables 6 and 7 do not appear to physically realizable, but are useful for determining the results for cases not given, since the expected averted costs depend linearly on the sump screen clogging probabilities.)

It is to be remembered that the large dry case refers to a Westinghouse reactor, like Callaway or Comanche Peak, which has a large dry containment, fan coolers which do not isolate (except possibly on a hi-hi containment pressure signal) and a large RWST of 420,000 gallons or more. It may therefore be a somewhat optimistic case for many reactors with large dry containments. Some plants with large dry containments may be intermediate between plants with large dry containments and plants with sub-atmospheric containments, if small break LOCAs are important.

5.0 Aggregate Benefits from Averting Accidents Associated with Sump Screen Clogging

Here, the aggregate benefits from fixing the sump screen clogging problem will be considered. Table 5-7 of the LANL GSI-191 parametric study gives for each "case ID" (surrogate plant) the likelihood of sump screen clogging for the various size LOCAs. Each ID is associated with either a plant with a large dry containment, a plant with a sub-atmospheric containment, or a plant with an ice condenser containment, as given in Table A-1 of the LANL report. Therefore, using the results given in Section 4 of the present report, it would be possible to determine the benefit from fixing the sump screen clogging problem for each surrogate plant represented by a case ID. The terms "very likely", "likely", "possible", and "unlikely" in this table are to be identified with probabilities of sump screen clogging (to the point of ECCS recirculation failure) of 1, 0.6, 0.4, and 0, as noted in the introduction. (For RCP seal LOCAs, the probability of sump screen clogging is treated by a base case where this probability is set to zero, and a sensitivity study where the probability of sump clogging given an RCP seal LOCA is set equal to the value for a small LOCA.) One can therefore obtain the benefits from fixing the sump screen clogging problem for various sets of plants. The first set of plants to be considered will be the 25 plants which are "very likely" to have the sump screens clogged for all size LOCAs. The second set of plants to be considered are those which are "very likely" to have the sump screen clogged for medium and large LOCAs, irrespective of their likelihood of sump screen clogging for small LOCAs. There are 31 plants in this category, including the 25 plants in the first set. The third set of plants adds to the 31 plant set the plants which are "very likely" to have sump screen clogging for large LOCAs, and are "likely" to have sump screen clogging for medium LOCAs. This adds 6 plants to the 31 plant set, so that the third set contains 37 plants. The results are given in Tables 8 and 9, where the three sets of plants considered above are labeled "25 plant set", "31 plant set", and "37 plant set". The column TotalCost in the tables represents total averted costs--in other words, total benefits. If one considers the t=14 years row as corresponding, in some average sense, to the case of no license renewal, then one sees, from Table 8, that the total benefit for the 25 plant case is 76 million dollars, for the case where P(sump-clogs|RCP seal LOCA)=P(sump-clogs|SLOCA). If one considers the case of all license renewal as corresponding in some average sense to the t=34 years row, then the total benefit for the 25 plant case is 158 million dollars, for the same assumptions concerning sump clogging on RCP seal LOCAs. The other tables are to be interpreted similarly.

Tables 8 and 9 also gives the average core damage frequency reduction (per plant) for each of the cases considered. For the case where the RCP seal LOCA sump clogging probability is the same as for a small LOCA (Table 8), the average core damage frequency exceeds 1E-4 per year. For the case where the RCP seal LOCAs do not contribute (Table 9), the average damage frequency reduction is about 8E-5 per year.

One can obtain, from the cost analysis portion of the analysis, that the cost for fixing N plants is given by:

($6.12E5)*N+$9.221E6 (year 2001 dollars)

For the purposes of the cost-benefit analysis, it was assumed that 85% of the plants would seek license renewal, and that the benefits could here be adequately approximated by taking the weighted average of the benefits for t=14 years, and t=34 years. Fourteen years is the average remaining lifetime for a PWR with the fix in place (in about 3 years from now). With a 20 year license renewal period, the average remaining lifetime would be 34 years. Then the total monetized benefits and costs are given in the table below:

Case	Benefit		Costs
	Table 8 values	Table 9 values	
25 plant case	$110E6	$71E6	$25E6
31 plant case	$140E6	$86E6	$28E6
37 plant case	$150E6	$92E6	$32E6

Here, the Table 9 values refer to the case where the probability of sump clogging on an RCP seal LOCA is taken as zero, while the Table 8 values refer to the case where the probability of sump clogging on an RCP seal LOCA is taken as equal to the value on a small LOCA. The Table 9 values are probably more realistic. The dollars used are 2001 dollars, and all costs and benefits are discounted to year 2001 using a 7% per year discount rate. One sees that every case is cost-beneficial.

It may be of interest to see how the benefits compare to the costs if onsite costs are omitted. One sees from Table 8 that if the probability of sump clogging on an RCP seal LOCA is the same as for a small break LOCA, and if 100% license renewal is assumed (the t=34 years line in the tables), then the offsite benefits for the 25 plant case ($23E6 averted offsite health costs and $3E6 averted offsite property costs, or $26E6) just about equal the costs of $25E6. For all other cases the costs exceed the benefits. Since 85% license renewal is assumed, the costs exceed the benefits when onsite costs are omitted, for all cases.

6.0 Uncertainties

The frequencies of the LOCAs are uncertain, because of sparse data. The uncertainty distributions for large and medium LOCAs were judged to be lognormal with an error factor of 10, in NUREG/CR-5750. The lognormal uncertainty distribution with the error factor of 10 was not developed by a statistical process, but was based on engineering judgement. Small pipe break LOCAs were treated by updating the WASH-1400 lognormal distribution by zero failures in 2102 reactor years. In this report, it will be assumed that, after taking into account the Summer event of 10/12/2000, the uncertainty distribution will still be lognormal with an error factor of 10. The table below gives the uncertainty in the initiating event frequencies, after inclusion of the Summer event for the large LOCA.

Initiating Event	Percentile Values		Mean Value
	5th	95th	
LLOCA	3E-7/yr	3E-5/yr	7E-6/yr
MLOCA	1E-6	1E-4	4E-5
SLOCA	1E-4	1E-3	5E-4
RCP SEAL LOCA	5.6E-4	5.4E-3	2.5E-3

These frequencies are per critical year; thus they are a little conservative with respect to frequencies per calendar year.

In addition, seismically-induced LOCAs were neglected based on the mean estimate of the frequency of seismically-induced LOCAs, for Surry. The inclusion of seismically-induced LOCAs would increase the benefits and would not change the decision.

The probability of sump screen clogging is also uncertain. The failure criteria used are uncertain, as is discussed in the LANL GSI-191 parametric report, in section 5.2. There are uncertainties arising from lack of plant specific information. Note that the probability of sump screen clogging does not represent a frequency of sump screen clogging in a large number of trials. It incorporates subjective uncertainty. This means that if one were interested in a "probability of frequency" description of uncertainty [as defined by Kaplan and Garrick, Risk Analysis **1**, p. 11 (1981)] one would first have to do this for the probability of sump screen clogging, obtaining a probability distribution for the frequency of sump screen clogging.

Human error probabilities enter into the assessment of recovery, given that it was necessary to go to sump recirculation and sump recirculation failed. The estimates used here came from two IPEs, which did not take into account the specific cause of loss of sump recirculation. Also, the assessment by LANL of the likelihood of loss of sump recirculation took into account the fact that the operator may shut off one pump if there is loss of net positive suction head, but it is unclear what likelihood was assigned to this operator action. The Westinghouse emergency response guidelines ECA-1.1 on loss of sump recirculation state that the operator should shut off any pump which has lost its suction source, so it is very likely that the operator would shut off an operating pump which has lost net positive suction head, at least if the plant specific procedures for the plant correspond to the Westinghouse guidelines.

The assumption was made that the likelihood of having to go to sump recirculation for a plant with a large dry containment was the same as the likelihood for a Westinghouse plant like Callaway or Comanche Peak, which have emergency fan coolers and large RWSTs. This may be optimistic for some plants with large dry containments.

The probability of having to go to sump recirculation in subatmospheric containments, given a small break LOCA, may have been overestimated. The frequency of small break LOCAs is not uniformly distributed across all break sizes; instead the smaller size piping is more likely to rupture. Section J-5.1.1 of NUREG/CR-5750 notes that ruptures that have occurred in primary system piping have all been in piping less than one inch in diameter. Thus the probability, given a small break LOCA in a subatmospheric containment, that one can reach RHR conditions, and that the RHR system will be operable may be greater than 30%. In other words, the probability of needing to go to sump recirculation may be less than 70% for a small break LOCA in a subatmospheric containment. However, at least at Surry, the RHR system is inside containment, and is not safety-grade or environmentally qualified. The operator procedures for post LOCA cooldown and depressurization at Surry leave the use of the RHR as an option; there is a step in the procedures where the operators are to consult with the technical support center to see if they should put the RHR into service. Because the RHR is not safety-grade, the operators may choose to use a safety-grade method of mitigating a small break LOCA.

A limited propagation of uncertainties was performed. For plants with large dry containments, and a probability of unity for sump clogging on all size LOCAs, the uncertainties in the averted CDF (the change in CDF) was propagated with the code SAPHIRE, using the Boolean expression for the change in CDF,

$$\sum \text{LOCA(N)*RECIRC*SUMP*NON-RECOV.}$$

In these uncertainty calculations, the uncertainty distributions for all the initiating event frequencies were assumed to be lognormal, with the 5th and 95th percentile bounds as given in the table above. The uncertainty distribution for RECIRC was taken as lognormal with an error factor of 3, and a mean value of 0.1. The uncertainty distribution for NON-RECOV was chosen as lognormal with an error factor of 4, and a median value of 0.1; this may be more realistic for an average over all large dry plants than choosing the mean value as 0.1. Two cases were run, corresponding to the cases where the probabilities of sump clogging on an RCP seal LOCA were 1 and 0. The results for the mean value of the averted CDF and the percentile values for the uncertainty distribution are given in the table below:

Case	Averted CDF Mean (1/yr)	Averted CDF Uncertainty distribution		
		5th percentile (1/yr)	median (1/yr)	95th percentile (1/yr)
P(sump|RCP LOCA)=0	5.4E-5	6.5E-6	2.9E-5	1.7E-4
P(sump|RCP LOCA)=1	6.6E-5	1.2E-5	4.1E-5	1.9E-4

These are the results for a single plant with a large dry containment. Some of the variation is plant to plant variation, and so the percentage uncertainty in the aggregate results are less than for a single plant. If the 17 large dry plants in the "25 plant case" had their averted CDFs drawn randomly and independently from the same distribution, then the distribution for the sum of the averted CDFs would, by the central limit theorem, approach a normal distribution. The median value of the average averted CDF would be close to the mean value given above, about 5.4E-5 per year for the case where the probability of sump clogging on an RCP seal LOCA is zero, instead of the median value of 2.9E-5 per year for an individual plant. This suggests that consideration of uncertainties will not affect the fact that, given the data on the probability of sump clogging from the LANL parametric report, the fixes of the sump clogging problem are cost effective.

