UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

NOV 12 1982

MEMORANDUM FOR: Darrell G. Eisenhut, NRR
Edward L. Jordan, IE
Richard E. Cunningham, NMSS
Robert M. Bernero, RES
Clemens J. Heltemes, Jr., AEOD
Joseph Scinto, ELD

FROM: Victor Stello, Jr., Chairman
Committee to Review Generic Requirements

SUBJECT: CRGR MEETING NUMBER 26

The Committee to Review Generic Requirements will meet on Wednesday, November 24, 1982, from 1-5 p.m. in Room 6507 MNBB.

1:00-2:00 p.m. S. Hanauer (NRR) will present for CRGR review the NRR recommendations concerning USI A-43, Containment Emergency Sump Performance. A copy of the materials forwarded for CRGR consideration is enclosed.

2:00-3:00 p.m. K. Goller (RES) will present for CRGR review the proposed revision (Revision 3) to Regulatory Guide 1.97, Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident. A copy of the materials forwarded for CRGR consideration is enclosed.

3:00-4:00 p.m. R. Bernero (RES) will brief the CRGR concerning questions that resulted from the ATWS briefing given at CRGR Meeting #24. The questions are listed in the Minutes of CRGR Meeting #24.

Persons making presentations to the CRGR are responsible for (1) assuring that the information required for CRGR review is provided to the Committee (CRGR Charter - IV.B), (2) coordinating and presenting views of other offices, (3) as appropriate, assuring that other offices are represented during the presentation, and (4) assuring that agenda modifications are coordinated with the CRGR contact (Walt Schwink, x24342) and others involved with the presentation. With regard to attendance at CRGR meetings, I request that Office Directors limit attendance of their staffs at CRGR

R-001

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meetings to those few senior staff needed to address the agenda item under discussion. As a minimum, Division Directors or higher management should attend meetings addressing agenda items under their purview.

Original Signed by
V. Stello

Victor Stello, Jr., Chairman
Committee to Review Generic
Requirements

Enclosure: As stated

cc: w/o encl.:
Commission (5)
W. J. Dircks, EDO
Office Directors
Regional Administrators
G. Cunningham, ELD
S. Hanauer, NRR
K. Goller, RES

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NAME	:WSchwink	:TMurley	:VStello	:	:	:	:
DATE	:11/12/82	:11/12/82	:11/ /82	:	:	:	:

CRGR AGENDA ITEM

SUMMARY INFORMATION

IDENTIFICATION: USI A-43, CONTAINMENT EMERGENCY SUMP PERFORMANCE

CRGR ACTION REQUESTED BY NRR:

Consideration prior to issuance (by NRR) for public comment. Items proposed to be issued are NUREG 0897 (draft) and the proposed revisions to R.G. 1.82 and SRP Section 6.2.2.

DESCRIPTION:

Proposed requirements to confirm and assure containment emergency sump capability during recirculation flow from containment floor to ECCS pumps. Current regulations and existing PRAs assume an operable sump. These proposed requirements originated from concern for sump blockage due to insulation fragments as well as the technical adequacy of current design methods to assure hydraulic performance of sumps.

Package submitted for CRGR review includes:

1. Memorandum, H. Denton to V. Stello, subject: "CRGR Review of Proposed Revisions to SRP Section 6.2.2. and R.G. 1.82" and the Supporting Technical Information Document NUREG 0897, as Related to USI-A43 "Containment Emergency Sump Performance."
2. Enclosure 1 Summaries of A43 References - Contractor reports on technical issues investigated.

3. Enclosure 2 Value-Impact Analysis - Staff's cost/benefit evaluation, discussion of recommended technical approach, proposed plan for implementation.
4. Enclosure 3 Background Information - Staff's response to questions in Section IV B of CRGR Charter.
5. Enclosure 4 Proposed Revision 4 to SRP 6.2.2.
6. Enclosure 5 Proposed Revision 1 to R.G. 1.82.
7. Enclosure 6 NUREG 0897 - "for comment" version.

STATUS OF REQUIREMENTS DEVELOPMENT

Submitted for CRGR review prior to issuance for public comment.

REQUIREMENT APPLICABILITY

Backfit on all operating reactors and OL applications. Forward fit on all CP and new applications via SRP revisions which include reference to revised R.G. 1.82.

REGULATORY INSTRUMENTS CRGR WILL BE ASKED TO APPROVE:

1. Draft Generic Letter to Licensees.
2. Proposed Revision 4 to SRP Section 6.2.2., Containment Heat Removal Systems.
3. Proposed Revision 1 to R.G. 1.82, Sump for Emergency Core Cooling and Containment Spray Systems.

4. NUREG 0897 (for comment) Containment Emergency Sump Performance.

AN INCREASE OVER EXISTING REQUIREMENTS?

Yes, as described in Table 3-1 of Enclosure 3 in package submitted for review.

COMMENT TO DATE BY INDUSTRY:

Proposed program of fixes discussed with staff at four plants -

Maine Yankee

Haddam Neck

Ginna

Vermont Yankee

Preliminary responses from these staffs indicate that NRC proposed costs to implement fix may be low. Occupational exposure data used by NRC was derived from data obtained from plants.

CRGR STAFF VIEWPOINTS

1. This issue is not a proposed risk reduction from the status quo - it is a set of actions proposed as necessary to assure that current predicted (by available PRAs) plant risk levels are in fact achieved.
2. Denton memorandum of October 27, 1982, covering CRGR package states that only three documents will be issued for public comment. Should NRC's value-impact analysis be available for critique by public also? (The current package also incorporates the proposed regulatory instrument for backfitting ORs in the value impact analysis.)

COST/BENEFIT CONSIDERATIONS

1. Assume 10^{-4} latent fatalities/man-rem (BEIR)

2. Calculated public dose averted is 65 person-rem per plant per year. (p. 21, Enclosure 2). Or, for 23 years average remaining life per plant, a total of ≈ 1500 pers-rem per plant.

3. Minimum expenditure to fix is $5000 (analysis only)

   Maximum expenditure to fix is $500K

Then:

1) On a maximum $\frac{\text{dollars}}{\text{pers rem}}$ basis; $\frac{500K}{1500} = 270 \frac{\text{dollars}}{\text{pers rem}}$

2) On a maximum cost per health effect basis:

$$10^{-4} \frac{LF}{\text{pers-rem}} \times 1500 \text{ pers rem} = .15 \text{ LF over life of plant}$$

$$\frac{\$500K}{.15LF} = 3.3\,(10)^6 \frac{\text{Dollars}}{LF}$$

ENCLOSURE 6

FOR NRC STAFF REVIEW

NUREG-0897
For Comment

Containment Emergency Sump Performance

Technical Findings Related to Unresolved Safety Issue A-43

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

A. W. Serkiz, Task Manager

 ENCLOSURE 6

FOR NRC STAFF REVIEW

NUREG-0897
For Comment

Containment Emergency Sump Performance

Technical Findings Related to Unresolved Safety Issue A-43

Manuscript Completed: August 1982
Date Published: November 1982

A. W. Serkiz, Task Manager

Division of Safety Technology
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ABSTRACT

This report summarizes key technical findings related to the Unresolved Safety Issue A-43, Containment Emergency Sump Performance, and provides recommendations for resolution of attendant safety issues. The key safety questions relate to: (a) effects of insulation debris on sump performance; (b) sump hydraulic performance as determined by design features, submergence, and plant induced effects; and (c) recirculation pump performance wherein air and/or particulate ingestion can occur.

The technical findings presented in this report provide information relevant to the design and performance evaluation of the containment emergency sump. These findings have been derived from extensive experimental measurements, generic plant studies and assessment of pumps utilized for long-term cooling. These results indicate a less severe post-LOCA situation than previously hypothesized (e.g., low levels of air ingestion over a wide range of sump designs and flow conditions, a debris hazard situation that is not widespread, and pump designs that can accommodate low levels of air ingestion). Therefore, these findings provide a technical basis for the development of changed proposed to the Standard Review Plan and Regulatory Guide 1.82.

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FOREWORD

NUREG-0897 is being issued for public comment. It provides a concise and self-contained reference which summarizes technical findings relevant to the unresolved Safety Issue A-43, "Containment Emergency Sump Performance." NUREG-0897 is not a substitute for the requirements set forth in General Design Criteria 16, 35, 36, 37, 38, 40 and 50 in Appendix A to 10CFR50, nor a substitute for requirements set forth in NRC's Standard Review Plan or Regulatory Guides. The information contained herein is of a technical nature which can be used as background relevant to the proposed revisions to SRP Section 6.2.2 and Regulatory Guide 1.82.

ACKNOWLEDGMENTS

The technical findings relevant to the Unresolved Safety Issue A43, Containment Emergency Performance, set forth in this report are the result of the combined efforts of staff at the Nuclear Regulatory Commission, the Department of Energy, Sandia National Laboratories (SNL), Alden Research Laboratory (ARL), Burns & Roe (B&R), Inc. and Creare, Inc. The following persons deserve special mention for their participation and contributions:

W. Butler, NRC/DSI
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F. Orr, NRC/DSI
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1.0 INTRODUCTION

1.1 Safety Significance

Following a loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR), water discharged from the break will collect on the containment floor and within the containment emergency sump. Although the emergency core cooling systems (ECCS) and containment spray systems (CSS) initially draw water from the refueling water storage tank (RWST), long-term core cooling is affected by realignment of these ECCS pumps to the containment emergency sump. Thus, successful long-term recirculation depends upon the sump providing adequate, debris-free water to the recirculation pumps for extended periods of time. Moreover, the flow conditions through the sump and associated piping must not result in pressure losses or air entrainment that would inhibit proper pump operation. Without a proper sump design, long-term cooling could be significantly impaired.

1.2 Background

The importance of the ECCS sump and safety considerations associated with its design were early considerations in containment design. Net positive suction head (NPSH) requirements, operational verification, and sump design requirements are issues that have evolved and are currently contained in the following Regulatory Guides (RG):

RG 1.1 -- Net Positive Suction Head for Emergency Core Cooling and Containment Heat Removal Systems Pumps, 1970.

RG 1.79 -- Preoperational Testing of Emergency Core Cooling Systems for PWRs, 1974.

RG 1.82 -- Sumps for Emergency Cooling and Containment Spray Systems, 1974.

Review of these Regulatory Guides reveals that the concerns of the Nuclear Regulatory Commission (NRC) staff regarding emergency sump performance were evolutionary in nature. Initially, staff concerns were addressed through in-plant tests (per RG 1.79) with a transition to containment and sump model tests in the mid-1970s. At that time, considerable emphasis was placed on "adequate" sump hydraulic performance during these model tests, and vortex formation was identified as the key determinant. The main concern was that formation of an air-core vortex would result in unacceptable levels of air ingestion and, subsequently, in severely degraded pump performance.

There was also concern about sump damage or blockage of the flow as a result of LOCA generated insulation debris, missiles etc. These concerns led to the formulation of some of the guidelines set forth in RG 1.82 (cover plates, debris screen, < 50 percent screen blockage, etc.).

In 1979, as a result of continued staff concern for safe operation of ECCS sumps, the Commission designated the issue as Unresolved Safety Issue (USI) A-43, "Containment Emergency Sump Performance." To assist in its resolution, the Department of Energy (DOE) provided funding for construction of a full-scale test facility at the Alden Research Laboratory (ARL) of Worcester Polytechnic Institute (WPI) (Reference 1). At about the same time, Task Action Plan (TAP) A-43 was developed to address all aspects of this safety issue.

1.3 Technical Issue

The principal concern is summarized in the following question:

> In the recirculation mode following a LOCA, will the pumps receive water sufficiently free of debris and air and at sufficient pressure to satisfy NPSH requirements so that pump performance is not impaired?

This concern can be divided into three areas for technical consideration: sump design, insulation debris effects, and pump performance. The three areas are not independent, and certain combinations of effects must be considered as well.

This report presents the technical findings derived from extensive, full-scale experimental measurements, generic plant calculations, and residual heat removal (RHR) and CSS pump performance assessments. These technical findings provide a basis for resolving USI A-43.

1.4 Summary of Technical Findings

The following key determinations are derived from the technical findings contained in Section 3.

1. The hydraulic performance of containment emergency sumps should be based primarily on level of air ingestion into the sump suction inlet(s). Visual observations cannot be used to quantify the amount of air ingestion occurring. However, observations of sump surface vortex activity, principally the lack thereof, can be used to infer the absence of air ingestion.

2. Relative to acceptable levels of air ingestion, two options are available: a) 0 percent air ingestion, and b) $\leq$ 2 percent air ingestion, provided NPSH requirements at the pump inlet are satisfied. For marginal designs, or flow conditions, vortex suppressors can reduce air ingestion to zero.

3. The sump design information, contained in Section 3.2, can be used to evaluate hydraulic design and performance. If the sump operational envelope falls outside of the A-43 experimental envelope, or recommended sump geometric features, additional analyses or data may be needed for support of proposed design.

4. The general sump design information set forth in RG 1.82, "Sumps for Emergency Core Cooling and Containment Spray Systems," such as use of screens and trash racks should be maintained. However, the currently specific 50 percent screen blockage can lead to non-conservative results. Finding 5 (below) addresses the question of screen blockage in a more rigorous manner.

5. The insulation debris evaluation methods, described in Section 3.3, provide a conservative means to determine quantities of debris that would be generated by a LOCA and to determine the resulting screen blockage and attendant pressure drop.

6. Plant insulation surveys have shown that a variety of insulations have been employed in plants and in large quantities. Nonencapsulated insulations (particularly calcium silicate, mineral wool and fibrous types) have been shown through plant specific calculations (see Section 3.3) to potentially result in total screen blockage following a LOCA. Plant specific studies have shown a strong plant layout and type of insulation dependence due to debris migration to the sump.

7. Recirculation pump operation can be assessed using the findings and methods provided in Section 3.2. Low levels of air ingestion ($\leq$ 2 percent) will not degrade pumping capability. However, as noted in Item 2, non-zero air entrainment conditions identified at the sump suction inlets should be evaluated for NPSH effects. Ingestion of small particles will not pose a pumping problem; however, pump bearing and bearing cooling systems warrant review from the viewpoint of possible clogging.

8. BWRs need not be reviewed in as much detail as PWRs for determination of long-term recirculation capabilities. For sake of completeness, some BWR-RHR suction tests (representative of Mark I, Mark II and Mark III designs) were tested to determine air ingestion characteristics. The results reveal low levels of air ingestion (see Section 3.4); this data set can be used to evaluate designs. The limited BWR insulation survey that was conducted revealed a high utilization of reflective metallic insulation and, therefore, debris effects are not believed to be significant.

2.0 KEY FINDINGS SUMMARY

2.1 Pump Performance

Sustained operation of RHR and CSS pumps in the recirculating mode presents two principal areas of concern:

- Possible degradation of the hydraulic performance of the pump (inability of pumps to maintain sufficient recirculation flow as a result of sump screen blockage, cavitation effects, or air ingestion).
- Possible degradation of pump performance over the long- or short-term due to mechanical problems (material erosion due to particulates or severe cavitation, shaft or bearing failure due to unbalanced loads, and shaft or impeller seizure due to particulates).

Pumps used in RHR and CSS systems are primarily single stage centrifugal designs of low specific speed. CSS pumps are generally rated at flows of about 1500 gpm, heads of 400 feet, and require about 20 feet of NPSH at their inlet; RHR pumps are generally rated at about 3000 gpm, heads of 300 feet, and require about 20 feet NPSH at maximum flow. Rating points and submergence requirements for the pumps are plant specific. Pump materials are generally highly resistant to erosion, corrosion, and cavitation damage.

Test results show that under normal flow conditions and in the absence of cavitation effects, performance is only slightly degraded when air ingestion is less than 2 percent. This value would be a conservative estimate for acceptable performance. For higher amounts of air ingestion, pump performance is dependent on many variables, but air ingestion in excess of 15 percent almost completely degrades the performance of pumps of this type.

Submergence or net positive suction head requirements (NPSHR) for RHR and CSS pumps (routinely determined by manufacturers' tests) are established by a percent degradation in pump output pressure. (Individual specifications determine that NPSH required be set according to a 1 percent or 3 percent criterion.) No standard exists for the percent degradation criterion, nor for the margin between NPSH available and that required in setting RHR and CSS pump submergence. Air ingestion affects NPSHR. Test data on the combined effects of air ingestion and cavitation are limited, but the combined effects of both increase the NPSH required. A value of 3 percent degradation in pump output pressure for the combined effects of air ingestion and cavitation appears to be a realistic value.

2.2 Effects of Debris on Sump Performance

The safety issues related to debris effects on sump performance concern screen blockage and attendant potential loss of pump suction pressure.

Results of the insulation debris studies are summarized below.

- Types of insulations used vary from plant to plant, with newer plants generally using reflective metallic insulation that is not likely to cause blockage problems. Types of insulation used in the 19 plants surveyed in this study are shown in Table 3.3.

- Detailed methods were developed for determining the quantities, sources, and transport mechanisms of debris that could be generated during a LOCA and for assessing the consequences of the blockage of sump inlets that might result (see Figure 3.9).

- The methods developed for debris assessment were evaluated by application to 5 selected plants to establish variability due to plant design, type(s) of insulation employed and sump design. Table 3.7 summarizes the calculated results as a function of break location and plant selected. Screen blockages greater than 50 percent were calculated, with 2 of the plant calculations resulting in 100 percent screen blockage. For the Salem plant, low flow velocities, large screen area, sump design and location resulted in low pressure losses through the blocked screen. Therefore, NPSH requirements were not impacted. For the Maine Yankee plant, large quantities of nonencapsulated mineral wool were calculated to be transported to a small sump screen area. In this case, a 100 percent screen blockage with high pressure drop was predicted. Although conservative assumptions have been embodied into these analyses methods, the variabilities due to plant design and types of insulations employed illustrate the need for plant specific evaluations.

- Mirror (reflective type) insulations do not appear to pose screen blockage problems. Velocities required for migration of such insulation is relatively high.

- Low density insulations, having a closed cell structure, will float and are not likely to impede flow through the pump screens except where the screens are not totally submerged.

- Low density hygroscopic insulation having equilibrium densities greater than water require a plant specific assessment of screen blockage effects.

- Non-encapsulated insulation (particularly mineral fiber, fiberglass, or mineral wool blanket) require a plant specific evaluation to determine the potential for sump screen blockage. (Section 3.3 provides a conservative method for assessing screen blockage effects.) Some debris will not be collected on sump screens by virtue of its size and shape distribution.

2.3 Sump Hydraulic Performance Findings

Data obtained from full-scale sump tests provide a sound base for assessing pump hydraulic performance. Both side-suction and bottom-suction designs were tested over a wide range of design parameters, and the effects of elevated water temperatures were assessed. Scaling experiments (1:4, 1:2, 1:1) were also conducted to provide a means for assessing the validity of previous scaled model tests. The effectiveness of certain vortex suppression devices was also evaluated. For completeness, plant specific and LOCA-introduced effects (condenser drain flow, break flow impingement, large swirl and sump circulation effects, and sump screen blockage) were evaluated experimentally at full scale. Results of this test program are summarized below.

- The broad data base from the sump studies resulted in the development of envelope curves for reliably quantifying the expected upper-bound for the hydraulic performance of any given sump whose essential features fall approximately within the flow and geometric ranges tested.

- Vortices are unstable, randomly formed, and, for cases where air ingestion occurs, cannot be used to quantify air ingestion levels, suction inlet losses, or intake pipe fluid swirl. The full-scale tests show that for water submergences greater than 8 feet, and inlet water velocities of less than 7 ft/sec, significant vortex activity disappears.

- Based on void fraction measurements, air ingestion was found to be less than 2 percent in most cases; only highly perturbed flow conditions associated with large screen blockage and/or deliberately induced approach water swirl at low submergences and high flow resulted in high levels of air ingestion. (These tests revealed the importance of measuring void fraction and demonstrated the ineffectiveness of visual observations of vortices as a means of quantitatively evaluating air entrainment.)

- Swirl angles in suction pipes were generally found to have decreased to about 4° at 14 pipe diameters from inlets; angles of up to 7° at 15 pipe diameters from inlets were observed in tests at low submergence with induced flow perturbations.

- Hydraulic grade line measurements for all experiments revealed that the sump loss coefficient was insensitive to sump design variation. Loss coefficients are basically a function of intake geometry, and the measured values are consistent with those obtained from standard hydraulic handbooks.

- High temperature testing (up to 165°F) revealed water temperature (or previously hypothesized Reynolds number effects) had no measurable effect on surface vortexing, air ingestion, pipe swirl, or loss coefficient.

- Vortex suppressor testing revealed that cage-type and submerged grid-type designs generally (a) reduce surface vortexing from a full air-core vortex to surface swirl only; (b) reduced air ingestion to or near zero; (c) reduced pipe swirl to less than 5°; and (d) had no significant effect on loss coefficient.

- There were no major differences in the hydraulic performance of vertical outlet sumps and horizontal outlet sumps of the same geometry and flow conditions.

- Comparison of the different scale model results showed that scale modeling down to 1:4 scale, using Froude number similitude, adequately predicted the performance variables (void fraction, vortex type, swirl, and loss coefficient) of full-scale tests. Tests on 1:4, 1:2, and 1:1 scale versions of the same pump under comparable operating conditions showed no significant scale effects in the modeling of air-withdrawal due to surface vortices or in free surface vortex behavior. Additionally, swirl and inlet losses were accurately predicted by model tests providing specified Reynolds number criteria were maintained.

- A parametric assessment of nonuniform approach flow into the sump due to specific structural features did not reveal any significant adverse effects.

- Drain flow impingement on the sump water surface resulted in extensive turbulence that tended to reduce vortexing and did not lead to increased air ingestion.

- Break flow impingement tests resulted in findings similar to those for drain flow; significant air entrainment did not occur.

- Screen blockage tests, in most instances, did not reveal significant increases in air ingestion or subsequent degradation in the hydraulic performance of the sump. There were some cases where certain screen blockage schemes, up to 75 percent screen area blocked, resulted in significant air ingestion (see Figures 3.11 and 3.14). However, in each case, the use of a vortex suppressor eliminated the air-core vortex and reduced the air ingestion to zero levels. Thus, the effectiveness of vortex suppressors (even such as submerged floor gratings) has been demonstrated.

The full-scale test program has resulted in an extensive data base that has broad applicability and that can be used in lieu of model tests, or in-plant tests (provided the sump design falls within the experimental envelope investigated).

3.0 TECHNICAL FINDINGS

3.1 Introduction

Prior to the development of a plan for the resolution of Unresolved Safety Issue A-43, the following key safety questions were identified:

1. What are the performance capabilities of pumps used in containment recirculation systems, and how tolerant are such pumps to air entrainment, cavitation and the potential ingestion of debris and particulates that may pass through screens?

2. Were a LOCA to occur, would the amount and type of debris generated from containment insulation (and its subsequent transport within containment) cause significant sump screen blockage and, if so, would such blockage be of sufficient magnitude to reduce NPSH available below NPSH required?

3. Can geometric and hydraulic sump system designs be established for which acceptable sump performance can be assured?

It was recognized that resolution of USI A-43 depended upon successful responses to these questions. This effort was undertaken in three parallel tasks, each designed to respond to one of the key safety questions.

The first question was addressed through an evaluation of the general physical and performance characteristics of RHR and CSS pumps used in existing plants. Conditions likely to cause degraded performance or damage to pumps were identified, and the effects of such conditions on pump performance were evaluated. This effort was undertaken by Creare, Inc., and the results are reported in Reference 2.

The second question was addressed in three parts: (a) a survey was conducted of 19 power reactor plants concerning the quantity, types, and location of insulation used within containment; (b) detailed methods were developed for determining the quantities and sources of debris that could be generated during a LOCA. This information, used in conjunction with the development of criteria for the initiation and continuation of debris movement, allowed estimates to be made of the quantities and character of insulation debris that could potentially be transported to sump screens. (c) Calculational methods were also developed that can provide estimates of head losses as a result of such debris buildup on sump screens. This work was undertaken by Burns and Roe, Inc., and is reported in References 3, 4, and 5. Experimental determinations were made of these parameters (debris generation by jets, velocity requirements for the onset and continuation of debris migration, the phenomena of debris buildup on sump screens and associated head losses) at Alden Research Laboratory. Results of these efforts are reported in References 6 and 7.

The third key safety question was addressed in an investigation of the behavior of ECCS sumps under diverse flow conditions that might occur during a LOCA. The test program was designed to cover a broad range of geometric and flow variables representative of emergency sump designs. This work was undertaken jointly by Alden Research Laboratory, of Worcester Polytechnic Institute, and Sandia National Laboratories, and is reported in Reference 9.

3.2 Performance of Residual Heat Removal and Containment Spray System Pumps -- Technical Findings

This section summarizes the general physical and performance characteristics of RHR and CSS pumps used in a sample of existing plants. Effects likely to cause degraded performance or damage are identified, and results from an analysis of these effects on RHR and CSS pump performance are presented.

3.2.1 Characteristics of RHR and CSS Pumps

A study of pumps used in 12 operating nuclear plants has shown that although individual pump details are plant specific, the pumps used in RHR and CSS services are similar in type, mechanical construction, and performance.

Similarities in the types of pumps are shown in Table 3.1, which lists the manufacturer, model number, and rated conditions for each of the pumps utilized in the plants surveyed. The column labeled "Specific Speed" provides a parameter conventionally used by pump manufacturers to specify hydraulic characteristics and, hence, the overall design configuration of a pump. As the table shows, all pumps are in the specific speed range of 800-1600 with specific speed defined as N_s = (Speed) (Volumetric Flow)$^{1/2}$/(Head)$^{3/4}$. Thus, all are relatively high head, centrifugal pumps with nearly radial impellers.

The class of pumps used for RHR and CSS service have similarities in mechanical construction:

Table 3.1

RHR and CSS Pump Data

Plant	-------Manufacturer*/Model-------- RHR	CSS	-------Rated Conditions------- (RPM) Speed	(FT) Head	(GPM) Flow	Specific Speed
Arkansas Unit #2	I-R 6x23 WD		1800	350	3100	1238
		I-R 8x20 WD	1800	525	2200	851
Calvert Cliffs 1&2	I-R 8x21 AL		1780	360	3000	1205
		B&W 6x8x11 HSMJ	3580	375	1350	1544
Crystal River #3	W 8HN-184		1780	350	3000	1205
		W6HND-134	3550	450	1500	1407
Ginna	Pac 6" SVC		1770	280	1560	1016
Haddom Neck	Pac 8" LX		1770	300	2200	1152
		Pac 8" LX	1770	300	2200	1152
Kewaunee	B-J 6x10x18 VDSM		1770	260	2000	1222
		I-B 4x11 AN	3550	475	1300	1257
McGuire 1&2	I-R 8x20 WD		1780	375	3000	1144
		I-R 8x20 WD	1780	380	3400	1205
Midland #2	B&W 10x12x21 ASMK		1780	370	3000	1156
		B&W 6x8x135 MK	3550	387	1300	1467
Millstone Unit 2	I-R (No Model #)		1770	350	3000	1198
		G3736-4x6-13DV	3560	477	1400	1370
Oconee #3	I-R 8x21 AL		1780	360	3000	1180
		I-R 4x11 A	3550	460	1490	1380
Prairie Island	B-J 6x10x18 VDSM		1770	285	2000	1141
		I-R 4x11 AN	3550	500	1300	1210
Prairie Island 1&2	B-J 6x10x18 VDSM	I-R 4x11 AN	1780	280	2000	1156
			3550	5100	1300	1210
Salem #1	I-R 8x20W		1780	350	3000	1205
		G 3415 8x10-22	1780	450	2600	929

*Pac -- Pacific
I-R -- Ingersoll-Rand
W -- Worthington
G -- Gould
B&W -- Babcock & Wilcox
B-J -- Byron Jackson

Specific Speed is defined as N_s = Speed $(\text{Flow})^{1/2}/(\text{Head})^{3/4}$

In this definition: Speed is in rpm, flow in gpm and head in ft.

- Impellers and casings are usually austenitic stainless steel -- highly resistant to damage by cavitation, corrosion and erosion.

- Impellers are shrouded, with wear rings to minimize leakage.

- Shaft seals are the mechanical type.

- Bearings are grease or oil lubricated ball-type.

A pump assembly typical of pumps using for RHR and CSS service is shown in cross-section in Figure 3.1.

Similarities in the performance of pumps used in RHR and CSS service are shown in Figure 3.2. Performance and cavitation data from each of the pumps listed in Table 3.1 have been plotted for comparison. Performance data are given in terms of normalized head vs. normalized flow rate where the best-efficiency-point head and flow are used for the reference values. Cavitation data are given in terms of NPSH required.

3.2.2 Effects of Cavitation, Air or Particulate Ingestion, and Swirl on Pump Performance

Several items have been identified as potential causes of long- or short-term degradation of CSS and RHR pumps:

- Cavitation -- may cause head degradation and damage to impellers

- Air ingestion -- may cause head degradation

- Particulate ingestion -- may cause damage to internal parts

- Swirl at the pump inlet -- may cause head degradation

All of these effects also have the potential for inducing hydraulic or mechanical unbalanced loads.

Cavitation

Net positive suction head is defined as the total pressure at the pump inlet above vapor pressure at the liquid temperature, expressed in terms of liquid head (pressure/specific weight), and is equivalent to the amount of subcooling at the pump inlet. If the NPSH available at the pump is less than the NPSH required, some degree of cavitation is assured and some degradation of performance and perhaps material erosion is likely.