The probability of early containment failure given core damage was based on the assumption that the LOCA was a small break LOCA. This is a conservative bias, since medium and large LOCAs are treated the same as small LOCAs, for the purpose of assessing the chance of early containment failure. Nevertheless, the chance of early containment failure was small (see Section 4), and this may not be significant. Note also that the benefits are dominated by the averted onsite costs (replacement power and accident cleanup costs), and are insensitive to an overestimate of the probability of early containment failure.

Table 1. BENEFIT FROM FIXING SUMP SCREEN-- Case 1

Sump screen clogging probability for RCP SEAL LOCA= 1
Sump screen clogging probability for S2 LOCA= 1
Sump screen clogging probability for S1 LOCA= 1
Sump screen clogging probability for A LOCA= 1

Plant type is Large Dry
Core Damage Freq= 6.45E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.27E+05	3.25E+04	8.03E+05	1.65E+04	1.08E+06
19	2.67E+05	3.83E+04	1.11E+06	1.94E+04	1.44E+06
24	2.96E+05	4.24E+04	1.40E+06	2.15E+04	1.76E+06
29	3.16E+05	4.52E+04	1.64E+06	2.29E+04	2.03E+06
34	3.30E+05	4.72E+04	1.84E+06	2.40E+04	2.24E+06

Plant type is Sub-Atmospheric
Core Damage Freq= 1.59E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	5.62E+05	8.04E+04	1.99E+06	4.08E+04	2.67E+06
19	6.61E+05	9.47E+04	2.75E+06	4.80E+04	3.56E+06
24	7.32E+05	1.05E+05	3.46E+06	5.31E+04	4.35E+06
29	7.81E+05	1.12E+05	4.06E+06	5.67E+04	5.01E+06
34	8.16E+05	1.17E+05	4.55E+06	5.93E+04	5.54E+06

Plant type is Ice-Condenser
Core Damage Freq= 5.17E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.82E+06	2.61E+05	6.44E+06	1.32E+05	8.65E+06
19	2.14E+06	3.07E+05	8.92E+06	1.56E+05	1.15E+07
24	2.37E+06	3.40E+05	1.12E+07	1.72E+05	1.41E+07
29	2.53E+06	3.62E+05	1.32E+07	1.84E+05	1.62E+07
34	2.64E+06	3.79E+05	1.47E+07	1.92E+05	1.80E+07

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 2. BENEFIT FROM FIXING SUMP SCREEN-- Case 2

Sump screen clogging probability for RCP SEAL LOCA= .6
Sump screen clogging probability for S2 LOCA= .6
Sump screen clogging probability for S1 LOCA= 1
Sump screen clogging probability for A LOCA= 1

Plant type is Large Dry
Core Damage Freq= 5.75E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.02E+05	2.90E+04	7.16E+05	1.47E+04	9.62E+05
19	2.38E+05	3.41E+04	9.92E+05	1.73E+04	1.28E+06
24	2.64E+05	3.78E+04	1.25E+06	1.92E+04	1.57E+06
29	2.82E+05	4.03E+04	1.46E+06	2.05E+04	1.81E+06
34	2.94E+05	4.21E+04	1.64E+06	2.14E+04	2.00E+06

Plant type is Sub-Atmospheric
Core Damage Freq= 1.14E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	4.03E+05	5.77E+04	1.43E+06	2.93E+04	1.92E+06
19	4.75E+05	6.80E+04	1.97E+06	3.45E+04	2.55E+06
24	5.25E+05	7.52E+04	2.48E+06	3.82E+04	3.12E+06
29	5.61E+05	8.03E+04	2.92E+06	4.07E+04	3.60E+06
34	5.86E+05	8.39E+04	3.27E+06	4.26E+04	3.98E+06

Plant type is Ice-Condenser
Core Damage Freq= 3.29E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.16E+06	1.66E+05	4.10E+06	8.42E+04	5.50E+06
19	1.36E+06	1.95E+05	5.67E+06	9.91E+04	7.33E+06
24	1.51E+06	2.16E+05	7.14E+06	1.10E+05	8.97E+06
29	1.61E+06	2.31E+05	8.38E+06	1.17E+05	1.03E+07
34	1.68E+06	2.41E+05	9.38E+06	1.22E+05	1.14E+07

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 3. BENEFIT FROM FIXING SUMP SCREEN-- Case 3

Sump screen clogging probability for RCP SEAL LOCA= .3
Sump screen clogging probability for S2 LOCA= .3
Sump screen clogging probability for S1 LOCA= .6
Sump screen clogging probability for A LOCA= 1

Plant type is Large Dry
Core Damage Freq= 3.62E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.28E+05	1.83E+04	4.51E+05	9.27E+03	6.07E+05
19	1.50E+05	2.15E+04	6.25E+05	1.09E+04	8.08E+05
24	1.66E+05	2.38E+04	7.86E+05	1.21E+04	9.88E+05
29	1.78E+05	2.54E+04	9.24E+05	1.29E+04	1.14E+06
34	1.85E+05	2.65E+04	1.03E+06	1.35E+04	1.26E+06

Plant type is Sub-Atmospheric
Core Damage Freq= 6.47E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.28E+05	3.26E+04	8.06E+05	1.66E+04	1.08E+06
19	2.68E+05	3.84E+04	1.12E+06	1.95E+04	1.44E+06
24	2.97E+05	4.25E+04	1.40E+06	2.16E+04	1.77E+06
29	3.17E+05	4.54E+04	1.65E+06	2.30E+04	2.04E+06
34	3.31E+05	4.74E+04	1.85E+06	2.41E+04	2.25E+06

Plant type is Ice-Condenser
Core Damage Freq= 1.72E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	6.06E+05	8.67E+04	2.14E+06	4.40E+04	2.88E+06
19	7.13E+05	1.02E+05	2.97E+06	5.18E+04	3.83E+06
24	7.89E+05	1.13E+05	3.73E+06	5.73E+04	4.69E+06
29	8.42E+05	1.21E+05	4.38E+06	6.12E+04	5.41E+06
34	8.80E+05	1.26E+05	4.90E+06	6.39E+04	5.97E+06

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 4. BENEFIT FROM FIXING SUMP SCREEN-- Case 4

Sump screen clogging probability for RCP SEAL LOCA= 0
Sump screen clogging probability for S2 LOCA= 0
Sump screen clogging probability for S1 LOCA= 1
Sump screen clogging probability for A LOCA= 1

Plant type is Large Dry
Core Damage Freq= 4.70E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.66E+05	2.37E+04	5.85E+05	1.20E+04	7.86E+05
19	1.95E+05	2.79E+04	8.11E+05	1.42E+04	1.05E+06
24	2.16E+05	3.09E+04	1.02E+06	1.57E+04	1.28E+06
29	2.30E+05	3.30E+04	1.20E+06	1.67E+04	1.48E+06
34	2.40E+05	3.44E+04	1.34E+06	1.75E+04	1.63E+06

Plant type is Sub-Atmospheric
Core Damage Freq= 4.70E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.66E+05	2.37E+04	5.85E+05	1.20E+04	7.86E+05
19	1.95E+05	2.79E+04	8.11E+05	1.42E+04	1.05E+06
24	2.16E+05	3.09E+04	1.02E+06	1.57E+04	1.28E+06
29	2.30E+05	3.30E+04	1.20E+06	1.67E+04	1.48E+06
34	2.40E+05	3.44E+04	1.34E+06	1.75E+04	1.63E+06

Plant type is Ice-Condenser
Core Damage Freq= 4.70E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.66E+05	2.37E+04	5.85E+05	1.20E+04	7.86E+05
19	1.95E+05	2.79E+04	8.11E+05	1.42E+04	1.05E+06
24	2.16E+05	3.09E+04	1.02E+06	1.57E+04	1.28E+06
29	2.30E+05	3.30E+04	1.20E+06	1.67E+04	1.48E+06
34	2.40E+05	3.44E+04	1.34E+06	1.75E+04	1.63E+06

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 5. BENEFIT FROM FIXING SUMP SCREEN-- Case 5

Sump screen clogging probability for RCP SEAL LOCA= 0
Sump screen clogging probability for S2 LOCA= 0
Sump screen clogging probability for S1 LOCA= 0
Sump screen clogging probability for A LOCA= 1

Plant type is Large Dry
Core Damage Freq= 7.00E-06 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.46E+04	3.53E+03	8.72E+04	1.79E+03	1.17E+05
19	2.90E+04	4.16E+03	1.21E+05	2.11E+03	1.56E+05
24	3.21E+04	4.60E+03	1.52E+05	2.33E+03	1.91E+05
29	3.43E+04	4.91E+03	1.78E+05	2.49E+03	2.20E+05
34	3.58E+04	5.13E+03	2.00E+05	2.60E+03	2.43E+05

Plant type is Sub-Atmospheric
Core Damage Freq= 7.00E-06 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.46E+04	3.53E+03	8.72E+04	1.79E+03	1.17E+05
19	2.90E+04	4.16E+03	1.21E+05	2.11E+03	1.56E+05
24	3.21E+04	4.60E+03	1.52E+05	2.33E+03	1.91E+05
29	3.43E+04	4.91E+03	1.78E+05	2.49E+03	2.20E+05
34	3.58E+04	5.13E+03	2.00E+05	2.60E+03	2.43E+05

Plant type is Ice-Condenser
Core Damage Freq= 7.00E-06 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	2.46E+04	3.53E+03	8.72E+04	1.79E+03	1.17E+05
19	2.90E+04	4.16E+03	1.21E+05	2.11E+03	1.56E+05
24	3.21E+04	4.60E+03	1.52E+05	2.33E+03	1.91E+05
29	3.43E+04	4.91E+03	1.78E+05	2.49E+03	2.20E+05
34	3.58E+04	5.13E+03	2.00E+05	2.60E+03	2.43E+05

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 6. BENEFIT FROM FIXING SUMP SCREEN-- Case 6

Sump screen clogging probability for RCP SEAL LOCA= 0
Sump screen clogging probability for S2 LOCA= 0
Sump screen clogging probability for S1 LOCA= 1
Sump screen clogging probability for A LOCA= 0