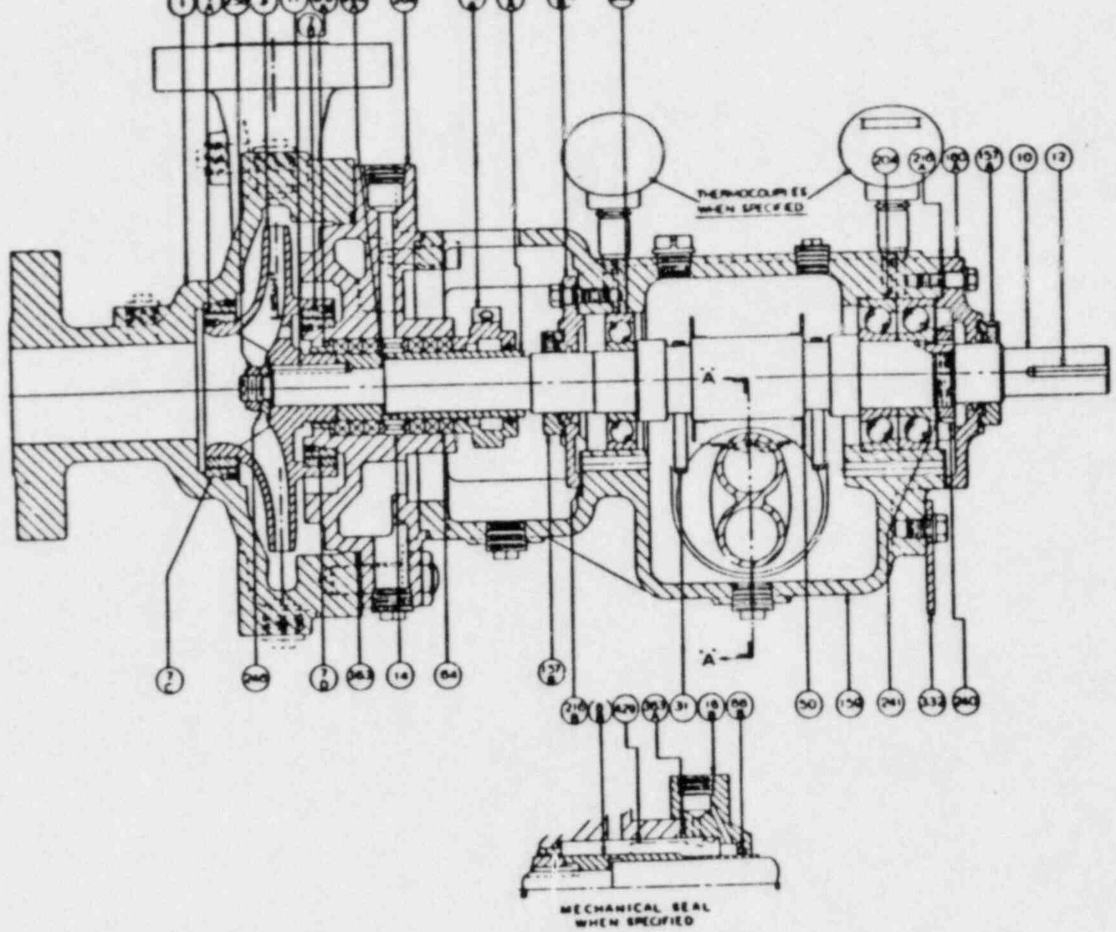

Figure 3.1. ASSEMBLY SCHEMATIC OF CENTRIFUGAL PUMP TYPICAL OF THOSE USED FOR RHR OR CSS SERVICE

RHR Pumps

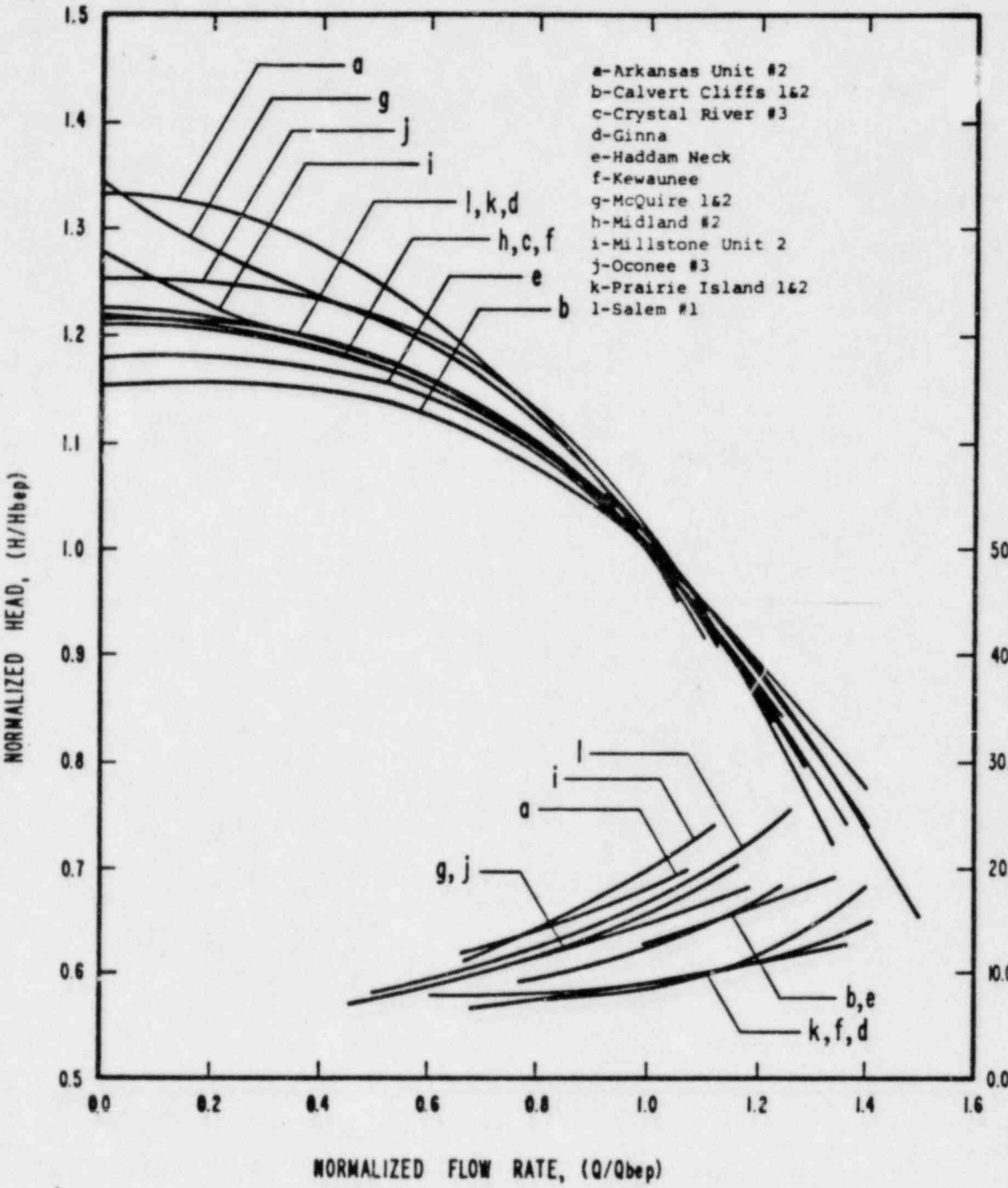

Figure 3.2a. Performance and Cavitation Curves for RHR Pumps. Head vs. Flow Rate Data Normalized by Individual Best Efficiency Point Values.

CSS Pumps

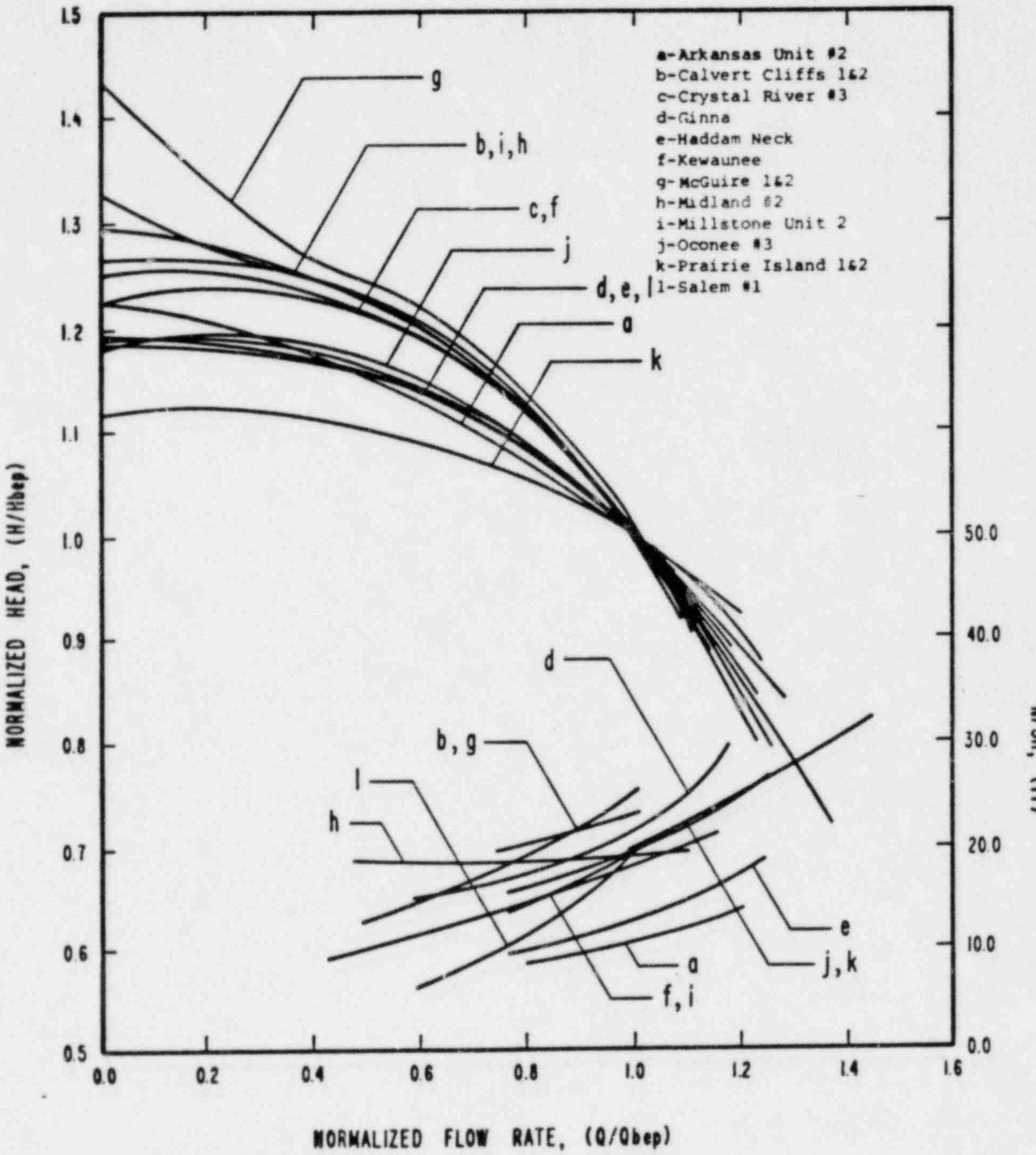

Figure 3.2b. Performance and Cavitation Curves for CSS Pumps. Head vs. Flow Rate Data Normalized by Individual Best Efficiency Point Values.

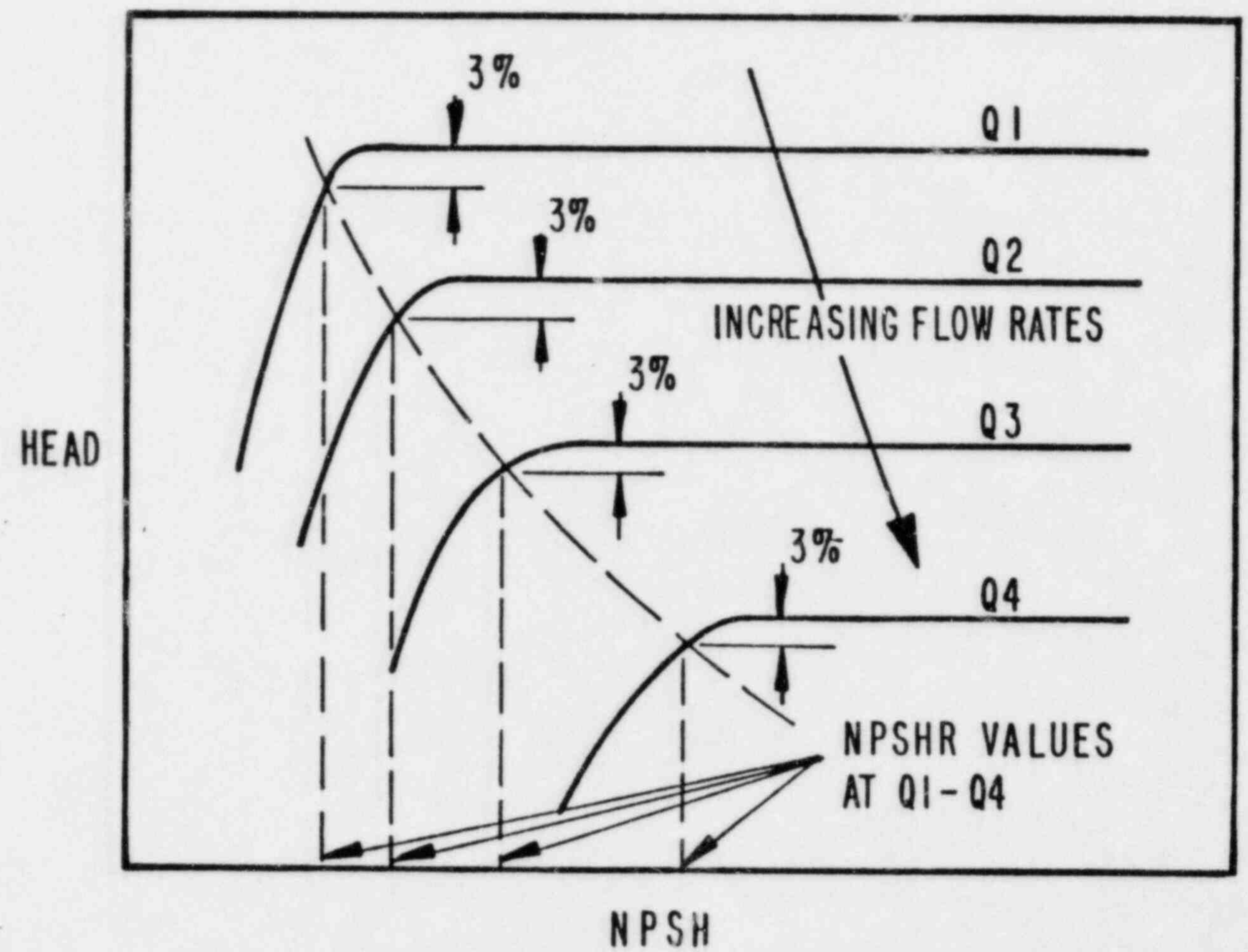

Figure 3.3. TYPICAL HEAD DEGRADATION CURVES DUE TO CAVITATION AT FOUR FLOW RATES (Q1, Q2, Q3 AND Q4

There is no fixed standard for identifying the NPSH required for a given pump. Unless stipulated by specifications, manufacturers have used some percentage (1 percent or 3 percent) in head degradation as the criterion for establishing the NPSH required at some flow condition. These are empirically established values for which very rapid degradation occurs and severe erosion is likely to occur. Figure 3.3 illustrates the changes in pump performance at several flow rates as a function of net positive suction head. (The curves are typical of those obtained by pump manufacturers to define the NPSH required for their pumps.) As NPSH is reduced for each flow rate shown (Q1-Q4), a point is reached below the 3 percent limit at which substantial degradation begins. Fluid system designers may choose to apply some margin to the NPSH requirements for a pump when designing RHR and CSS systems, but currently no standard margin between NPSH required and NPSH available has been established by NRC regulations.

Some conservatism may be introduced in the calculation of NPSH following guidelines established in RG 1.1 where no credit is allowed for increased containment pressure. However RG 1.1 does not address sub-atmospheric conditions in containment with respect to NPSH.

Cavitation behavior of pumps changes at elevated liquid temperatures. Figure 3.4 from the Hydraulic Institute Standards (Reference 10), shows that as liquid temperatures increase, less NPSH is required by the pump. As a result, increases in liquid temperature have two effects on NPSH: (1) the vapor pressure increases, which reduces NPSH available; (2) the NPSH required is reduced by an amount given in Figure 3.4.