Plant type is Large Dry
Core Damage Freq= 4.00E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.41E+05	2.02E+04	4.98E+05	1.02E+04	6.69E+05
19	1.66E+05	2.37E+04	6.90E+05	1.20E+04	8.92E+05
24	1.83E+05	2.63E+04	8.68E+05	1.33E+04	1.09E+06
29	1.96E+05	2.80E+04	1.02E+06	1.42E+04	1.26E+06
34	2.05E+05	2.93E+04	1.14E+06	1.49E+04	1.39E+06

Plant type is Sub-Atmospheric
Core Damage Freq= 4.00E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.41E+05	2.02E+04	4.98E+05	1.02E+04	6.69E+05
19	1.66E+05	2.37E+04	6.90E+05	1.20E+04	8.92E+05
24	1.83E+05	2.63E+04	8.68E+05	1.33E+04	1.09E+06
29	1.96E+05	2.80E+04	1.02E+06	1.42E+04	1.26E+06
34	2.05E+05	2.93E+04	1.14E+06	1.49E+04	1.39E+06

Plant type is Ice-Condenser
Core Damage Freq= 4.00E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.41E+05	2.02E+04	4.98E+05	1.02E+04	6.69E+05
19	1.66E+05	2.37E+04	6.90E+05	1.20E+04	8.92E+05
24	1.83E+05	2.63E+04	8.68E+05	1.33E+04	1.09E+06
29	1.96E+05	2.80E+04	1.02E+06	1.42E+04	1.26E+06
34	2.05E+05	2.93E+04	1.14E+06	1.49E+04	1.39E+06

Key:

t= Number of years of reactor operation with the fix in place
OffHealth = Expected Averted Monetized Offsite Health Costs
OffProp = Expected Averted Offsite Property Costs
OnProp = Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose= Expected Averted Onsite Occupational Dose Costs
TotalCost= Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 7. BENEFIT FROM FIXING SUMP SCREEN-- Case 7

Sump screen clogging probability for RCP SEAL LOCA= 1
Sump screen clogging probability for S2 LOCA= 1
Sump screen clogging probability for S1 LOCA= 0
Sump screen clogging probability for A LOCA= 0

Plant type is Large Dry
Core Damage Freq= 1.75E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	6.16E+04	8.82E+03	2.18E+05	4.48E+03	2.93E+05
19	7.26E+04	1.04E+04	3.02E+05	5.27E+03	3.90E+05
24	8.03E+04	1.15E+04	3.80E+05	5.83E+03	4.77E+05
29	8.57E+04	1.23E+04	4.46E+05	6.23E+03	5.50E+05
34	8.95E+04	1.28E+04	4.99E+05	6.50E+03	6.08E+05

Plant type is Sub-Atmospheric
Core Damage Freq= 1.12E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	3.96E+05	5.67E+04	1.40E+06	2.88E+04	1.88E+06
19	4.66E+05	6.68E+04	1.94E+06	3.39E+04	2.51E+06
24	5.16E+05	7.39E+04	2.44E+06	3.75E+04	3.07E+06
29	5.51E+05	7.89E+04	2.87E+06	4.00E+04	3.54E+06
34	5.75E+05	8.24E+04	3.21E+06	4.18E+04	3.91E+06

Plant type is Ice-Condenser
Core Damage Freq= 4.70E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.66E+06	2.37E+05	5.85E+06	1.20E+05	7.86E+06
19	1.95E+06	2.79E+05	8.11E+06	1.42E+05	1.05E+07
24	2.16E+06	3.09E+05	1.02E+07	1.57E+05	1.28E+07
29	2.30E+06	3.30E+05	1.20E+07	1.67E+05	1.48E+07
34	2.40E+06	3.44E+05	1.34E+07	1.75E+05	1.63E+07

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

TABLE 8. AGGREGATE BENEFITS FROM FIXING THE SUMP SCREEN CLOGGING PROBLEM: Probability of sump screen clogging on an RCP seal LOCA assumed equal to probability for a small LOCA (sensitivity study)

25 plant case

Average CDF reduction = 1.4E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.60E+07	2.29E+06	2.29E+06	1.16E+06	7.60E+07
19	1.88E+07	2.70E+06	2.70E+06	1.37E+06	1.01E+08
24	2.08E+07	2.98E+06	2.98E+06	1.51E+06	1.24E+08
29	2.22E+07	3.19E+06	3.19E+06	1.62E+06	1.43E+08
34	2.32E+07	3.33E+06	3.33E+06	1.69E+06	1.58E+08

31 plant case

Average CDF reduction = 1.4E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.52E+07	2.18E+06	2.18E+06	1.11E+06	7.24E+07
19	1.80E+07	2.57E+06	2.57E+06	1.30E+06	9.65E+07
24	1.99E+07	2.84E+06	2.84E+06	1.44E+06	1.18E+08
29	2.12E+07	3.04E+06	3.04E+06	1.54E+06	1.36E+08
34	2.21E+07	3.17E+06	3.17E+06	1.61E+06	1.50E+08

37 plant case

Average CDF reduction = 1.2E-04 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.60E+07	2.29E+06	2.29E+06	1.16E+06	7.60E+07
19	1.88E+07	2.70E+06	2.70E+06	1.37E+06	1.01E+08
24	2.08E+07	2.98E+06	2.98E+06	1.51E+06	1.24E+08
29	2.22E+07	3.19E+06	3.19E+06	1.62E+06	1.43E+08
34	2.32E+07	3.33E+06	3.33E+06	1.69E+06	1.58E+08

Key:

t=	Number of years of reactor operation with the fix in place
OffHealth =	Expected Averted Monetized Offsite Health Costs
OffProp =	Expected Averted Offsite Property Costs
OnProp =	Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose=	Expected Averted Onsite Occupational Dose Costs
TotalCost=	Expected Total Averted Costs

(All costs are in 2001 dollars, and are discounted to year 2001.)

Table 9. AGGREGATE BENEFITS FROM FIXING THE SUMP SCREEN CLOGGING PROBLEM: P(sump-clogs|RCP seal LOCA)=0; BASE CASE

23 plant case:

Average CDF reduction = 8.84E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	7.78E+06	1.11E+06	1.11E+06	5.65E+05	3.70E+07
19	9.16E+06	1.31E+06	1.31E+06	6.66E+05	4.93E+07
24	1.01E+07	1.45E+06	1.45E+06	7.36E+05	6.03E+07
29	1.08E+07	1.55E+06	1.55E+06	7.86E+05	6.95E+07
34	1.13E+07	1.62E+06	1.62E+06	8.21E+05	7.68E+07

31 plant case:

Average CDF reduction = 8.65E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	9.45E+06	1.35E+06	1.35E+06	6.86E+05	4.49E+07
19	1.11E+07	1.59E+06	1.59E+06	8.08E+05	5.98E+07
24	1.23E+07	1.76E+06	1.76E+06	8.94E+05	7.32E+07
29	1.31E+07	1.88E+06	1.88E+06	9.54E+05	8.43E+07
34	1.37E+07	1.97E+06	1.97E+06	9.97E+05	9.32E+07

37 plant case:

Average CDF reduction = 7.78E-05 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
14	1.01E+07	1.45E+06	1.45E+06	7.36E+05	4.81E+07
19	1.19E+07	1.71E+06	1.71E+06	8.67E+05	6.41E+07
24	1.32E+07	1.89E+06	1.89E+06	9.59E+05	7.85E+07
29	1.41E+07	2.02E+06	2.02E+06	1.02E+06	9.04E+07
34	1.47E+07	2.11E+06	2.11E+06	1.07E+06	9.99E+07

Key:

t= Number of years of reactor operation with the fix in place
OffHealth = Expected Averted Monetized Offsite Health Costs
OffProp = Expected Averted Offsite Property Costs
OnProp = Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose= Expected Averted Onsite Occupational Dose Costs
TotalCost= Expected Total Averted Costs
(All costs are in 2001 dollars, and are discounted to year 2001.)

COST ANALYSIS FOR GSI-191, "ASSESSMENT OF DEBRIS ACCUMULATION ON PWR SUMP PERFORMANCE" (Rev. 1)

Sidney Feld

1.0 Assumptions and Bases

The staff's best estimate is that 31 of the 69 pressurized water reactors (PWRs) currently in operation could potentially benefit from corrective action to control sump debris. For sensitivity analysis purposes, the staff adopts high and low estimates of the number of PWRs requiring a sump modification of 37 and 25 PWRs, respectively. These estimates are based on Los Alamos National Laboratory's (LANL) work on GSI-191, Sump Debris, and are consistent with the assumptions employed in the preceding benefit analysis.

Consistent with LANL's findings, the corrective action to control sump debris for all affected reactors is assumed to be a physical modification that increases the screen area.

All costs are expressed in year 2001 constant dollars, and all costs incurred in the future are present valued to 2001 based on a 7 percent per annum real discount rate. Discounting all costs to year 2001 adjusts for the fact that costs incurred at different points in time are not equivalent.

All costs are categorized as either: (1) Up-front analytical activities; (2) physical modification activities; and (3) other cost elements. For the purposes of this cost analysis, the up-front analytical costs are assumed to occur in mid-year 2003, whereas the physical modification and other cost elements are expected to be borne in mid-year 2004.

NRC and utility wage rates are both estimated at $80.00 per hour in 2001 constant dollars. This represents a composite labor rate for engineering/technical staff with an allowance for management and clerical support. These wage rates represent the incremental cost to the NRC and the licensee and as such, only include wages and associated fringe benefits.

Contractor support to the NRC and licensee is costed at $140.00 per hour in 2001 constant dollars. This higher value reflects the fact that in addition to the direct cost of labor, contractors will also recover all overhead, general and administrative expenses, and profit or fees from the NRC and licensees. In effect, the contractor's total cost structure is incremental to the client.

Following is a discussion of the major NRC and industry costs likely to be associated with a requirement to increase the screen area at select PWRs.

2.0 Up-Front Analytical Activities:

If the NRC determined that resolution of GSI-191 would require further evaluation by licensees and possible modifications at select PWRs, it is assumed the following up-front analytical activities would be performed:

Revise Regulatory Guide and Issue Generic Communication

It is expected that NRC would revise Regulatory Guide (RG) 1.82, "Water Sources for Long-Term Recirculation Cooling Following a Loss of Coolant Accident." The revision would provide non-prescriptive performance criteria that PWRs must meet in order to control sump debris. Development of this RG would likely entail public meetings, preparation of a draft RG, a public comment period, and issuance of a final RG. For the purposes of this cost analysis, it is assumed that this would be followed by the development of a generic communication that would advise the affected licensees of their responsibilities pursuant to this issue. Activities of this nature were performed by the NRC to support resolution of the Boiling Water Reactor (BWR) Strainer Blockage issue. Based on this BWR experience and discussion with NRC staff that would be responsible for this new effort, it is estimated that the revision and issuance of the RG and generic communication would involve about 1.5 person-months of contractor effort and about 10 person-months of effort on the part of the NRC. This results in a total cost of about $170k.

Develop Uniform Guidelines

It is expected that industry would prepare utility resolution guidance that lays out uniform guidelines on how licensees' are to interpret revised RG 1.82. This industry document would tend to prescribe in considerable detail precisely how licensees are to respond to NRC's guidance. Assuming a similar industry effort as for the BWR Strainer Blockage study conducted by industry (Boiling Water Reactor Owners Group (BWROG) and General Electric (GE)), it is estimated that the cost to industry to develop this document would be on the order of $900K, based on a level of effort of about 5.5 person-years. In addition, the NRC would be expected to participate during development and in the review of the industry guidelines. Based on NRC's involvement for BWRs, the staff estimates NRC's costs at about $250k which represents about 4 person-months of NRC staff time and about $200K in contractor support.

Reactor-Specific Engineering Analysis

An up-front engineering analysis would be required at each PWR to assess whether a reactor has a sump debris problem that requires remedy. Reactor-specific analyses of this nature have already been conducted by Pacific Gas & Electric (PG&E) for one of their nuclear power plants. PG&E estimates that such an analysis for a two unit plant required an in-house effort of about 6 person-months. This results in a cost estimate of about $40k per reactor. Alternatively, a commercial vendor has estimated that the cost of such an engineering analysis would be about $225K per reactor. Part of this cost differential can be explained by the contractor's higher labor charge because their rates recover fixed costs. In addition, PG&E's per reactor cost reflects certain economies in performing similar analyses for two reactors whereas the contractor's estimate likely assumes a single unit plant.

Recognizing that contractor support and single unit plants are likely to be involved in a number of these analyses, the staff adopted an average value that gives equal weight to the PG&E and vendor estimates. This results in an average industry cost of about $130K per reactor, and the corresponding industry cost for the total PWR population of 69 reactors is estimated at about

$9,000k. (Note, that although only a subset of the PWRs are assumed to require a fix, the industry-wide cost recognizes that all 69 PWRs would require an up-front engineering analysis in order to assess whether a fix is needed or not.

In summary, if the NRC determined that the resolution of GSI-191 would require further evaluation by licensees, the up-front analytical costs in the aggregate are estimated at $420k for the NRC and $9,900k for industry. On a 2001 present value basis, the NRC and industry costs are about $370k and $8,650k, respectively.

3.0 Physical Modification - Increase Screen Area

As indicated above, for the staff's base case, it is assumed that approximately 31 PWRs may require modifications to increase the screen area. Modifications of this nature have been performed at one nuclear power plant, and according to the licensee (PG&E), its cost was on the order of $600k for unit 1, and $320k for unit 2. The lower cost for the second unit is largely attributable to learning curve efficiencies.

These estimates comprise five broad categories of cost. The first is engineering and drafting which covers costs for such activities as drawings, loadings, design packages and technical specifications. The second is engineering effort and expenses incurred in developing a mock-up and utilizing the mock-up to model and test the design against simulated levels of debris. The third category is implementation and largely includes labor and material costs for demolition and installation. The fourth is the disposal of radioactive waste, and the fifth category is for miscellaneous expenses which are largely administrative in nature.

The staff also obtained a vendor's estimate on the order of $1 million per PWR for a reactor-specific design and installation. This estimate also includes allowances for materials, manufacturing, and inspections/quality control, and assumes a safety grade system.

The staff views the PG&E and vendor estimates as providing a reasonable range of installation costs. The PG&E estimates are reasonable given that the entire installation effort, including manufacture of the redesigned screen, was performed in-house by PG&E staff, and there were no major constraints adversely affecting design and installation activities. Alternatively, the higher vendor estimate is viewed as a reasonable value because other licensees may require outside contractors and manufacturers for this work and this could have a significant impact on these costs. In addition the staff anticipates that space constraints which were not a factor at the PG&E plant could be an issue at other PWRs and could inflate costs significantly.

Based on these findings, for the purposes of this cost analysis, the staff assumes the average cost for a reactor-specific modification at $750k per reactor. This estimate is an average of the PG&E and vendor estimates assuming equal weight for each. Given that the best estimate of the number of reactors requiring such a fix is 31, the industry-wide cost is estimated at about $23,200k. On a 2001 present value basis, the per reactor and industry-wide costs are $612k and $19,000k, respectively. Under the high and low scenarios of 37 and 25 PWR's, the industry-wide cost on a 2001 present worth basis is $22,600k and $15,300k, respectively.

Furthermore, since the work is being performed in a radioactive environment and requires the reactor to be in a shutdown mode, the staff also considered additional cost elements during implementation to account for occupational exposure and replacement energy costs. Occupational exposure averaged 2 person-rem per reactor for the modifications performed by PG&E. Based on NRC's $2000/person-rem valuation, this would result in a cost of $4K per reactor which is viewed as negligible. In addition, based on PG&E's experience, the staff concludes that no replacement energy cost penalties should be ascribed to this modification. The PG&E modifications required no incremental downtime as the work was completed within a relatively short duration and was easily accommodated within a normal outage period.

4.0 Other Cost Elements

Based on the BWR experience, it is anticipated that the licensees' reactor-specific engineering analyses and the actual modifications would be subject to NRC audits and inspections. For BWRs, audit reports and site visits were performed for a sample of 4 sites involving a total of 6 reactors. Assuming the same number of site visits and audit reports are conducted for PWRs, and costs comparable with the BWR experience, the total NRC cost for this activity is estimated at about $200k. This estimate assumes about $125k in contractor support and about $75k in NRC staff costs. On a 2001 present worth basis, this cost is about $160k.

The staff also considered whether there were likely to be any recurring costs associated with a redesigned sump screen. This could include such activities as periodic maintenance on the part of the licensee and periodic inspections by the NRC. However, given that the sump screen is a passive system, the need for these activities is unlikely and no recurring costs are assumed in the staff's estimates.

5.0 Total Costs

The staff's best estimates of NRC and industry-wide 2001 present value costs are $0.53M and $27.65M, respectively. In the aggregate, the total present worth cost is estimated at approximately $28.2M. Distributing this cost among the 31 reactors that are assumed to require a modification, results in a per reactor cost of $0.9M.

For sensitivity analysis purposes, the staff assumed that the number of reactors requiring a physical modification could range between 25 and 37. At the low end this translates into a total present worth cost of about $24.5M. At the high end, the total present worth cost is estimated at about $31.8M.

NUCLEAR ENERGY INSTITUTE

Alexander Marion
DIRECTOR ENGINEERING
NUCLEAR GENERATION DIVISION

August 31, 2001

Mr. Michael E. Mayfield
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Office of Nuclear Regulatory Research
Mail Stop T10-D20
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Washington, DC 20555

SUBJECT: Comments on NRC Contractor Draft Report, LA-UR-XXX, *GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance*

PROJECT NUMBER: 689

This letter provides NEI's comments on the NRC contractor draft report, LA-UR-XXX, *GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance.* These comments were developed with input from the NEI PWR SUMP Performance Task Force and are offered in response to the NRC staff's invitation to comment on the draft report. We understand that this report will be used as an input to the NRC staff's disposition of generic safety issue GSI-191, *Assessment of Debris Accumulation on PWR Sump Performance.*

As a general comment, the draft report lacks sufficient information to permit independent evaluation of the work performed. Our review concludes that:

- The report provides graphical summaries of the results obtained from the application of the evaluation methodology, however it does not identify details of this methodology.
- Assumptions are stated, but bases for those assumptions are not provided (why they are applicable and/or appropriate).
- Governing equations (mathematical models) are not given.
- Inputs to calculations are described only in general terms; detailed listing of specific inputs is not given. Alternate sources of information are described, but the input values are not identified.
- Applicability limits are discussed only in general terms. Typically, the discussion is provided in terms of information not available to NRC and its contractor and the approach taken by NRC to address the lack of information.
- Open items, such as unverified assumptions, assumptions made due to lack of plant design or operating information, etc., were not clearly identified. Consequently, we have

been unable to assess the impact of these open items and resulting conclusions.

In summary, without greater detail, the specific conclusions drawn in the report are difficult to corroborate. However, we recognize that additional detail was provided during the discussion at the July 26 and 27, 2001 public meeting. This detail should be incorporated into the final report. Furthermore, we anticipate that the NRC will be providing further documentation of its research in several NUREGs that are being prepared. Detailed comments on the draft report are provided in Table 1.

We recommend that that the NRC revise the report by addressing the general comments discussed above and detailed comments provided in Table 1. In addition, we propose that the revised report and the associated NUREGs be issued for public comment prior to it being used to as an input to the disposition of GSI-191.

At the July meeting, the NRC presented a preliminary risk analysis associated with PWR sump performance. The draft report did not include risk analysis information. Several of the comments provided in Table 1 are related to the preliminary risk analysis. We request that NRC consider these comments as they complete their risk analysis. We propose a meeting with the NRC staff to discuss the risk methodology and assumptions. We believe this meeting should be conducted prior to the disposition of GSI-191.

If you have questions or wish to discuss these comments, please contact Kurt Cozens at (202) 739-8085, koc@nei.org, or me.

Sincerely,

Alex Marion

Alexander Marion

KOC/maa
Enclosure

c: Mr. Robert B. Elliot, U. S. Nuclear Regulatory Commission
Mr. Frank P. Gillespie, U. S. Nuclear Regulatory Commission
Mr. Michael L. Marshall, Jr., U. S. Nuclear Regulatory Commission

TABLE 1
COMMENTS ON

LA-UR-XXX, GSI-191: *Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance* (Draft)

Comment No.	Comment
1	As discussed at the July 26 and 27 public meeting: Confirm that the "Zone Of Influence" used to estimate the region of debris generation accounts for physical barriers, such as a crane wall or refueling canal, for the sixty-nine (69) cases evaluated in the draft report. Identify if any cases have been reevaluated so as to account for these physical barriers, and if so, the impact on the conclusions drawn for these cases.
2	The draft report states that "numeric simulations" confirm the selection of ½ the pool height as the "failure criteria" for partially submerged sump screens. Additional information and/or references should be added to the report, which provide the basis for the chosen failure criteria.
3	The study acknowledges that time was not taken into account. The element of time is important, and should be accounted for in considering the timing of the sequence of events attributing to debris generation, transport to the sump and subsequent postulation of sump screen blockage. Other comments associated with time are provided in this table.