The austentic stainless steels specified for impellers and casings in RHR and CSS pumps are highly resistant to erosion damage caused by cavitation. Erosion rates for extended operation are not significant as long as the NPSH available exceeds the NPSH requirement of the pump.

Air Ingestion

The key findings derived for RHR and CSS pumps with respect to air ingestion are based primarily on data from carefully conducted tests in air/water mixtures on pumps of a scale and specific speed range comparable to RHR and CSS pumps.* Test

*All relevant test data were gathered through reviews of technical papers and interviews with pump manufacturers. Manufacturers' test data on air/water performance of pumps are sparse, applying primarily to the development of commercial pumps for the paper industry. Although these pumps are similar to those used for RHR and CSS service, test methods and results are generally poorly documented. Therefore, manufacturers' data

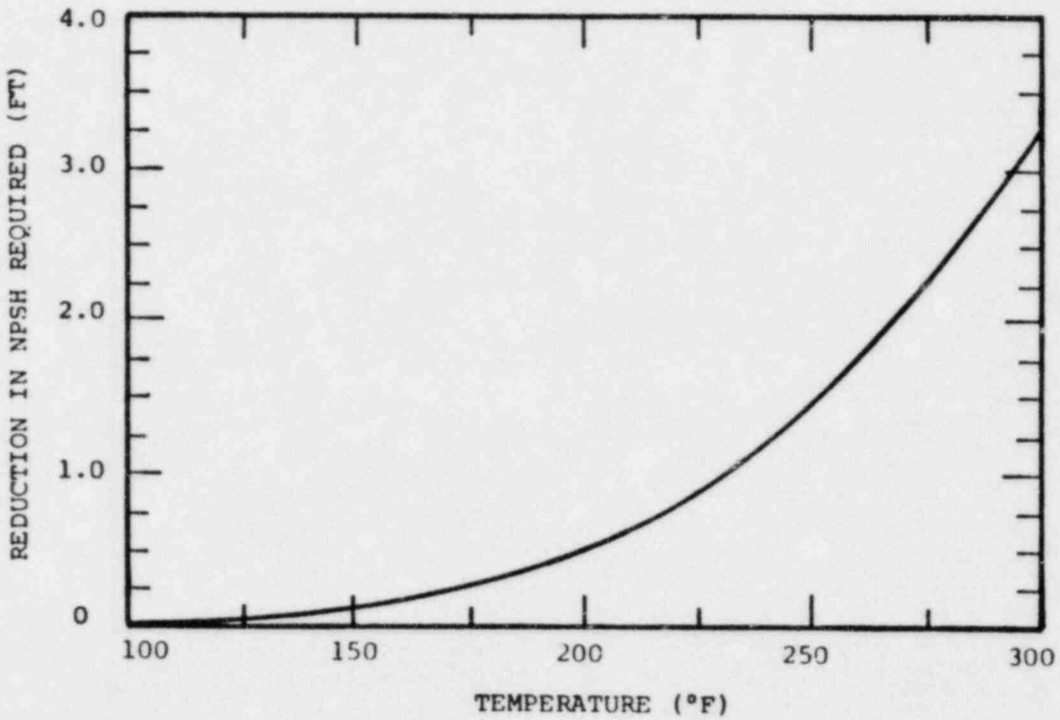

Figure 3.4. REDUCTION IN PUMP NPSH REQUIREMENTS AS A FUNCTION OF LIQUID TEMPERATURE (REFERENCE 12).

data from independent programs on different pumps have been plotted in Figure 3.5 to illustrate the degradation in head at different levels of air ingestion (percent by volume) at several operating points. Performance degradation is indicated by the ratio of the two-phase (air/water) pressure rise to the single-phase (water) pressure rise.

Figure 3.5 shows that for low levels of air ingestion, the degradation in pump head follows the curve (dashed line) predicted by the change in average fluid density due to the air content. Above 2 percent void fraction, the data depart from this theoretical line and the rate of degradation increases.

Above void fractions of about 15 percent, pump performance is almost totally degraded. The degradation process between 2 and 15 percent void fraction is dependent on operating conditions, pump design, and other unidentified variables. (These findings closely approximate the guidelines empirically established by pump manufacturers: at air ingestion levels of less than 3 percent, degradation is generally not a concern; for air ingestion levels of approximately 5 percent, performance is pump and site dependent; for an ingestion greater than 15 percent, the performance of most centrifugal pumps is fully degraded.)

For CSS or RHR pump operation at very low flow rates (< about 25 percent of best efficiency point) even small quantities of air may accumulate resulting in air "binding" and complete degradation of pump performance.

Combined Effects of Cavitation and Air Ingestion

Few data on the combined effects of cavitation and air ingestion are available. Figure 3.6, using test results from Reference 11, shows that as air ingestion rates increase, the

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have not been used to establish the air/water performance characteristics of pumps in this report. (Manufacturers' data and testimonials do, however, corroborate published data.) Only sources of information meeting the following criteria were used:

- Subject pumps must be low specific speed (N_s = 800-2000)
- Subject pumps must be of "reasonable" design -- pumps having efficiencies of $\geq$60 percent and impellers >6" diameter.
- Reasonable care must have been used in experimental techniques and in the documentation of results.

Test results meeting these criteria were then reduced to common, normalizing parameters and plotted for comparison.

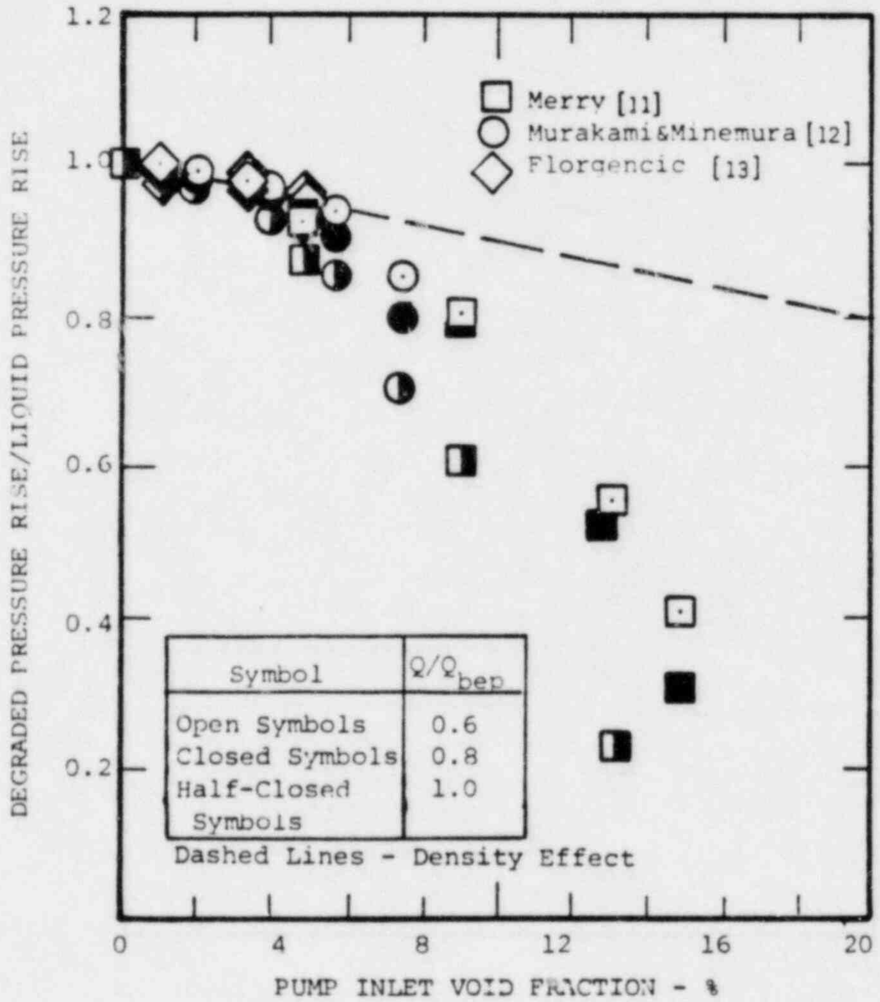

Figure 3.5. HEAD DEGRADATION UNDER AIR INGESTING CONDITIONS AS A FUNCTION OF INLET VOID FRACTION (% OF TOTAL FLOW RATE BY VOLUME).

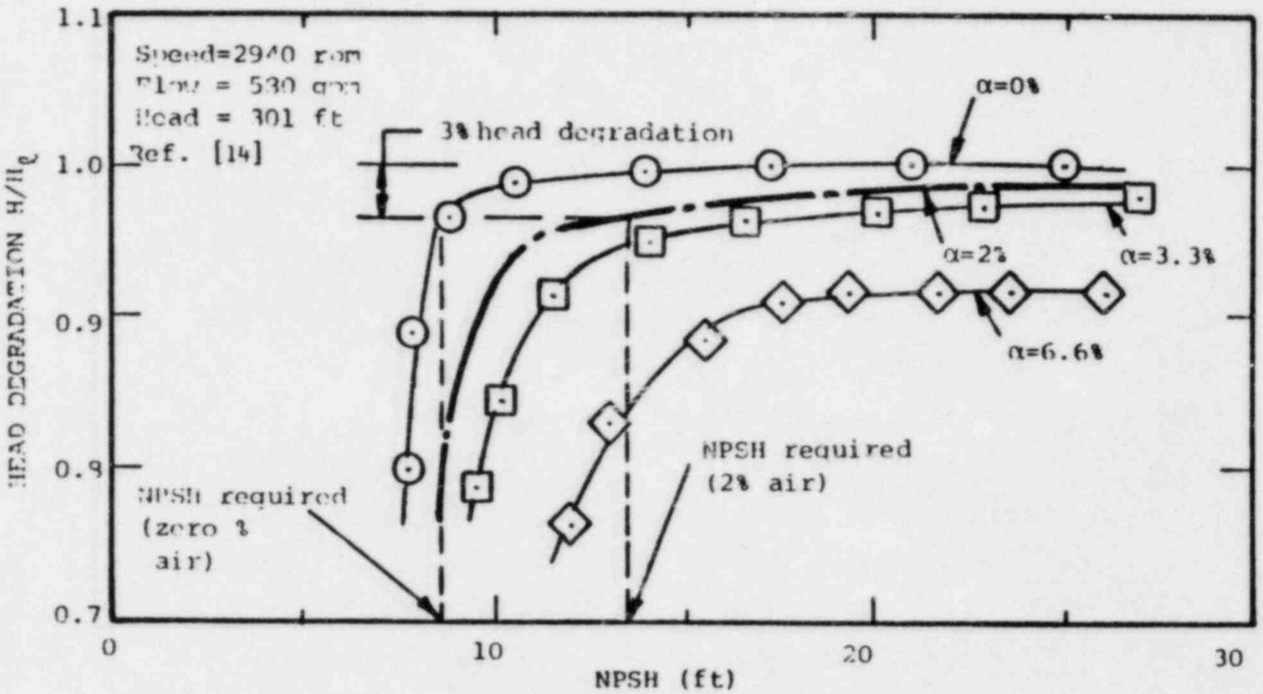

Figure 3.6. EFFECT OF AIR INGESTION ON NPSH REQUIREMENTS FOR A CENTRIFUGAL PUMP.

NPSH requirement for a pump also increases. The curves for this particular pump show that air ingestion levels of about 2 percent results in a 50 percent increase in the NPSH required (allowed head degradation based upon 3 percent degradation from the liquid head performance).

Particulate Ingestion

The assessment of pump performance under particulate ingesting conditions is based on estimates of the type and concentrations of debris likely to be transported through the screens to the pump inlet. In the absence of comprehensive test data to quantify types and concentrations of debris which will reach the pumps it has been estimated that concentrations of fine, abrasive precipitated hydroxides are of the order of 0.1 percent by mass and concentrations of fibrous debris are of the order of 1 percent by volume.* The effects of particulates in these quantities has been assessed on the basis of known behavior of this type pump under similar operating circumstances.

Ingestion of particulates through pumps is not likely to cause performance degradation for the quantities and types of debris estimated above. Due to the presence of upstream screens, particulates likely to reach the pumps should be small enough to pass directly through the minimum cross-section passages of the pumps. Because of generally low pipe velocities on the pump suction side, particulates reaching the pumps should be of near neutral buoyancy and, therefore, behave like the pump fluid.

Manufacturers tests and experience with these types of pumps have shown that abrasive slurry mixtures up to concentrations of 1 percent by mass should cause no serious degradation in performance. Similarly, tests on pumps of similar construction to evaluate the capability of pumps of this type to handle fibrous paper stock have shown that quantities up to 4 percent should cause no appreciable degradation.

A major concern in the effects of particulates on performance and operability of the pumps has been the effects of fibrous or other debris (such as paint chips) on pump seal systems. It is possible that porting within cyclone separators

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*The concentration for abrasive AlO(H) was obtained from Reference 16 where 3000 pounds of precipitate was estimated to develop in 30 days and recirculate with 3.7 million pounds of water (Reference 16). The 1 percent by volume concentration of fibrous debris is based on the quantity of fibrous insulation reaching the sump screens from Maine Yankee plant (Table 3.6) mixing with 200,000 gallons from RWST and being recirculated through the pumps.

and in the flush ports for mechanical shaft seals may become clogged with debris. In such an event, seal failure is likely. However, the construction of mechanical face seals used in these pumps is such that complete pump degradation failure is not likely even in the event of seal failure.

Swirl

The effects of swirl due to sump vortices on pump performance are negligible if the pumps are located at significant distances from sumps. Tests discussed in Section 3.4 of this report indicate that swirl angles in the suction pipe 14 pipe-diameters from the outlet of the sump were typically 4° (swirl will decay with distance in a pipe). RHR and CSS pumps are generally preceded by valves, elbows, and piping with characteristic lengths on the order of 40 or more pipe diameters; this system of piping components is more likely to determine the flow distributions (swirl) at the pump inlet than is the swirl caused by sump hydraulics. For pumps with inlet bells directly in the sumps, vortices and accompanying swirl in the inlet bell can cause severe problems, due to asymmetric hydraulic loads in the impeller. This configuration should be avoided.

3.2.3 Calculation of Pump Inlet Conditions

Given the findings noted above, the following steps outline the resulting calculational procedure for assessing the inlet conditions to the pump. The procedure follows routine calculation methods used for estimation NPSH available, except that steps are also incorporated which allow for air ingestion effects. Figure 3.7 shows a schematic of the pump suction system with appropriate nomenclature.

1. Determine the hydrostatic water pressure (gage), P_{sg}, at the sump suction inlet centerline, accounting for temperature dependency and minimum water level.

2. Based on the sump hydraulic assessment, determine the potential level of air ingestion at the sump suction pipe α_s, as discussed in Section 5.2.

3. Calculate the pressure losses in the suction pipe between the sump and the pump inlet flange. Pressure losses are calculated for each suction piping element (i.e., inlet loss, elbow loss, valves, pipe friction) using the average velocity through each element V_i, and a loss coefficient, K_i, for each element. The total pressure losses are then:

$$P_\ell = (\gamma/144) \sum K_i V_i^2/2g$$

where γ is the specific weight of water (lb/ft^3) and 144 is the conversion from psf to psi.

The loss coefficients are defined as:

$$K_i \equiv \frac{h\ell_i}{V_i^2/2g}$$

where: $h\ell_i$ is the head loss in ft of water in element i,

g is the acceleration due to gravity, and

V_i is the average velocity in element i in fps.