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Comment No.	Comment
4	The transport fraction for pool transport was determined utilizing observations from the tank tests and the flume tests conducted at the University of New Mexico. If this understanding is correct, appropriate consideration may not have been given to establishing the conditions required for similitude between the tank tests and a representative containment. The quoted test flow rates produced velocities that approximate the velocities expected in plants. However, there are many other significant differences between the tests and plants. These include: Containment pool vs. tank volume, which effects volume exchange time and time for transport of debris to the sump screen. The volumetric turnover in the test is about five to seven (5 – 7) times for each turnover expected for a representative plant. Differences between introduction of water into pools in the test articles (all in one location) versus the plant (break location, overflow from refueling canal, runoff from containment walls and floors). This results in tests having higher local turbulence levels in the pool, which promotes both the suspension of particulates and, possibly, fibrous debris, as well as the transport of those debris to the sump screen. Increases in turbulence levels in the tests compared to the plants due to the non-linear scaling of turbulence associated with linear scaling between test models and the prototype. The increase in local turbulence levels in the tests, promotes the suspension and transport of both particulates and, possibly, fibrous debris. Basis for both the amount and the composition (debris make-up; % RMI, % fibrous, etc.) of debris used in the tank tests compared to plants. If the tank test were to be used as a guide for transport fraction, good test practice would suggest that approximately proportionate debris would be introduced into the flow stream for the test as would be expected in the plant. The fraction of debris transported to the sump by spray washdown was given as 75%. This value may not be representative as the spray nozzles are installed so as to deliver the majority of the spray inventory to the operating deck floor. From there, the fluid is (generally) ducted into the refueling canal where additional settling of particulates and potential entrapment of fibrous debris might occur. It is recommended that this comment be addressed in the final report.
5	The head loss correlation given in NUREG/CR-6224 suggests the use of various physical parameters for each of the constituents of the debris bed, e.g. fiber diameter, particulate diameter, macro and microscopic densities, etc. Neither the report nor the presentation at the July meeting identified the debris characteristics used in calculating the NUREG/CR-6224 head loss correlation. These should be included in the report.

Comment No.	Comment
6	The methodology of NUREG/CR-6224 uses a high filtration efficiency for fibers. For particulates, the filtration efficiency is proportional to the fiber bed thickness. Significant overestimation of head loss can occur if high filtration efficiency is used for particulates. The filtration efficiency for the different debris used in the head loss calculations should be included in the report.
7	Compaction of the debris bed may be a critical factor in determining head loss through the debris bed. It was not clear from the draft report what was assumed for debris bed compaction in the calculation of head loss across the debris bed. NUREG/CR-6224 indicates that the head loss correlation may over-predict head loss for thin beds coupled with high particulate-to-fiber mass ratios. Was this over-prediction addressed in the determination of thin bed head loss and if so, a description should be included in the report?
8	During the public meeting, industry representatives identified several conservative assumptions and approaches used in the draft. The NRC contractor generally acknowledged this with statements that there were one or more orders of magnitude difference between the estimated head loss and allowable margin. This large difference was given as the basis for not evaluating the impact of these conservative assumptions. This was the general response by the contractor. We recommend that the report discuss these conservatisms and the impact to estimated head loss and allowable margin.
9[1]	It is unclear why RCP Seal LOCA was categorized as a particular size of LOCA when other mechanical-failure-induced LOCAs (e.g., stuck/spuriously opened primary relief or safety valve, as listed on Slide #4 of the PRA presentation) were not. The rationale for concluding that a difference exists between debris-generation mechanisms for RCP Seal LOCA and other small LOCAs should be provided.
10[1]	There is a note indicating that the NUREG/CR-5750 large LOCA frequency has been updated to account for the V.C. Summer piping weld crack. What was the basis for assignment completely to the large LOCA category (as opposed to medium or small categories)?

[1] This comment address the NRC staff risk presentation made during the July 26 and 27, 2001 public meeting.

Comment No.	Comment
11[1]	Consideration of seismically induced LOCAs is included in the assessment. However, as potential seismic impacts are highly site-specific, the consideration of such events would generally also require the consideration of plant location as a parameter, unless the objective is to perform a "bounding" assessment (i.e., not particularly realistic for any plant site). It was not clear, purely from slides how the seismic effects are being factored into the overall assessment and how these effects might influence the resulting cost-effectiveness decisions. Additional discussion of this topic is requested.
12[1]	The seismic initiating event frequency assigned to the Large LOCA category seems high. The category of events are those seismic events for which there is a high confidence that a consequential primary pipe break in the large size range would occur. As noted in question #10, this is a function of plant location, and the seismic fragilities of plant systems, structures, and components (SSCs). Aside from the fact that no detail is provided regarding how these issues are being accounted for, the magnitude of the frequency assigned for seismic Large LOCA seems inconsistent with the values assigned for medium and small LOCA categories. Additional discussion of this topic is requested.
13[1]	There is a note indicating that the "old (1988) LLNL hazard curves" from NUREG-1150 (Surry) are being used. What is the basis for selection of this particular hazard curve? Uncertainties in the debris accumulation study related to use of this particular seismic hazard curve should be addressed in the report.

Comment No.	Comment
14[1]	It is not clear how the "RECIRC" and "NON-RECOVERY" events are being used in the assessment relative to the probabilities being assigned. In many PWR PRAs, sequences requiring ECCS injection also require successful ECCS recirculation to result in a "success" end state (i.e., no core damage). Further, in these PRAs, any small LOCA sequence is generally modeled as requiring ECCS injection for success. Procedurally driven alternatives are usually not considered, since they would require significant plant and scenario-specific involving human actions with sufficiently significant failure probabilities such that default to the recirculation scenario is likely. For the Small LOCA assumptions, it is not clear what the assigned "RECIRC" probabilities represent, or how they were assigned, particularly for the large dry containment case. Additional discussion of this topic is requested. For both the Small LOCA and the RCP Seal LOCA cases, is "NON-RECOVERY" equivalent to failure of ECCS recirculation in the absence of consideration of debris-related sump blockage, or failure of ECCS recirculation including consideration of debris effects? The values listed for "NON-RECOVERY" probabilities seem high if this event is intended to be ECCS recirculation failure (given successful ECCS injection) without consideration of debris-related blockage effects, especially for plants with automatic switchover to recirculation on low RWST (refueling water storage tank) level. Additional discussion of this topic is requested. For the case of RCP Seal LOCA, there is a high likelihood that the resulting leak will be sufficiently small that the event is effectively a Very Small LOCA (in which case the assumption on Slide #5 regarding no recirculation requirement applies). In this case, the assigned "RECIRC" probabilities make sense. It is unclear why the plant response postulated for ice condenser plants following Small LOCA is different than that postulated for RCP Seal LOCA (i.e., "RECIRC" probability = 0.43 for RCP Seal LOCA but = 1.0 for Small LOCA). Given the overlapping ranges of possible break size equivalents for these two events, the application of different probabilities implies some unstated assumptions regarding distribution of events within these size ranges. Otherwise, it would seem that the same probabilities would apply. Additional discussion of this topic is requested. For the Sub-atmospheric containment Small LOCA case, it is not clear how the differentiation in assigned "RECIRC" probability (relative to the other cases) is justified. Failure of RHR, which is environmentally qualified, is not guaranteed given actuation of containment spray; further, failure of RHR does not guarantee failure of ECCS recirculation cooling, since plants with sub-atmospheric containments typically have a second system (e.g., recirculation spray cooling system) to provide recirculation cooling.

Comment No.	Comment
15[1]	How were values shown for the parametric evaluation of probability of sump clogging selected? The values shown imply that, unless there is no chance of clogging (i.e., P=0, the "unlikely" case), there is a significant chance of clogging (i.e., P=0.3, the "possible" case). The values selected do not appear to represent a reasonable probability distribution, unless the research results indicate an extreme sensitivity of clogging to the presence/generation of any debris at all. Changing the assigned probabilities by factors of ~2 is not likely to produce insights. Unless there is always a significant chance of clogging the sump screen and the probability is not zero, then a more meaningful selection of values for this sensitivity might be P=1.0, P=0.1, P=0.01 or 0.001, and P=0.
16[1]	Slide 11 of the PRA presentation gave the impression that the assessment of Monetized Benefits from Averting Accidents Associated with Sump Clogging is being performed in a way that maximizes impact (and therefore maximizes benefits of aversion). This can be a valid approach, depending on the decision that the risk assessment is intended to support. That is, if the intent were to figure out what the worst possible effect could be in order to determine whether or not a more detailed estimate is needed, then a bounding approach is useful as a first (and potentially only) step. But if it is already known that a better estimate will be needed, then more realistic assumptions (and associated ranges or sensitivities to cover various cases) would be expected. The information on Slide 11 suggests that the population dose analysis being applied is conservative in several ways. Stated conservatisms include application of effects of a scenario in which failure was during injection rather than recirculation and assignment of effects from Small LOCA to all events. Other conservatisms appear to be application of the Zion population density (even at the 80th percentile) as representative of all plants (many of which would have much lower population densities). Further, the statement that "The [results for the?] large dry containment type of plant may be optimistic for some plants ..." seems to imply an inconsistent distinction of a particular plant characteristic that might result in less bounding results within this process, given the apparent application of layers of conservatisms elsewhere in the assessment. The risk evaluation should use realistic assumptions, with sensitivities, rather than conservative assumptions when applied to the Monetized Benefits assessment

Comment No.	Comment
17	At the February 14, 2001 public meeting on GSI-191, industry identified a basis for using initiating event frequencies based on industry-sponsored Risk Based In-Service Inspection (RB-ISI) and break opening times from public literature. At that meeting, NRC was requested to identify how they would disposition that industry information. These event frequencies should be used in the risk assessments used in evaluating the significance of this issue.
18	At the February 14, 2001 public meeting on GSI-191, industry presented data that coatings failures reported by Savannah River Technical Center were beyond the conditions expected to occur in a PWR containment under normal and design basis accident conditions. The draft report specifically identifies the SRTC observations as a possible debris source. Based on this data the reference to the SRTC data should be removed from the report, since it is not applicable to plant operations.

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

1 As discussed at the July 26 and 27 public meeting:

Confirm that the "Zone Of Influence" used to estimate the region of debris generation accounts for physical barriers, such as a crane wall or refueling canal, for the sixty-nine (69) cases evaluated in the draft report.

Identify if any cases have been reevaluated so as to account for these physical barriers, and if so, the impact on the conclusions drawn for these cases.

RESPONSE:

The type and location of debris sources are an important factor in determining whether debris accumulation on sump screens will result in loss of NPSH margin. During the public meeting it was stated that the zone of influence does not account for physical barriers nor does it account for the exact location of debris sources. None of the cases have been reevaluated to account for physical barriers. Physical barriers may reduce the amount of debris generated by some LLOCAs. For large and medium LOCAs, the debris generated by small LOCAs provides meaningful insights into how a reduction of the amount of debris generated may effect the possibility of debris accumulation on sump screens leading to loss of NPSH margin.

The parametric evaluation methodology can be divided into two parts. The first part is estimating the amount of debris needed to cause loss of NPSH margin (i.e., a minimum debris threshold). The second part is estimating the amount of debris expected to reach the sump screen using favorable and unfavorable assumptions. Many of the cases had very small minimum debris thresholds (i.e., $\leq 2ft^3$), which are not dependent upon the amount of debris generated or amount of debris transport.

Changing the ZOI to account for physical barriers would not change the findings of the GSI-191 parametric evaluation.

2 The draft report states that "numeric simulations" confirm the selection of ½ the pool height as the "failure criteria" for partially submerged sump screens. Additional information and/or references should be added to the report, which provide the basis for the chosen failure criteria.

RESPONSE:

The basis for the failure criterion used in the GSI-191 parametric evaluation will be documented in a separate technical report. The technical reports that are being produced to document the work conducted to support the GSI-191 parametric evaluation should be released to the public by the end of December 2001.

3 The study acknowledges that time was not taken into account. The element of time is

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important, and should be accounted for in considering the timing of the sequence of events attributing to debris generation, transport to the sump and subsequent postulation of sump screen blockage.

RESPONSE:

Many of the time dependent parameters or plant conditions that affect timing vary widely from plant to plant. The GSI-191 parametric evaluation methodology was designed to minimize the need to rely upon time dependent parameters or plant conditions that affect timing. Because of the plant-to-plant variability with regard to the number of time dependent parameters, this comment would be best addressed by plant-specific analyses.

4a The transport fraction for pool transport was determined utilizing observations from the tank tests and the flume tests conducted at the University of New Mexico. If this understanding is correct, appropriate consideration may not have been given to establishing the conditions required for similitude between the tank tests and a representative containment. The quoted test flow rates produced velocities that approximate the velocities expected in plants. However, there are many other significant differences between the tests and plants. These include:

Containment pool vs. tank volume, which effects volume exchange time and time for transport of debris to the sump screen. The volumetric turnover in the test is about five to seven (5 – 7) times for each turnover expected for a representative plant.

Differences between introduction of water into pools in the test articles (all in one location) versus the plant (break location, overflow from refueling canal, runoff from containment walls and floors). This results in tests having higher local turbulence levels in the pool, which promotes both the suspension of particulates and, possibly, fibrous debris, as well as the transport of those debris to the sump screen.

Increases in turbulence levels in the tests compared to the plants due to the non-linear scaling of turbulence associated with linear scaling between test models and the prototype. The increase in local turbulence levels in the tests, promotes the suspension and transport of both particulates and, possibly, fibrous debris.

Basis for both the amount and the composition (debris make-up; % RMI, % fibrous, etc.) of debris used in the tank tests compared to plants. If the tank test were to be used as a guide for transport fraction, good test practice would suggest that approximately proportionate debris would be introduced into the flow stream for the test as would be expected in the plant.

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

RESPONSE:

The tank tests do not represent a scale model of a containment floor. In order for credible scaled tests to be conducted that simulated conditions and configuration of an operating PWR, proportionate debris would have to be used. The results from the tank test were never intended to be applied to operating PWRs. The purpose of the tank tests was to demonstrate the feasibility of using data collected from the large flume tests and CFD prediction of flow patterns in containments to predict transport for a range of debris sizes (i.e., fines, shreds, and fluff) for inclusion in a detailed (i.e., similar to plant-specific) analysis. A detailed analysis was not conducted as part of the parametric evaluation.

Some of the tests conducted during the GSI-191 Technical Assessment were intended to support analyses that were not pursued because of changes in technical approach.

A separate technical report is being prepared to describe what tests were conducted to support the GSI-191 parametric evaluation. The technical reports that are being produced to document the work conducted to support the GSI-191 parametric evaluation should be released to the public by the end of December 2001.

4b The fraction of debris transported to the sump by spray washdown was given as 75%. This value may not be representative as the spray nozzles are installed so as to deliver the majority of the spray inventory to the operating deck floor. From there, the fluid is (generally) ducted into the refueling canal where additional settling of particulates and potential entrapment of fibrous debris might occur.

It is recommended that this comment be addressed in the final report.

RESPONSE:

Plant data collected during the sump and containment survey distributed by NEI was augmented with plant specific data from one of the two volunteer plants that participated in the GSI-191. Location of spray nozzles was not a question in the survey, so the volunteer plants were used to ascertain the impact of sprays on transport. Both of the volunteer plants had spray nozzles located below the operating deck.

Depending on the location and operation of sprays at different plants, the fraction of debris transported by spray washdown may vary widely from plant to plant. Also, if debris other than fines were included in the parametric evaluation, the percent of debris transported by washdown may be less, but the total amount of debris may increase. Because of the plant-to-plant variabilities with regard to spray location and operation, this comment would be best addressed by comparing plant-specific analyses.

A separate technical report is being prepared to better explain how debris transport was

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

estimated in the GSI-191 parametric evaluation. The technical reports that are being produced to document the work conducted to support the GSI-191 parametric evaluation should be released to the public by the end of December 2001.

5 The head loss correlation given in NUREG/CR-6224 suggests the use of various physical parameters for each of the constituents of the debris bed, e.g. fiber diameter, particulate diameter, macro and microscopic densities, etc. Neither the report nor the presentation at the July meeting identified the debris characteristics used in calculating the NUREG/CR-6224 head loss correlation. These should be included in the report.

RESPONSE:

The parametric evaluation only considered four types of debris that are common to most PWRs: (1) fiberglass, (2) metal, (3) calcium silicate, and (4) particulates. The fiberglass used to develop and benchmark the NUREG/CR-6224 correlation has the same physical characteristics as the fiberglass commonly found in thermal insulation used in PWRs. The NUREG/CR-6224 correlation produces accurate estimates of head loss associated with fiberglass or combinations of fiberglass and particulates up to 50 ft of H_2O per inch of debris bed thickness. The NUREG/CR-6224 correlation has been shown to significantly under-predict the head loss caused by calcium silicate debris. Use of the NUREG/CR-6224 correlation is appropriate without additional testing for a study intended to demonstrate whether debris accumulation is a problem for PWRs. Use of the correlation for plant-specific analyses that involve debris types (e.g., calcium silicate) that were not part of the development of the correlation may be inappropriate.

6 The methodology of NUREG/CR-6224 uses a high filtration efficiency for fibers. For particulates, the filtration efficiency is proportional to the fiber bed thickness. Significant overestimation of head loss can occur if high filtration efficiency is used for particulates. The filtration efficiency for the different debris used in the head loss calculations should be included in the report.

RESPONSE:

The methodology used in NUREG/CR-6224 does not have a hardwired filtration efficiency. Filtration efficiency is used to estimate the amount of particulate captured by the debris bed. The filtration efficiency of a debris bed varies with time. The efficiency of the debris bed increases as the debris bed thickness increases and porosity decreases. Typically it is best to conduct tests with the expected proportions of debris to measure variation in filtration efficiency with changes in debris bed thickness. At a point in time, a maximum filtration efficiency will be reached.

Unlike the methodology described in NUREG/CR-6224, the GSI-191 parametric evaluation methodology does not account for time. The parametric evaluation can be divided into two parts. The first part is estimating the amount of debris needed to cause loss of NPSH margin (i.e., a minimum debris threshold). The second part is estimating the maximum amount of fine fibrous and particulate debris expected to reach the sump screen using favorable and unfavorable assumptions. Since the GSI-191 parametric evaluation methodology only considers the maximum amounts of debris estimated to reach the sump screen, this approach is insensitive to filtration efficiency.

The findings of the GSI-191 parametric evaluation are not dependent upon filtration efficiency.

7 Compaction of the debris bed may be a critical factor in determining head loss through the debris bed.

It was not clear from the draft report what was assumed for debris bed compaction in the calculation of head loss across the debris bed.

NUREG/CR-6224 indicates that the head loss correlation may over-predict head loss for thin beds coupled with high particulate-to-fiber mass ratios. Was this over-prediction addressed in the determination of thin bed head loss and if so, a description should be included in the report?

RESPONSE:

High particulate-to-fiber mass ratios typically result in very large head loss that may challenge the integrity of an uniform debris bed. The limit associated with the NUREG/CR-6224 correlation is 50 ft of H_2O per inch of debris bed thickness. Most of the NPSH margins for the cases in the parametric evaluation were less than 5 ft of H_2O which is significantly below the limit.

Because NPSH margins for the majority of cases were very small, high particulate-to-fiber mass ratio has no effect on the GSI-191 parametric evaluation findings.

8 During the public meeting, industry representatives identified several conservative assumptions and approaches used in the draft. The NRC contractor generally acknowledged this with statements that there were one or more orders of magnitude difference between the estimated head loss and allowable margin. This large difference was given as the basis for not evaluating the impact of these conservative assumptions. This was the general response by the contractor. We recommend that the report discuss these conservatisms and the impact to estimated head loss and allowable margin.

RESPONSE:

The impact of all assumptions and conventions used in the GSI-191 parametric evaluation that may change the findings have been considered either qualitatively or

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

quantitatively. Aside from no credit for physical barriers and the use of licensing NPSH margin, which may be considered conservative, there are no other assumptions or conventions that should be characterized as conservative in the parametric evaluation. However, there are a number of assumptions and approaches that could be characterized as non-conservative. Those include:

1. Treating calcium silicate debris as a particulate in the NUREG/CR-6224 correlation. The correlation is known to significantly underpredict the head loss caused by calcium silicate.

2. Ignoring head loss contribution of RMI in debris beds formed with fiberglass, particulates and metal.

3. Using relatively small values (even for "unfavorable" values) for particulate debris.

4. Using fiberglass instead of other fibrous materials (e.g., mineral wool) known to lead to greater head losses.

5. Ignoring all debris types and sizes except fine fiberglass, small mass of particulates, calcium silicate, and metal when estimating amount of debris available for transport.

6. Decreasing the ZOI below the distance observed during testing.

7. Ignoring head loss caused by debris beds thinner that 1/8 or 1/4 inch.

The assumptions referenced in this comment have been addressed in responses to other comments.

9 It is unclear why RCP Seal LOCA was categorized as a particular size of LOCA when other mechanical-failure-induced LOCAs (e.g., stuck/spuriously opened primary relief or safety valve, as listed on Slide #4 of the PRA presentation) were not. The rationale for concluding that a difference exists between debris-generation mechanisms for RCP Seal LOCA and other small LOCAs should be provided.