Loss coefficients can be found in standard hydraulic data references such as found in Reference 10.

4. Calculate the absolute static pressure at the pump inlet P_p.

$$P_p = P_{sa} - P_\ell + P_h - P_d$$

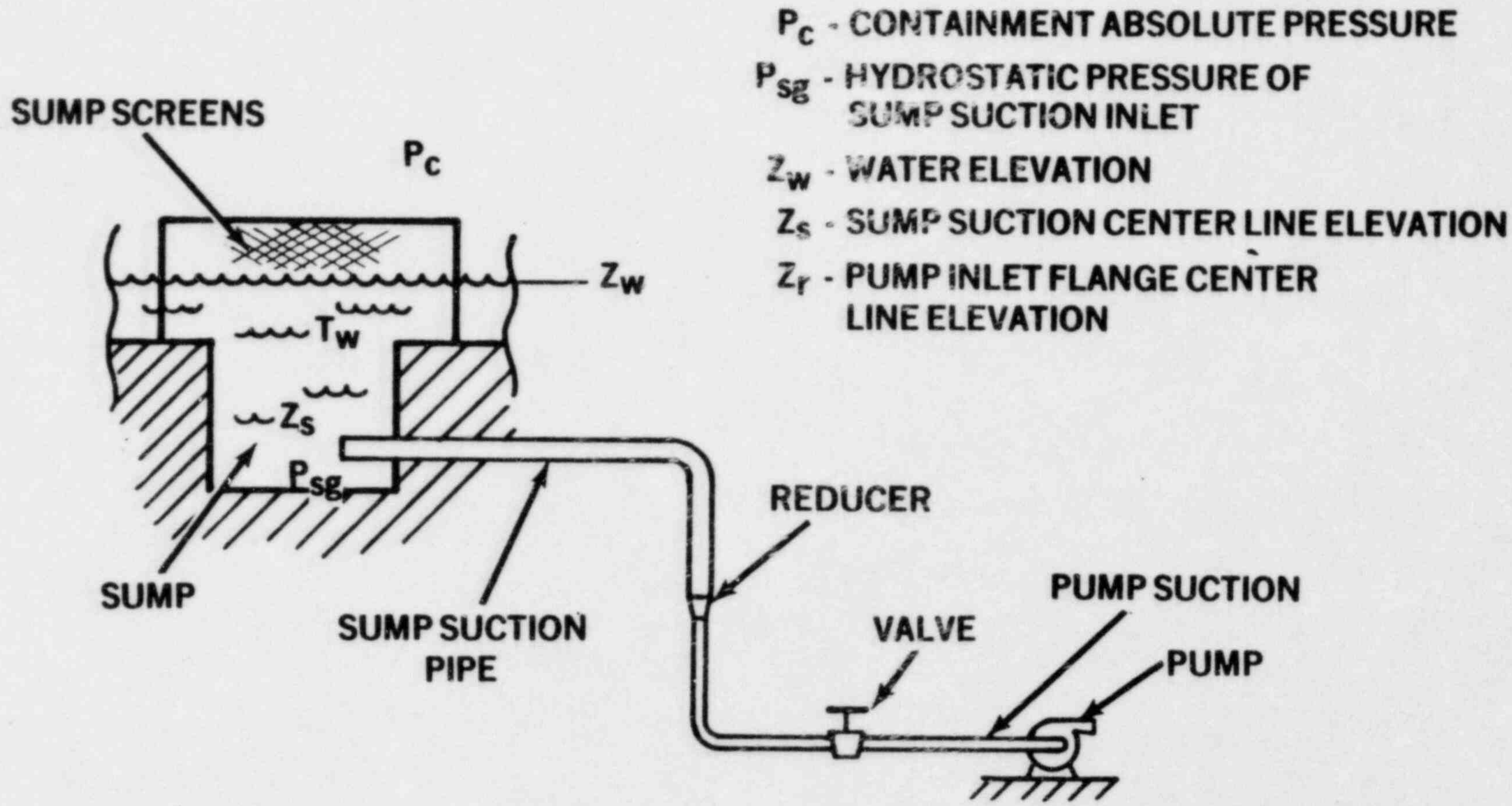

Figure 3.7. Schematic of Suction Systems for Centrifugal Pump

where: P_{sa} is the total absolute pressure at the sump suction pipe centerline which is the sum of the hydrostatic pressure, P_{sg}, and the containment absolute pressure, P_c, (determined in accordance with RG 1.1 and 1.82 for NPSH determination).

P_ℓ is the suction loss determined in Step 3.

P_h is the hydrostatic pressure due to the elevation difference between the sump suction pipe centerline, Z_s, and the pump inlet flange centerline, Z_p.

$$P_h = (\gamma /144)\ (Z_s - Z_p)$$

P_d is the dynamic pressure at the pump inlet flange using the average velocity at the pump suction flange, V_p.

$$P_d = \frac{\gamma}{144}\ \frac{V_p^2}{2g}$$

The value for P_p will be used to correct the volumetric flow rate of air at the sump suction pipe for density changes. If air ingestion is zero, Steps 4, 5 and 6 can be ignored.

5. Calculate the corrected air volume flow rate at the pump inlet, α_p, based on perfect gas, isothermal process:

$$\alpha_p = (P_{sa}/P_p)\alpha_s$$

6. If α_p is greater than 2 percent, inlet conditions are not acceptable.

7. Calculate NPSH at the pump inlet flange, taking into account requirements of RG 1.1 and 1.82.

$$NPSH = (P_c + P_{sg} - P_\ell + P_h - P_{vp})\ (144/\gamma)$$

where P_{vp} is the vapor pressure of the water at evaluation temperature.

8. If air ingestion, α_p, is not zero, NPSH required from the pump manufacturer's curves must be modified to account for air ingestion.

$$\beta = 0.50\ (\alpha_p) + 1.0$$

where α_p is the air ingestion level percent by volume at the pump inlet flange. Then:

NPSH required (air/water) = β x (NSPH required for water)

9. If NPSH from Step 7 is greater than NPSH required from Step 8, pump inlet conditions should be satisfactory.

3.3 Debris Assessment

The safety concerns related to LOCA generation of debris resulting from the breakup of thermal insulation, and the potential for sump screen blockage were addressed generically as follows:

1. A survey of nineteen reactor power plants was conducted to identify insulation types used, quantities and distribution, methods of attachment, components and piping insulated, variability of plant layouts, sump designs and location.

2. A calculational procedure was developed for estimating quantities of insulation which the pipe break jet might destroy or dislodge, for estimating debris migration during the recirculation mode and for estimating the degree of screen blockage that might occur. A series of engineering models were established and concise review methods were developed.

3. The debris calculational methods described in 2, above, were then applied to five PWRs to determine the influence of various types of insulations and plant layout effects (i.e., sump location versus break location). In addition, the calculational methods and results obtained were subjected to external, independent technical review (i.e., peer panel reviews).

4. Experiments were conducted to establish the onset of insulation debris generation from typical mineral wool and fiberglass insulations, their buoyancy and migration characteristics, and the potential of such insulations and their debris to create screen blockage.

The results are summarized in the following subsections.

3.3.1 Plant Insulation Survey Findings

Table 3.2 lists the plants surveyed.

The results of these insulation surveys are summarized in Table 3.3, wherein tabulations of the respective insulations are made for the respective plants and comparison of the

TABLE 3.2

Reactor Plants Selected for Insulation Survey

Plant and Location	Reactor	Rating	Start-Up Date	Utility	Architect/Engineer
Oconee Unit 3 Seneca, SC	B&W-PWR	860 MWe	1974	Duke Power Co.	Duke Power Co.
Crystal River Unit 3 Red Level, FL	B&W-PWR	825 MWe	1977	Florida Power Corp.	Gilbert
Midland Unit 2 Midland, MI	B&W-PWR	805 MWe	1983*	Consumers Power Co.	Bechtel
Haddam Neck Haddam Neck, CT	W-PWR	575 MWe	1968	Connecticut Yankee Atomic Power Co.	Stone & Webster
Robert E. Ginna Ontario, NY	W-PWR	490 MWe	1970	Rochester Gas & Electric Corp.	Gilbert
H. B. Robinson Hartsville, SC	W-PWR	665 MWe	1971	Carolina Power & Light Co.	Ebasco
Prairie Island 1 & 2 Red Wing, MN	W-PWR	520 MWe	1973¶	Northern States Power Co.	Fluor Power Services
Kewaunee Carlton, WI	W-PWR	535 MWe	1974	Wisconsin Public Services Corp.	Fluor Power Services
Salem Unit 1 Salem, NJ	W-PWR	1090 MWe	1977	Public Service Electric & Gas Co.	Public Service Electric & Gas Co.
McGuire Units 1 & 2** Gowans Ford, NC	W-PWR	1180 MWe	1981*	Duke Power Co.	Duke Power Co.

*Estimated dates

**Unit 2 estimated start-up date is 1983
Source: Nuclear News, February 1981

¶Unit 2 start-up date is 1974
Source: Nuclear News, August 1981

TABLE 3.2 (Continued)

Plant and Location	Reactor	Rating	Start-Up Date	Utility	Architect/Engineer
Sequoyah Unit 2 Daisy, TN	W-PWR	1148 MWe	1982*	Tennessee Valley Authority	Tennessee Valley Authority
Maine Yankee Wiscassett, ME	CE-PWR	790 MWe	1972	Maine Yankee Atomic Power Co.	Stone and Webster
Millestone Unit 2 Waterford, CT	CE-PWR	870 MWe	1975	Northeast Utilities	Bechtel
St. Lucie Unit 1 Hutchinson Island, FL	CE-PWR	777 MWe	1976	Florida Power & Light Co.	Ebasco
Calvert Cliffs Units 1 & 2 Lusby, MD	CE-PWR	850 MWe	1975**	Baltimore Gas & Electric Co.	Bechtel
Arkansas Unit 2 Russellville, AR	CE-PWR	858 MWe	1980	Arkansas Power & Light Co.	Bechtel
Waterford Unit 3 Taft, LA	CE-PWR	1165 MWe	1983*	Louisiana Power & Light Co.	Ebasco
Cooper Brownsville, NB	GE-BWR I	778 MWe	1974	Nebraska Public Power District	Burns and Roe
WPPSS Unit 2 Hanford, WA	GE-BWR II	1150 MWe	1983*	Washington Public Power Supply System	Burns and Roe

*Estimated dates

**Unit 2 start-up date is 1977

Source: Nuclear News, August 1981

TABLE 3.3

Types and Percentages of Insulation Used Within the Primary Coolant System Shield Wall in Plants Surveyed

Plant	Types of Insulation and Percentage*					
	Reflective Metallic	Totally Encapsulated	Mineral Fiber/Wool Blanket	Calcium Silicate Block	Unibestos Block	Fiberglass
Oconee Unit 3	98	--	--	--	--	2
Crystal River Unit 3	94	5	1	--	--	--
Midland Unit 2	78	--	--	--	--	22
Haddam Neck	3	--	--	--	95¶	1
Robert E. Ginna	--	--	5	80	10	--
H. B. Robinson	--	--	--	15	85	--
Prairie Island Units 1 & 2	98	--	--	--	--	2
Kewaunee	61	--	--	--	39	--
Salem Unit 1	39	8	53**	--	--	--
McGuire Units 1 & 2	100	--	--	--	--	--
Sequoyah Unit 2	100	--	--	--	--	--
Maine Yankee	13	--	48	25	13	1
Millstone Unit 2	25	35	5	30	--	--
St. Lucie Unit 1	10	--	--	90	--	--
Calvert Cliffs Units 1 & 2	41	59	--	--	--	--
Arkansas Unit 2	46	53	--	--	--	1
Waterford Unit 3	15	85	--	--	--	--
Cooper	30	70	--	--	--	--
WPPSS Unit 2	100	--	--	--	--	--

*Tolerance is ± 20 percent

**Both totally and semi-encapsulated Cerablanket is used, however, inside containment only totally encapsulated is employed.

¶Unibestos is currently being replaced by Calcium Silicate. However, both types of insulation have the same sump blockage characteristics.

respective amounts of insulations used in a particular plant is provided on a percentage basis. Additional detailed information for each plant surveyed has been assembled into reference data packages and has been published as NUREG/CR-2403 and NUREG/CR-2403, Supplement No. 1 (References 3 and 4). These reports detail the types and amounts of insulation employed, their location in containment, components insulated, material characteristics, methods of installation, etc. In addition, the plant sump designs and screen details are provided in simplified drawings for ease of reference. Appendix A of this report illustrates the plant specific sump designs and plant layouts; the variability plant-to-plant is quite evident. Plant design information was obtained for plants representative of the 4 U.S. light water reactor vendors and the selected sample consisted of plants designed by 8 U.S. architect-engineering firms. New and old plants were surveyed.

The types of insulation employed in nuclear power plants are as follows:

1. Reflective metallic insulation, generally constructed from stainless steel, although aluminum internal foils have also been used.

2. Totally encapsulated insulation panels which utilize more effective thermal insulators (e.g., mineral wool fiber, fiberglass, calcium silicate, etc.). The principal point of distinction is that the encapsulation material (i.e., stainless steel) provides a container that is resistant to break jet forces and promotes the maintenance of the insulation in large blocks.

3. Nonencapsulated insulations (e.g., mineral wool, fiber wool, calcium silicate blocks, fiberglass blankets, unibestos block, etc.) which, if directly impacted by the break jet and subsequently immersed in the steam-water environment within containment, can be viewed to pose screen blockage problems and must be evaluated.

The plant variability and selection/utilization variability noted above preclude a singular generic debris assessment. Rather, the prevalant situations lead to the necessity of developing logical and consistent debris calculational methods for assessment and quantification of debris generated and screen blockage severity. The following subsection outlines calculational methods and models for systematically performing debris calculations. Past evaluations have relied to a great extent on R.G. 1.82 which addresses an assumed acceptable limit of 50 percent screen blockage, but does not require an engineering estimate of the amounts of insulation debris which a LOCA might generate, nor an assessment of the attendent sump screen blockage.

3.3.2 Calculational Methods for Assessing Debris Hazards

The calculational methods described herein were developed by Burns & Roe, Inc., engineering staff and are applicable for analyzing the diversity of plant layouts, sump locations, insulation types and piping runs typified by the plant surveys conducted (see Section 3.3.1 and Appendix A).

These calculational methods (which are described in greater detail in Reference 5) provide an analysis tool which allows a systematic estimation of the quantities of debris generated. The assumption is made at the outset that the postulated pipe ruptures are those defined in NRC's Standard Review Plan (NUREG-0800), Section 3.6.2, and use is made of an accepted break jet model provided in Reference 17. In the treatment given here, the jet model has been modified to provide more conservatism in the results. In addition, jet impingement effects are calculated*, short-term transport due to blowdown forces and long-term transport due to the flow of recirculated water are estimated as is the screen blockage by debris.