RESPONSE:

Of the three LOCAs included in the GSI-191 parametric evaluation, the RCP seal LOCA is closest to the small LOCA. The RCP seal LOCA was included because it may produce debris whereas safety or relief valves will not produce debris if they discharge to atmosphere or a quench tank.

10 There is a note indicating that the NUREG/CR-5750 large LOCA frequency has been

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

updated to account for the V.C. Summer piping weld crack. What was the basis for assignment completely to the large LOCA category (as opposed to medium or small categories)?

RESPONSE:

A crack in a large pipe will propagate to a LLOCA. Also, the GSI-191 parametric evaluation included LLOCAS in large pipes, MLOCAs in medium pipes, and SLOCAS in small pipes.

11 Consideration of seismically induced LOCAs is included in the assessment. However, as potential seismic impacts are highly site-specific, the consideration of such events would generally also require the consideration of plant location as a parameter, unless the objective is to perform a "bounding" assessment (i.e., not particularly realistic for any plant site). It was not clear, purely from slides how the seismic effects are being factored into the overall assessment and how these effects might influence the resulting cost-effectiveness decisions. Additional discussion of this topic is requested.

RESPONSE:

After the public meeting, the seismic contribution was recalculated with the revised LLNL hazard curves. The seismic contribution with the revised hazard curves was small, and therefore, it has been neglected. The proposed fix is cost-beneficial without including the seismic contribution; a more refined site-specific analysis will not change this conclusion.

12 The seismic initiating event frequency assigned to the Large LOCA category seems high. The category of events are those seismic events for which there is a high confidence that a consequential primary pipe break in the large size range would occur. As noted in question #10, this is a function of plant location, and the seismic fragilities of plant systems, structures, and components (SSCs). Aside from the fact that no detail is provided regarding how these issues are being accounted for, the magnitude of the frequency assigned for seismic Large LOCA seems inconsistent with the values assigned for medium and small LOCA categories. Additional discussion of this topic is requested.

RESPONSE:

After the public meeting, the seismic contribution was recalculated with the revised LLNL hazard curves. The seismic contribution with the revised hazard curves was small, and therefore, it has been neglected.

13 There is a note indicating that the "old (1988) LLNL hazard curves" from NUREG-1150 (Surry) are being used. What is the basis for selection of this particular hazard curve?

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

Uncertainties in the debris accumulation study related to use of this particular seismic hazard curve should be addressed in the report.

RESPONSE:

After the public meeting, the seismic contribution was recalculated with the revised LLNL hazard curves. The seismic contribution with the revised hazard curves was small, and therefore, it has been neglected.

14a It is not clear how the "RECIRC" and "NON-RECOVERY" events are being used in the assessment relative to the probabilities being assigned. In many PWR PRAs, sequences requiring ECCS injection also require successful ECCS recirculation to result in a "success" end state (i.e., no core damage). Further, in these PRAs, any small LOCA sequence is generally modeled as requiring ECCS injection for success. Procedurally driven alternatives are usually not considered, since they would require significant plant and scenario-specific involving human actions with sufficiently significant failure probabilities such that default to the recirculation scenario is likely.

For the Small LOCA assumptions, it is not clear what the assigned "RECIRC" probabilities represent, or how they were assigned, particularly for the large dry containment case. Additional discussion of this topic is requested.

For both the Small LOCA and the RCP Seal LOCA cases, is "NON-RECOVERY" equivalent to failure of ECCS recirculation in the absence of consideration of debris-related sump blockage, or failure of ECCS recirculation including consideration of debris effects?

The values listed for "NON-RECOVERY" probabilities seem high if this event is intended to be ECCS recirculation failure (given successful ECCS injection) without consideration of debris-related blockage effects, especially for plants with automatic switchover to recirculation on low RWST (refueling water storage tank) level. Additional discussion of this topic is requested.

RESPONSE:

RECIRC means that ECCS recirculation is required to avoid core damage. In other words, cooldown and depressurization and use of the RHR in a hot shutdown mode of cooling is not successful. The procedures being used are those consistent with emergency response guidelines ES-1.2, "Post-LOCA Cooldown and Depressurization."

NON-RECOVERY refers to the failure of the recovery actions referred to in ECA-1.1, "Loss of Containment Sump Recirculation."

The change in the core damage frequency from fixing the sump screen clogging

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

problem is given by the quantification of the following Boolean expression:

LOCA(n)*RECIRC*SUMP-CLOGS*NON-RECOVERY

If the sump clogging problem is fixed, it is assumed that this probability is zero. Note that the frequency associated with the above expression is zero if the probability of sump clogging is zero; the quantification of the above expression gives the change in core damage frequency from fixing the sump screen clogging problem. Failure of ECCS recirculation in the absence of consideration of debris-related sump blockage does not enter this expression.

14b For the case of RCP Seal LOCA, there is a high likelihood that the resulting leak will be sufficiently small that the event is effectively a Very Small LOCA (in which case the assumption on Slide #5 regarding no recirculation requirement applies). In this case, the assigned "RECIRC" probabilities make sense.

It is unclear why the plant response postulated for ice condenser plants following Small LOCA is different than that postulated for RCP Seal LOCA (i.e., "RECIRC" probability = 0.43 for RCP Seal LOCA but = 1.0 for Small LOCA). Given the overlapping ranges of possible break size equivalents for these two events, the application of different probabilities implies some unstated assumptions regarding distribution of events within these size ranges. Otherwise, it would seem that the same probabilities would apply. Additional discussion of this topic is requested.

RESPONSE:

For ice condenser plants, the plant response is different for SLOCAs and for some RCP seal LOCAs. Some RCP seal LOCAs are so small that the containment spray is not actuated, and it is possible to avoid ECCS recirculation by cooling down and depressurizing, and using the RHR in shutdown cooling mode. But the containment spray will actuate on all SLOCAs, in ice condenser plants.

14c For the Sub-atmospheric containment Small LOCA case, it is not clear how the differentiation in assigned "RECIRC" probability (relative to the other cases) is justified. Failure of RHR, which is environmentally qualified, is not guaranteed given actuation of containment spray; further, failure of RHR does not guarantee failure of ECCS recirculation cooling, since plants with sub-atmospheric containments typically have a second system (e.g., recirculation spray cooling system) to provide recirculation cooling.

RESPONSE:

The RHR system is not environmentally qualified at Surry. This may not be the case for all plants with sub-atmospheric containments. Because the RHR system is not safety grade at Surry, it is not clear whether the operators will attempt to use it to mitigate a

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

small break LOCA. However, some credit was given for the RHR system.

Failure of ECCS recirculation from causes other than sump screen clogging really does not enter into the expression for the change in core damage frequency from fixing the sump screen clogging problem.

15 How were values shown for the parametric evaluation of probability of sump clogging selected? The values shown imply that, unless there is no chance of clogging (i.e., P=0, the "unlikely" case), there is a significant chance of clogging (i.e., P=0.3, the "possible" case). The values selected do not appear to represent a reasonable probability distribution, unless the research results indicate an extreme sensitivity of clogging to the presence/generation of any debris at all. Changing the assigned probabilities by factors of ~2 is not likely to produce insights.

Unless there is always a significant chance of clogging the sump screen and the probability is not zero, then a more meaningful selection of values for this sensitivity might be P=1.0, P=0.1, P=0.01 or 0.001, and P=0.

RESPONSE:

The values for sump clogging probability are based on the qualitative designations for the results of each case in the GSI-191 parametric evaluation. The parametric evaluation used four qualitative designations to classify the results of the evaluation for each case and LOCA size: (1) Very Likely, (2) Likely, (3) Possible, and (4) Unlikely.

For cases where both the favorable and unfavorable conditions resulted in debris estimates greater than the minimum amount of debris needed to cause loss of NPSH, those cases and LOCA sizes were classified as Very Likely. Given the condition addressed in the parametric evaluation, cases with the Very Likely classification were assigned a probability of one, because both favorable and unfavorable conditions exceeded a minimum amount of debris, loss of NPSH could be considered a certainty.

For cases where both the favorable and unfavorable conditions resulted in debris estimates smaller than the minimum amount of debris needed to cause loss of NPSH, those cases and LOCA sizes were classified as Unlikely. Cases with the Unlikely classification were assigned a probability of zero, because neither favorable nor unfavorable conditions exceeded the minimum amount of debris. For a number of the Unlikely cases (esp. regarding LLOCA) the types of debris (e.g., metallic) used in the parametric cases are very difficult to transport and cause less head loss than other types of debris (e.g., calcium silicate).

For cases where the favorable condition resulted in debris estimates smaller than the minimum amount of debris needed to cause loss of NPSH and the unfavorable conditions resulted in debris estimates greater than the minimum amount of debris needed to cause loss of NPSH, those cases and LOCA sizes were classified as Possible or Likely. Since the results of the evaluation were not as conclusive as the other two classifications, a value between zero and one was assigned.

16 Slide 11 of the PRA presentation gave the impression that the assessment of Monetized Benefits from Averting Accidents Associated with Sump Clogging is being performed in a way that maximizes impact (and therefore maximizes benefits of aversion). This can be a valid approach, depending on the decision that the risk assessment is intended to support. That is, if the intent were to figure out what the worst possible effect could be in order to determine whether or not a more detailed estimate is needed, then a bounding approach is useful as a first (and potentially only) step. But if it is already known that a better estimate will be needed, then more realistic assumptions (and associated ranges or sensitivities to cover various cases) would be expected.

The information on Slide 11 suggests that the population dose analysis being applied is conservative in several ways. Stated conservatisms include application of effects of a scenario in which failure was during injection rather than recirculation and assignment of effects from Small LOCA to all events. Other conservatisms appear to be application of the Zion population density (even at the 80th percentile) as representative of all plants (many of which would have much lower population densities). Further, the statement that "The [results for the?] large dry containment type of plant may be optimistic for some plants ..." seems to imply an inconsistent distinction of a particular plant characteristic that might result in less bounding results within this process, given the apparent application of layers of conservatisms elsewhere in the assessment.

The risk evaluation should use realistic assumptions, with sensitivities, rather than conservative assumptions when applied to the Monetized Benefits assessment.

RESPONSE:

The values used are given for the Zion plant in Table 5.3 of NUREG/BR-0184, "Regulatory Analysis Technical Evaluation Handbook," January 1997. The population density around Zion is not used; rather the population density at the 80th percentile of all sites is used. In other words, the results are as if the Zion plant had been moved to a place where the population density was equal to that of the 80th percentile nuclear power plant site in terms of the population density surrounding the site. The offsite consequence analysis for large dry and subatmospheric containment plants used Zion offsite consequences. Ice condenser plants used Sequoyah offsite consequences, and did not have the same conservatism as large dry containment plants. The change in core damage frequency associated with sump clogging may be underestimated for large dry containment plants which do not have emergency fan coolers and large RWSTs.