As can be expected, plant layout, types of insulation employed, and quantities thereof are the controlling inputs. Since the majority of postulated rupture locations (PRLs) are located within the crane wall region, and attention to that portion of the plant is required. Reflective metallic insulations will sink and transport will be along the plant flows. Low density insulation (if non-hygroscopic) will float and migrate to the screens--but will not cause blockage if water levels are high enough. Nonencapsulated insulations will be subjected to direct high temperature, high pressure water and steam jets. Destruction, dispersion and displacement will likely occur. Encapsulated insulation sections will tend to maintain a geometric structural shape which is large, and although migration could occur, a densely packed (or blocked) screen situation is less likely. The insulation material of primary concern is the nonencapsulated, or free (due to jet breakup) fibrous insulation as characterized by mineral wool, fiber glass, wool blanket materials. It has been demonstrated

*In recent NRC supported research of two-phase jet phenomena and jet loads (References 18 and 19) stagnation pressure in two-phase jets and pressure loading on two-dimensional targets were investigated. This research has shown that the target load depends upon the thermodynamic conditions immediately upstream of the break and the distance to the target. For highly subcooled vessel conditions a potential exists for extremely high pressures (greater than 2000 psia for PWRs) on targets within several diameters of the break.

(References 7,14 and 15) experimentally that free fibers and shreds can migrate (at near neutral buoyancy) to the screens where they can adhere and form layers sufficiently thick to result in significant screen blockages with high attendant pressure drops.

These methods for sequential evaluation are outlined in Figure 3.8, Sheets 1, 2, 3 and 4 in which the respective steps described below are identified.

STEP 1 -- Identification of the number, orientation, and location of the PRL to be analyzed. These postulated pipe ruptures are defined in the NRC Standard Review Plan, Section 3.6.2, which provides guidance for selecting the number, orientation, and location of the postulated ruptures within containment.* In general, PRLs are selected for analysis as follows:

1. All PRLs which are identified in the Final Safety Analysis Report (FSAR)
2. From PRLs identified, select breaks that are:
   a) located in large diameter, high energy lines
   b) oriented toward principal sources of insulation (steam generators, coolant pumps, pressurizers, hot legs, cold legs, cross-over piping, etc.).
3. Four or five breaks are selected for further analysis by noting jet travel direction for unrestrained or restrained pipes and breaks are selected that project insulation toward the sump area. (Breaks dislodging the greatest amount of insulation that will be transported toward the sump should be selected without regard for initial transport direction).

STEP 2 -- Estimation of the amount of insulation debris that might be generated by postulated pipe rupture. Debris is generated by three mechanisms:

1. Jet Impingement -- generates debris by subjecting the insulation to a high velocity, high differential pressure field that strips the insulation from the target.

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*For plants that have already filed FSARs, the design basis break locations inside containment have been tabulated and may be found in FSAR, Section 3.6.2, for plants filing FSARs under the revised format. Information for FSAR plants that filed prior to the revised format effective date may be found in Accident Analysis (Chapter 15), Design of Structures, Components, Equipment and Systems (Chapter 3), and Engineered Safety Features (Chapter 6 or an Appendix).

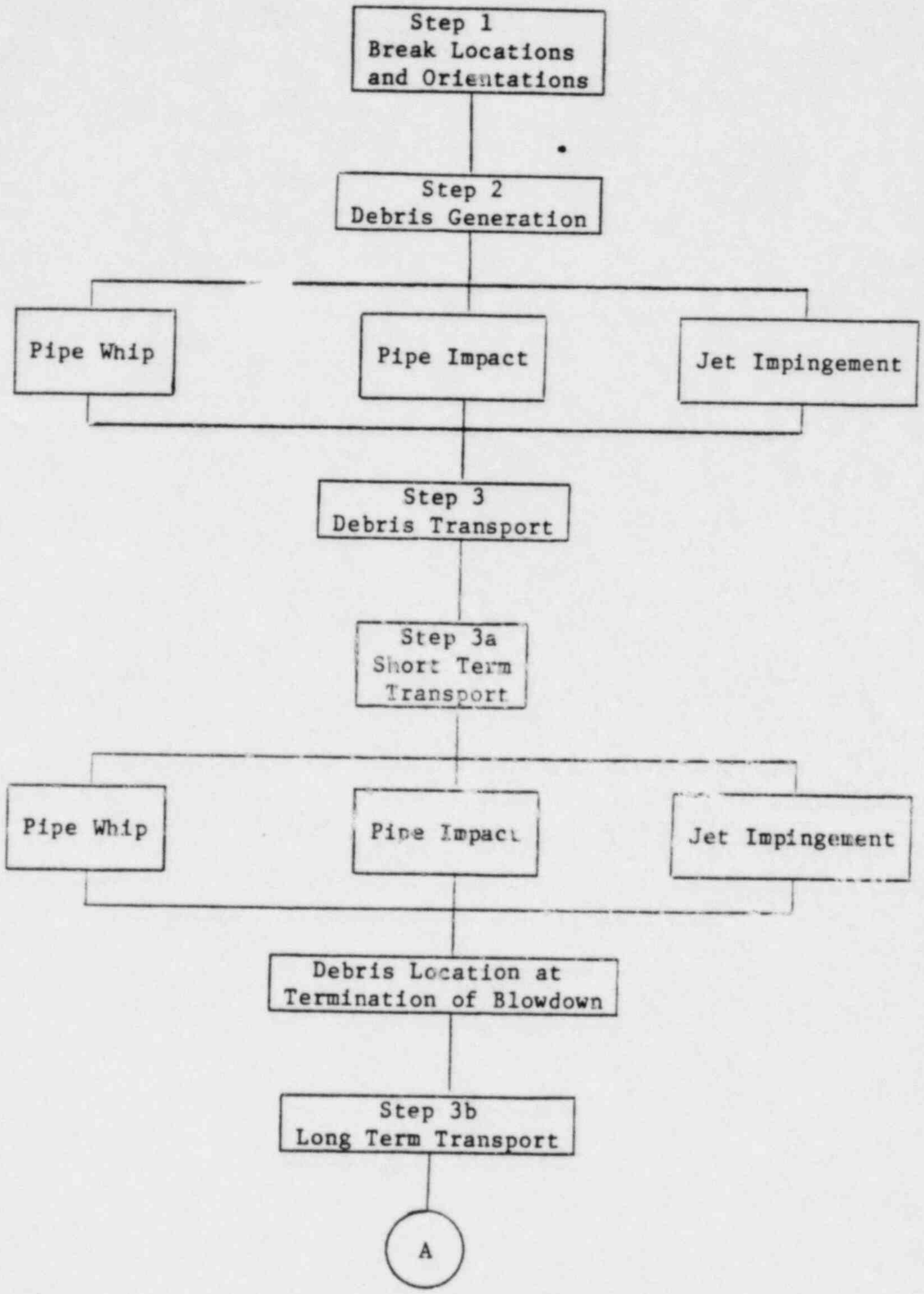


Figure 3.8 - Sheet 1
Outline of Methods

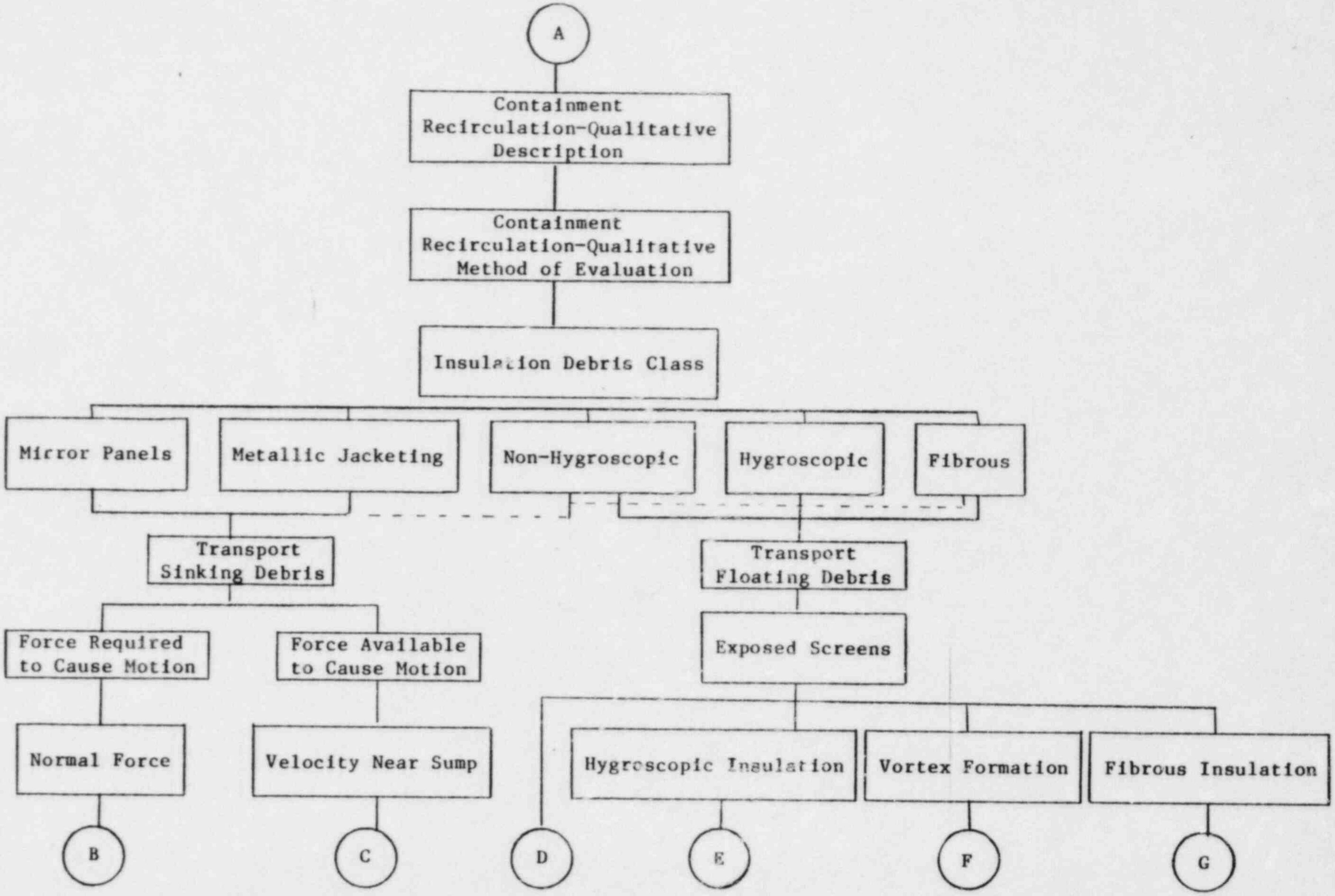


Figure 3.8 - Sheet 2
Outline of Methods

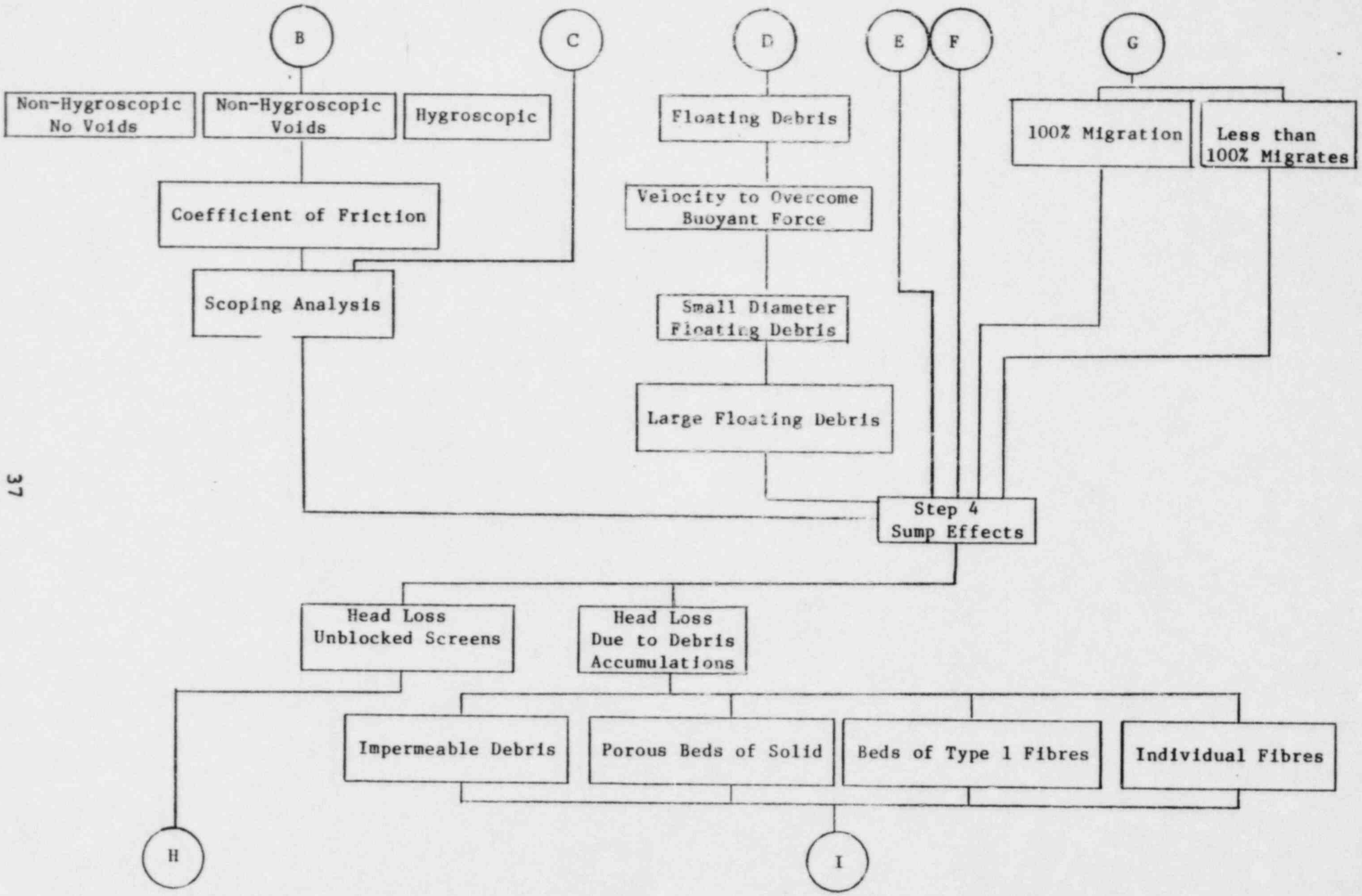


Figure 3.8 - Sheet 3
Outline of Methods

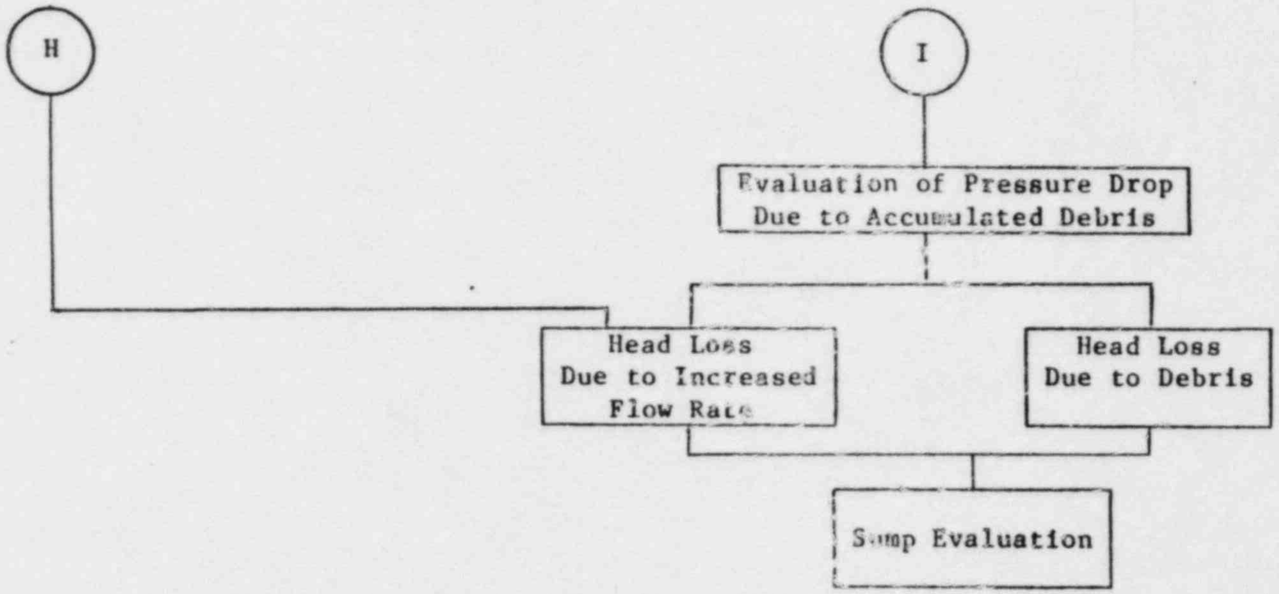


Figure 3.8 - Sheet 4
Outline of Methods

This is the principal debris generation mechanism (i.e., 90 percent of debris generated).

2. Pipe Whip -generates insulation debris due to the motion of unrestrained piping segments.

3. Pipe Impact -- generates additional insulation debris by the impact of unrestrained piping segments with insulated structures, components, or other piping systems.

Specific methods for calculating the amount of debris generated by each mechanism are given in Reference 5. Methods for calculating the magnitude of jet thrust, jet impingement forces, stagnation pressure as a function of distance, and other hydrodynamic effects were adapted from Standard Review Plan, Section 3.6.2, and engineering handbooks.

STEP 3 -- Calculation of short-term and long-term transport of insulation debris.

1. Short term transport -- debris motion caused by pipe whip, pipe impact, jet impingement mechanisms -- terminates at the end of the blowdown transient.

   Velocities of debris caused by pipe whip and pipe impact are assumed to cause motion in a straight line that continues until impact with walls or other obstructions. Debris then drops vertically to floors, grates, or other structures.

   Debris generated and entrained into the jet by jet impingement will not stop upon impact with obstructing structures, but will change direction. Consequently, debris can pass through doorways or other openings not directly in line with pipe breaks. The jet force at an obstruction is determined using the stagnation pressure equation (Reference 5).

2. Long-term transport -- begins with activation of the containment recirculation system. Fluid velocity, debris density, debris size, and effects of coolant on debris integrity are analyzed to determine if long-term transport could occur. For debris transport, the migration patterns of dislodged insulation within containment are established. Insulation debris may be typed either as Sinking (mirror panels, metallic jacketing or hygroscopic insulation with equilibrium densities greater than that of water) or Floating (non-hygroscopic, hygroscopic, fibrous).

Sinking Debris -- will be transported to the sump if the water velocity is sufficient to overcome drag force. The analysis considers the hydrodynamic forces needed to move debris on the containment floor to the sump inlet, and determines the local velocities that exist within containment. Experimental studies allow estimates of those velocities required to transport insulation debris to sump screens.

Floating Debris -- is assumed to migrate to the sump. The possibility of sump blockage is determined by evaluating the local velocity required to overcome the buoyant force of the debris and comparing this value to the local velocity existing at the sump. The floating debris model is valid also for predicting the behavior near sump intakes of floating fibrous insulation. Suspended fibrous debris is assumed to migrate to the sump. The effect of blockage is determined by evaluating the pressure drop across the resulting debris mat formed on the sump screen.

STEP 4 -- Determination of Screen Blockage and Attendant Pressure Drops. The results of Steps 1 through 3 can now be used to estimate the extent of screen blockage that might occur due to debris migration. These debris migration models can be used to estimate screen blockages in terms of the quantities of debris transported and screen blockage patterns can be deduced. Attendant pressure drop is the critical parameter for determining effects on required pump NPSH. Careful consideration should be given to head losses for blocked screens. In the calculation of blockage by fibrous debris, the equivalent insulation blockage thickness (t_i), should be calculated as:

$$t_i = \frac{\text{Volume of debris transported}}{\text{Available Screen Area}} .$$

Pressure drop calculations, using the above relationship, have been made on two selected examples where blockage has been calculated to be total (Salem Unit I and Maine Yankee). Such calculations, provided in Reference 5, have made use of the methods and assumptions present in the referenced report. In the estimation of pressure drops at sump screens due to fibrous insulation debris, the methods provided in Reference 5 are applicable. However, the pressure drop versus insulation debris thickness information developed experimentally should be used in calculations of sump acceptability (Reference 7).

These four steps of the debris analysis provide a conservative method for evaluating the potential for generation of insulation debris in a power reactor station, the potential for blockage of the sump screens due to LOCA-generated insulation debris, and for assessing the impact of insulation debris on sustained operation of the containment recirculation system. They provide a set of methods for assessing the potential safety hazard of insulation debris and can be used to aid in assessing debris effects (screen blockage) in any reactor primary containment.

3.3.3 Application of Methods to 5 Sample Plants

The methods described in the previous section were applied to 5 plants selected from the 19 originally surveyed. Sample calculations were performed to prove the methods and to identify any problem areas for plant or insulation types. Plants of varying design with different insulation inventories were selected. Table 3.4 summarizes these plants by type, owner, location, size, and architect/engineer. Tables 3.2 and 3.3 summarize the types of insulation present in each plant. The tables show that a broad spectrum of insulation types, both singly and in combinations, were found to be in use.

Table 3.5 describes the location of the emergency sump, summarizes the location of the various types of insulation in the plant, and provides an assessment of the migration potential of debris generated as a result of a pipe break, as derived from the development provided in Reference 5.

Table 3.6 summarizes, for each plant, the PRLs, the quantities of debris generated, the quantities of debris transported to the sump screens, unblocked screen areas, blocked screen areas, and the percentages of sump inlet areas that are blocked; the table concludes with a qualitative indication of the severity of the potential sump blockage. The estimates provided in this summary derive from Reference 5.

Although the estimated quantities of debris and attendant screen blockages show a high variability, the findings are quite revealing. Large quantities of debris are estimated to be produced. This results from the conservative assumption that all jet-targeted insulation is stripped and conservative assumptions as to transport to the sump. In addition, calculated screen blockages vary due to sump screen variability and the screens. Screen blockages in excess of 50 percent (see the Sequoyah #2 results) have been calculated. However, adverse screen pressure drops at Sequoyah have been determined to be negligible, since Sequoyah utilizes all reflective metallic insulation. Plants having large screen areas (i.e., Salem

TABLE 3.4

Reactor Plants Selected for Detailed Investigation of Insulation Debris Generation Potential

Plant and Location	Reactor	Rating	Start-Up Date	Utility	Architect/Engineer
Maine Yankee Wiscassett, ME	CE-PWR	790 MWe	1972	Maine Yankee Atomic Power Co.	Stone and Webster
Arkansas Unit 2 Russellville, AR	CE-PWR	858 MWe	1980	Arkansas Power & Light Co.	Bechtel
Salem Unit 1 Salem, NJ	W-PWR	1090 MWe	1977	Public Service Electric & Gas Co.	Public Service Electric & Gas Co.
Sequoyah Unit 2 Daisy, TN	W-PWR	1148 MWe	1982*	Tennessee Valley Authority	Tennessee Valley Authority
Prairie Island Unit 1 Redwing, MN	W-PWR	520 MWe	1973	Northern States Power Co.	Fluor Power Services

*Estimated date

TABLE 3.5

Summary Table for 5 Plant Sample Calculations

Plant and Reactor Manufacturer	Type of Insulation Utilized	Location of Emergency Sump	Final Assessment of Migration Potential of Debris Generated as a Result of a Pipe Break
Maine Yankee (CE) (Conbustion Engineering)	Reactor vessel uses reflective metallic insulation. Pressurizer, reactor coolant pumps, and steam generators use calcium silicate molded block jacketed insulation for nonremovable sections and mineral fiber/wool for the removable sections. Primary coolant piping uses removable mineral fiber/wool blankets. Main steam, feedwater, residual heat removal, and chemical and volume control system piping use calcium silicate or unibestos molded block insulation. Component cooling lines use fiberglass jacketed antisweat insulation.	Outside the reactor coolant system shield wall below basement floor.	Plant calculations show that for some of the postulated breaks total screen blockage can occur due to the transport of unencapsulated fibrous insulation. Since the sump screen area is small (108 ft^2), the calculated pressure drop (6.3 psi) is excessive. Further investigation is necessary to confirm the fibrous bed pressure drop correlation employed.
Arkansas Unit 2 (CE)	Reactor coolant piping, reactor vessel bottom head of steam generator, and pressurizer use reflective metallic insulation. Feedwater pressurizer safety relief valve, and balance of steam generator blowdown use totally encapsulated calcium silicate or expanded perlite molded block insulation. Main steam piping uses calcium silicate or expanded perlite block with stainless steel jacketing. Chilled water piping uses fiberglass with stainless steel jacketing.	Outside the reactor coolant system shield wall below basement floor.	Total debris is large (76,800 Ft^2) but is incapable of either migrating to the sump (reflective metallic) or being drawn into the screens (calcium silicate). Extensive blockage of the inboard screens occurs but outboard screens are more than adequate to pass the required flow without introducing excessive head losses.

TABLE 3.5 (Continued)

Plant and Reactor Manufacturer	Type of Insulation Utilized	Location of Emergency Sump	Final Assessment of Migration Potential of Debris Generated as a Result of a Pipe Break
Salem Unit 1 (W) (Westinghouse)	Reactor vessel, primary coolant piping, pressurizer, reactor coolant pumps, and bottom part of steam generator use reflective metallic insulation. Upper part of steam generator uses semi-encapsulated cerablanket insulation. Main steam, feedwater, residual heat removal, safety injection, and chemical and volume control system piping use totally encapsulated cerablanket. Service water and component cooling-water piping use antisweat insulation.	Outside the reactor coolant system shield wall below basement floor. Water drains into emergency sump through trenches in the floor in addition to directly from annular space outside of shield wall.	Postulated breaks resulted in large quantities of debris. Calculations indicate total screen blockage to occur. Calculations showed that large quantities of debris would be generated by postulated breaks. They further showed the potential for total screen blockage. However, this plant design has large debris intercept areas, in addition to the local sump screen. This, when coupled with the low recirculation velocities within containment, results in a low blocked screen ΔP which does not result in insufficient NPSH.
Sequoyah Unit 2 (W)	All piping and equipment within the shielded crane wall area use reflective metallic insulation.	Inside the crane shield wall below containment floor.	While a large percentage of the sump intake area was blocked (approximately 74%), the remaining screen area is capable of passing the required recirculation flow without excessive head loss. Pump NPSH requirements are not impaired.
Prairie Island Unit 1 (W)	Mirror insulation is used on reactor vessel, steam generator, reactor coolant pump, pressurizer, excess letdown heat exchanger, regenerative heat exchanger, surge line, high pressure safety injection loop, primary coolant piping, steam generator blowdown lines, pressurizer spray piping, chemical and volume control piping, accumulator, low pressure safety injection, feedwater, main steam, auxiliary feedwater, residual heat removal, steam generator supports. Fiberglass insulation is used on main steam and feedwater hangers and restraints.	Outside reactor coolant shield wall, below basement floor.	The quantity of insulation debris generated is large (>3000 Ft^2) but is unable to migrate to the sump since reflective metallic is extensively employed. The quantity of fibrous insulation generated is not sufficient to block a sump intake area large enough to cause excessive pressure drop.

TABLE 3.6

Summary of Findings

Plant	Break	Debris* Generated	Debris* At Sump	Total* Sump Screen Area	Blocked* Sump Screen Area	Percent Blockage	Note
Salem Unit 1	Hot Leg	2692	1197	1078**	1078**	100	1
	Cold Leg	4737	2290	1078**	1078**	100	1
	Main Steam	----	0	1078**	0	0	2
	Feedwater	----	0	1078**	0	0	2
Arkansas Unit 2	Main Steam	7161	6517	287	95	33	3
	Feedwater 1	278	0	287	189	66	4
	Feedwater 2	97	---	---	---	---	5
Maine Yankee	Main Steam	3314	---	108	---	---	6
	Hot Leg 1	1071	---	108	---	---	6
	Hot Leg 2	1642	---	108	---	---	6
	Crossover 1	1642	---	108	---	---	6
	Crossover 2	1596	394	108	108	100	7
	Cold Leg	431	---	108	---	---	6
	Emerg. Feed.	215	---	108	---	---	6
Sequoyah Unit 2	Feedwater	248	15	41	15	37	8
	Hot Leg	2840	27	41	27	66	9
	Coolant Pump	1009	15	41	15	37	8
	Hot Leg	2840	27	41	27	66	9
	S.G. No. 4	528	20	41	20	49	9
	S.G. No. 1	3257	15	41	15	37	8
	Loop Closure	5632	15	41	15	37	8
Prairie Island Unit 1	Main Steam	4316	39	60	39	65	8
	Feedwater	1299	0	60	0	0	10
	Hot Leg	4131	39	60	39	65	8
	Cold Leg	1221	0	60	0	0	10
	Crossover	5009	39	60	39	65	8

*Units of ft^2

**Total debris intercept area available in this plant to accept LOCA-generated debris. The sump screen area at the sum is 68 ft^2.

NOTES:

1. As insulation is fibrous, uniform deposition is assumed (i.e., 100% of sump screens are blocked). Pressure drop is insufficient to adversely affect NPSH.
2. No debris reaches the sump region due to gratings as shown in Figure A-24.
3. Entire inboard screen blocked; outboard screen has sufficient unblocked area.
4. Entire outboard screen blocked; inboard screen has sufficient unblocked area.
5. Scoping analysis -- Feedwater 1 was more severe.
6. These cases are parts of a scoping analysis. Cold leg failure was most limiting.
7. Screen blockage is calculated to be total. Calculated pressure drop across fibrous debris bed is sufficient to offset any available NPSH margin, subject to assumption of total sump screen blockage with no credit for debris capture in transport.
8. Blockage acceptable from pressure drop standpoint.
9. Blockage as percentage of screen area is high, but pressure drop is acceptable.
10. Insulation does not reach sump.

Unit 1 with a 936 ft^2 screen) can tolerate large quantities of transported debris. On the other hand, plants with smaller screens and fibrous, nonencapsulated insulation targeted by principal pipe breaks (such as Maine Yankee) have been identified as having a potential for unacceptable pressure drops.

Plant and insulation effects are evident. The methods given above, however, can be used to evaluate plants for the degree of screen blockage that various insulations can pose. The methods have been tested against a broad spectrum of plants and evaluated independently (see Section 4.2). The results point out the deficiency of the 50 percent screen blockage guidance set forth in RG 1.82, which has been used in the past at times without the benefit of plant specific debris evaluations and attendant loss in required NPSH. These calculations also show that both conservative and non-conservative results can be obtained. The plant dependence is clearly controlling.

3.3.4 Experimental Studies on Debris

Following the studies conducted by Burns and Roe, discussed in Section 3.3, experimental work was carried out at Alden Research Laboratory to examine the generation, buoyancy, and transport characteristics, as well as the potential for sump blockage of typical as-fabricated insulation and insulation debris.