The conservatisms in the consequence analysis portion of the analysis are small, and do not affect the results. The greatest contribution to the benefits is the onsite property

Table 1: Responses to NEI Comments Attached to Letter Dated 08/31/01

cost.

17 At the February 14, 2001 public meeting on GSI-191, industry identified a basis for using initiating event frequencies based on industry-sponsored Risk Based In-Service Inspection (RB-ISI) and break opening times from public literature. At that meeting, NRC was requested to identify how they would disposition that industry information. These event frequencies should be used in the risk assessments used in evaluating the significance of this issue.

RESPONSE:

The initiating frequencies from the RB-ISI program and other sources including NUREG/CR-5750 and NUREG/CR-1150 were considered. The values listed in NUREG/CR-5750 were considered the best available for the purposes of the GSI-191 averted CDF and benefit estimates.

18 At the February 14, 2001 public meeting on GSI-191, industry presented data that coatings failures reported by Savannah River [Technology] Center were beyond the conditions expected to occur in a PWR containment under normal and design basis accident conditions. The draft report specifically identifies the SRTC observations as a possible debris source. Based on this data the reference to the SRTC data should be removed from the report, since it is not applicable to plant operations.

RESPONSE:

The GSI-191 parametric evaluation does not explicitly use any particular type of particulate. It does list different types of particulate which include coating particulates. Whether coating particulates are include as a debris source should be determined on a plant specific basis. References to the SRTC coating study will not be removed from the technical report.

Table 2: Responses to Comments Raised During Open Discussion of July 26 and 27, 2001 Public Meeting Concerning GSI-191

1 Expected NPSH margin not licensing NPSH margin should have been used in GSI-191 parametric evaluation.

RESPONSE:

At public meetings with the industry during the varous stages of the GSI-191 technical assessment, it was clearly stated that GL 97-04 would be used as the source for NPSH margin data. Expected NPSH margins were not made available for use by the NRC or NRC contractor.

2 The methodology used in the GSI-191 parametric evaluation does not provide any insight into when sump failure would occur.

RESPONSE:

Many of the time dependent parameters or plant conditions that effect timing vary widely from plant to plant. The GSI-191 parametric evaluation methodology was designed to minimize the need to rely upon time dependent parameters or plant conditions that effect timing. Because of the plant to plant variability with regard to number of time dependent parameters, this comment would be best addressed by plant-specific analyses.

3 The basis for assuming uniform accumulation of debris is unclear.

RESPONSE:

The parametric evaluation focused primarily on fine fibrous debris and particulate debris. Larger debris that may accumulate predominately at the bottom of the sump screen and debris that would accumulate at the top of the sump screen were not considered in the parametric evaluation. A number of debris accumulation tests were conducted with fine fibrous and particulate debris to demonstrate that they would be retained by mesh with 1/8 inch and 1/4 inch openings.

A separate technical report is being prepared to describe what tests were conducted to support the GSI-191 parametric evaluation. The technical reports that are being produced to document the work conducted to support the GSI-191 parametric evaluation should be released to the public by the end of December 2001.

4 The flowrate for non-Westinghouse PWRs used in the GSI-191 parametric evaluation appears to be too high.

RESPONSE:

This comment was raised with respect to a CE plant response to SLOCA events. The methodology for the parametric evaluation used 2500 gpm for ECCS recirculation flow following a SLOCA event. This information was based on a review of information contained in NUREG/CR-5640 for Westinghouse PWR high-pressure pump flow rates. The total ECCS flow available when the system has depressurized (to 500 psig) was assumed to be the nominal flow for use in the study. Review of the NUREG/CR-5640 information for Westinghouse PWRs concluded that this total available flow ranged from approx. 1900 gpm to 4800 gpm, with a median value of around 2500 gpm.

After the public meeting a review of SLOCA ECCS flow rates has been conducted for CE units. The information source for this review was the collection of nuclear plant information books on the U.S. NRC web site. Based on this review, it is concluded that the 2500 gpm value for ECCS recirculation flow is appropriate for use with CE units. For some units for which the ECCS flow rate used in the parametric study may be half the value used. Plant variabilities such as this should be addressed in plant specific analyses.

It should be noted that the flow rate used to estimate the minimum amount of debris needed to cause loss of NPSH given a SLOCA, include the total ECCS and containment spray - not just ECCS flow rates.

5 The GSI-191 program did not include any head loss tests to benchmark the NUREG/CR head loss correlation against the type of debris assumed in the GSI-191 parametric evaluation.

RESPONSE:

The parametric evaluation only considered four types of debris that are common to most PWRs: (1) fiberglass, (2) metal, (3) calcium silicate, and (4) particulates. The fiberglass used in testing to develop and benchmark the NUREG/CR-6224 correlation has the same physical characteristics as the fiberglass commonly found in thermal insulation used in PWRs. The NUREG/CR-6244 correlation produces accurate estimates of head loss associated with fiberglass or combinations of fiberglass and particulates up to 50 ft of H_2O per inch of debris bed thickness. However, the NUREG/CR-6224 correlation has been shown to significantly under predict the head loss caused by calcium silicate debris. Use of the NUREG/CR-6224 correlation is appropriate without additional testing for a study intended to demonstrate whether debris accumulation is a problem for PWRs. Use of the correlation for plant specific analyses that involve debris types (e.g., calcium silicate) that were not part of the development of the correlation may be inappropriate.

6 Since the LLOCAs assumed in the GSI-191 parametric evaluation ranged from 6 inches up, it seems inappropriate to use the 95-percentile debris generation value in the estimate of debris on sump screen.

Table 2: Responses to Comments Raised During Open Discussion of July 26 and 27, 2001 Public Meeting Concerning GSI-191

RESPONSE:

The use of the 95th percentile is appropriate for the parametric evaluation. The parametric evaluation does not include all possible debris sources and location of the debris sources is unknown. The use of the 95th percentile for debris generation was chosen to partially offset these limitations in the parametric evaluation.

After the public meeting all the parametric cases were re-evaluated assuming that the LLOCA debris quantity was the 50th percentile value, which represent a significant decrease in debris. The use of the 50th percentile resulted in a modest increase (i.e., 6) in cases being classified as Unlikely.

The debris threshold is not dependent upon the debris generation or transport. For most cases the debris threshold was 2 ft^3 or less. So the use of a 95th percentile had little impact on the finding of the study.

7 It was unclear from report and presentation if breaks were postulated in only high-energy lines inside the crane wall. It seems inappropriate to include non-high energy piping and piping outside of the crane wall in the parametric evaluation.

RESPONSE:

Breaks were postulated in high-energy (i.e., >500 psig) lines only. Breaks located outside the crane wall were included in the analysis. Because many plants have the ability to isolate breaks outside of the crane wall and thus prevent transition to recirculation, they could have been excluded from the parametric evaluation.

Because there is less piping in the zone of influence for breaks outside of the crane wall, inclusion of those breaks skews the distribution of possible debris volumes to lower values. If these breaks are removed from consideration, the 95th percentile debris volume used to characterize small breaks may increase. So exclusion of breaks outside of the crane wall will not change the findings of the study.

8 The effectiveness of trash racks in reducing the amount of debris that could reach the sump screen was neglected.

RESPONSE:

The purpose of trash racks, which typically are built with floor gratings with 1 by 3 inch openings, is to stop large debris from reaching the sump screen. Large debris was not considered in the parametric evaluation. Only fine fibrous debris and particulate debris was considered in the parametric evaluation, typically trash racks would not accumulate fine fibrous debris and particulate debris. Analyses that consider all debris sources are better suited for assessing the effectiveness of trash racks.

Table 2: Responses to Comments Raised During Open Discussion of July 26 and 27, 2001 Public Meeting Concerning GSI-191

9 It is unclear how distance debris travels in test facilities translates to distance debris travels in actual containment.

RESPONSE:

The distance in the tank tests do not scale to distances in actual containments. The tank tests do not represent a scale model of a containment floor. In order for credible scaled tests to be conducted that simulated conditions and configuration of an operating PWR, proportionate debris would have to be used. The results from the tank test were never intended to be applied to operating PWRs. The purpose of the tank tests was to demonstrate the feasibility of using data collected from the large flume tests and CFD prediction of flow patterns in containments to predict transport for a range of debris sizes (i.e., fines, shreds, and fluff) for inclusion in a detailed (i.e., similar to plant-specific) analysis. A detailed analysis was not conducted as part of the parametric evaluation.

Some of the tests conducted during the GSI-191 Technical Assessment were intended to support analyses that were not pursued because of changes in technical approach.

A separate technical report is being prepared to describe what tests were conducted to support the GSI-191 parametric evaluation. The technical reports that are being produced to document the work conducted to support the GSI-191 parametric evaluation should be released to the public by the end of December 2001.

Attachment 7

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D.C. 20555-0001

September 14, 2001

Dr. William D. Travers
Executive Director for Operations
US Nuclear Regulatory Commission
Washington, DC 20555-0001

Dear Dr. Travers:

SUBJECT: GENERIC SAFETY ISSUE-191, "ASSESSMENT OF DEBRIS ACCUMULATION ON PWR SUMP PUMP PERFORMANCE"

During the 484th and 485th meetings of the Advisory Committee on Reactor Safeguards, July 11-13 and September 5-7, 2001, we heard presentations by and held discussions with representatives of the NRC staff regarding the Office of Nuclear Regulatory Research recommendation for resolving Generic Safety Issue (GSI)- 191, "Assessment of Debris Accumulation on PWR Sump Pump Performance." During this review, we had the benefit of the documents referenced.

We agree with the staff that potential issues associated with the performance of pressurized water reactor containment sumps have been identified. The NRC staff should expeditiously resolve GSI-191. If plant-specific analyses are required as part of the resolution, guidance for performing these analyses should be developed. We would like to review the proposed final disposition of this issue.

Sincerely,

George E. Apostolakis
Chairman

Reference:
Letter dated August 29, 2001, from Michael E. Mayfield, Office of Nuclear Regulatory Research, NRC, to John T. Larkins, Advisory Committee on Reactor Safeguards, Subject: RES's Proposed Recommendation for Resolution of GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance," attaching:

(1) Rao, D., et al., "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance," LA-UR-XXX, Los Alamos National Laboratory, Los Alamos, New Mexico, July 2001.

(2) Buslik, A., Risk Considerations and Benefits Associated with GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance," U.S. NRC, August 8, 2001.

(3) Feld, S., Cost Analysis for GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance," U.S. NRC, August 14, 2001.