In studying the generation of insulation debris, three types of fibrous type insulation used in power plants were examined (Reference 6). Characteristics of these insulations are provided in Appendix C. These insulations were subjected to a 2" diameter water jet at ambient temperature for periods not less than 5 minutes in duration over stagnation pressures ranging from 5 psi to 65 psi. Tests were conducted with the insulation blankets both normal to and at an angle of 45° to the impinging jet. The threshold of failure (determined by the onset of covering failure) of these blankets was at 20 psi under a jet impingement angle of 45°. Details of these experiments are provided in Reference 6 and a summary is given in Appendix C.

Buoyancy tests as of-fabricated and fragmented fibrous insulations revealed the following:

(1) Mineral wool does not readily absorb water and sink,

(2) All forms of fiberglass insulation readily absorb water and sink,

(3) Air can be trapped in undamaged insulation blankets keeping them afloat for periods ranging from more than 20 minutes to days,

(4) Fiberglass insulations, with damaged coverings, absorb water and sink quickly, and

(5) Mineral wool and fiberglass insulations absorb water and sink more rapidly with increasing water temperature.

Details of these experiments and their results are provided in Reference 7.

Studies were undertaken to determine transport requirements of as-fabricated fibrous insulations, fibrous insulation debris and reflective metallic insulation. These efforts determined water velocities required for the onset of insulation migration, for sustained migration along a flow path and for rotating whole blankets from a horizontal floating or sunken position to a vertically oriented position against sump screens. Details of these experiments are provided in Reference 7 and a summary of results is given in Table 5.8

Head losses were measured for flow through various thicknesses of as-fabricated, fragmented and shredded fibrous insulations (Reference 7). The results of these investigations showed:

(1) Head losses through as-fabricated fibrous insulation are high (ΔH through 2 in. mineral wool of 3.5 ft., ΔH through 1 in. fiberaglass of about 20 ft.),

(2) Head losses through mats of accumulated fibrous insulation debris can be significant (ΔH through 2 in. as-fabricated equivalent thickness mineral wool ranged from 0.7 to 1.9 ft., ΔH through 1 in. as-fabricated equivalent thickness fiberglass ranged from 1.3 to 4.2 ft.),

(3) At low approach flow velocities (~ 0.2 ft/sec), head losses through mats of accumulated fiberglass fragments were found to be reasonably represented by the relationship abstracted from Reference 5:

$$\Delta H = [3.5 \mu q S_v^2](1 - E)^{1.5} [1 + 57(1 - E)^3] \ell$$

where

ΔH is head loss through mat (dynes/cm^2),
ℓ is the mat thickness (cm),
μ is fluid viscosity (poise),
q is fluid flow rate (cm^3/sec),
S_v is fiber specific surface (cm^2/cm^3), and
E is the mat void fraction.

It was found that at higher flow velocities, losses for accumulated fiberglass mats increased more rapidly than the above expression would yield. The above relation was found to inadequately represent head losses through as-fabricated fiberglass,

(4) For otherwise identical flow blockage conditions, head losses for fibrous insulations decreased with increasing water temperature, and

(5) Both as-fabricated insulation and accumulated mats exhibited hysteresis head loss effects. Higher head losses were observed for material that had been earlier subjected to higher throughflows than those constituting test conditions.

As noted, the above results became available following the completion of analytical studies on debris generation, transport, and its potential for sump blockage conducted by Burns and Roe (Reference 5). Such applicable experimental data may be used to complement the calculational methods developed in Reference 5 (see Section 5.3 and Appendix B).

3.4 Sump Hydraulic Performance

To investigate the behavior of ECCS sumps under flow conditions that might occur during a LOCA, a test program was designed to cover a broad range of geometric features and flow variables representative of containment emergency sump designs. Because some of the hydraulic phenomena of concern, particularly air ingestion, could involve scale effects if tested at reduced scale, a full-scale experimental facility was used. Three broad areas of interest for ECCS sump design were investigated:

- Fundamental behavior of the sump with reasonably uniform approach flow conditions

- Changes in the fundamental behavior of the sump as a result of potential accident conditions -- screen blockage, break and drain flow, obstructions, nonuniform approach flow, etc., -- that could cause degraded performance in the recirculation system

- Design and operational items of special concern in ECCS sumps.

The test program was designed to allow information from initial tests to be used to plan or redirect later tests; hence, the tests were not necessarily conducted in the order listed below. Although the experimental program was modified, and tests were added on several occasions, tests used in the investigation may be divided into 7 series:

Factorial Tests -- A fractional factorial matrix of tests was used to study primary sump flow and geometric variables. The factorial matrix provided a wide range of parameter variations and a method for effectively testing a large number of variables and determining their interdependencies.

Secondary Geometric Variable Sensitivity Tests -- The effects on sump performance of secondary geometric variables and design parameters of special concern in ECCS sumps were tested by holding all sump variables constant except one, for which several values were tested.

Severe Flow Perturbations Tests -- The behaviors of selected sump geometries subjected to approach flow perturbations were investigated. Major flow disturbances considered were screen blockage (up to 75 percent), nonuniform approach velocity distribution, break-flow and drain-flow impingement, start-up transients, and obstructions as illustrated in Figures 3.9 and 3.10.

Vortex Suppression Tests -- The effectiveness of several types of vortex suppressors and inlet configurations were evaluated.

Scale Tests -- Scaling effects in geometrically scaled models using Froude number similitude and pipe velocity similitude were tested.

Boiling Water Reactor (BWR) Suction Pipe Inlet Tests -- The hydraulic performance of BWR suction pipe geometries typical of Mark I, II, and III designs was evaluated.

Fibrous Insulation Material Blockage Tests -- Head loss due to blockage of sump screens by fibrous insulation material was evaluated.

Data resulting from the sump performance studies were analyzed using two approaches: (1) functional correlations of the dependent variables in which the correlations were the result of response-surface regression analysis or nondimensional empirical data fitting, and (2) bounding envelope analyses in which boundary curves indicate the maximum response of the data for each of the hydraulic performance parameters as a function of the sump flow variables (the Froude number in particular). Due to the extremely small values of the dependent variables and to the complex time-varying nature of the three-dimensional flows in the sump, the functional correlations approach showed no consistent, generally applicable, correlation between the dependent and independent variables; hence, the hydraulic performance of a particular sump under given flow and submergence conditions could not be reliably predicted using this approach. However, the broad data base resulting from the sump studies made possible the use of envelope analyses for reliably predicting the expected upper-bound for the hydraulic performance (void fraction, vortex type, swirl angle, and inlet loss coefficient) of any given sump whose essential features fall approximately within the flow and geometric ranges tested.

The ability to describe the performance of ECCS sumps, with or without flow perturbations, using bounding envelope

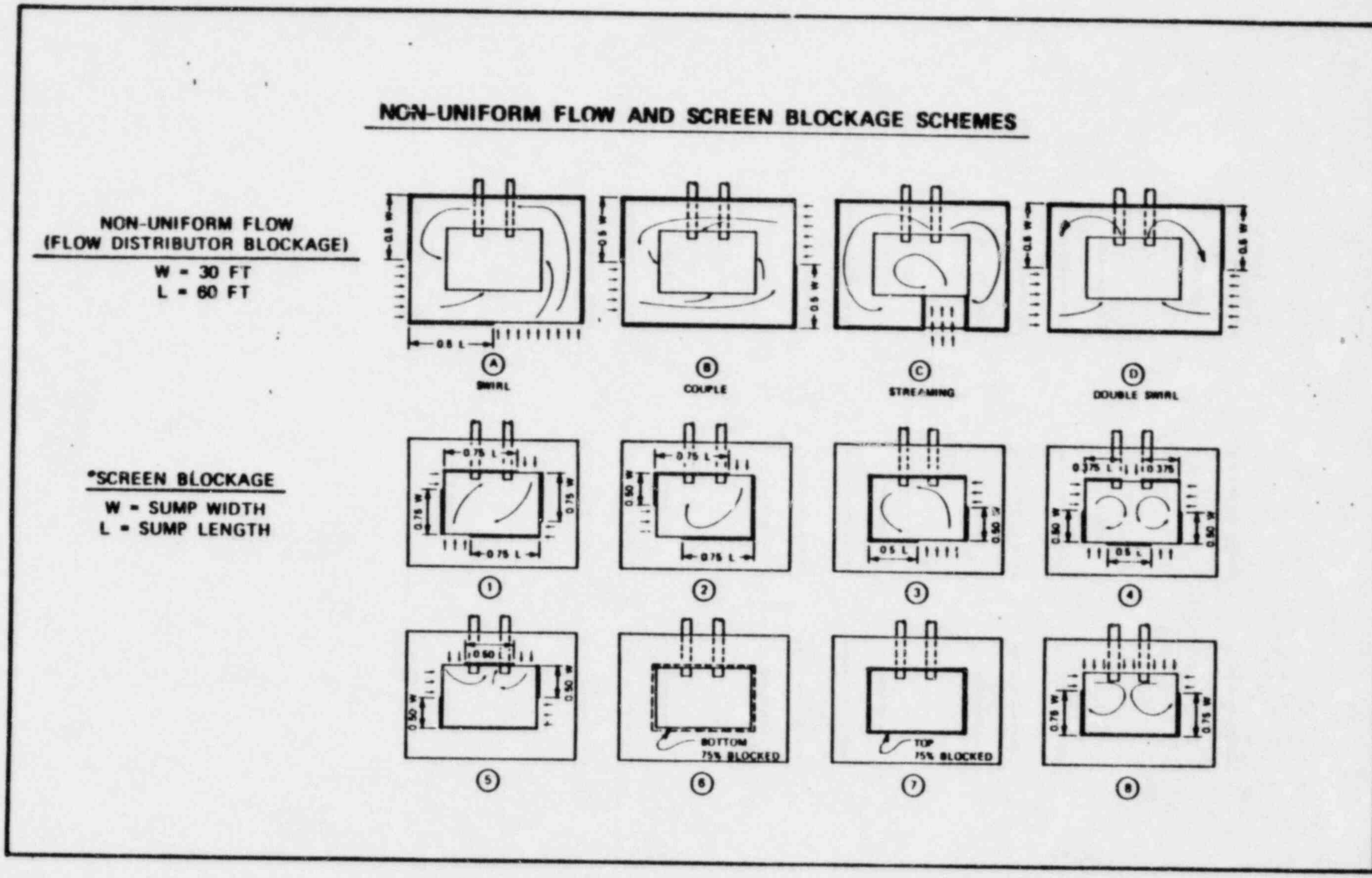
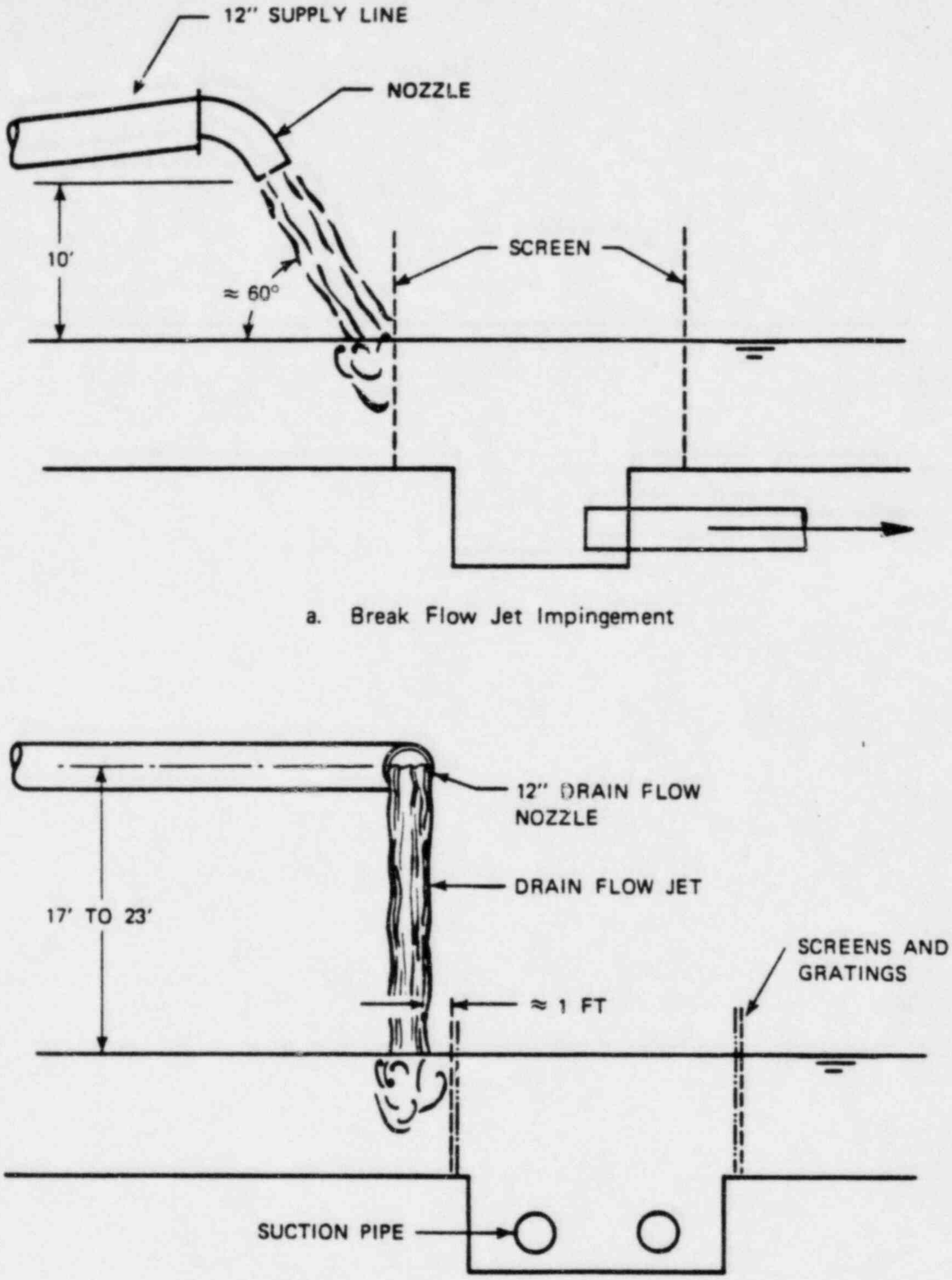


Figure 3.9. Approach Flow Perturbations and Screen Blockage Schemes.



a. Break Flow Jet Impingement

b. Drain Flow Jet Impingement

Figure 3.10. Break and Drain Flow Impingement.

curves is a most significant result of the test program. The application of an envelope analysis to test data resulting from all the sump performance tests is discussed in the following subsection of this report. Findings of the sump performance tests are described in greater detail in subsequent sections.

3.4.1 Envelope Analysis

The sump performance test program generated a data base covering a broad range of ECCS geometric variables, flow conditions (including potential accident conditions), and design options (horizontal or vertical inlets, single or dual pipes, etc.). An envelope analysis applied to this broad range of data resulted in boundary curves that describe the maximum expected air ingestion, surface vortex activity, swirl, and sump head loss as a function of key sump flow variables (Froude number, velocity, etc.).

Figures 3.11, 3.12, and 3.13 show typical envelope analysis curves for air ingestion, surface vortex activity, and swirl in sumps with dual, horizontal outlets. Figures 3.14, 3.15, and 3.16 show typical envelope analysis curves for air ingestion, surface vortex activity, and swirl in sumps with dual, vertical outlets.

3.4.2 General Sump Performance (All Tests)

Free Surface Vortices -- Vortex size and type resulting from a given geometric flow condition are difficult to predict and are not reliable indicators of sump performance. Performance parameters -- void fraction, pressure loss coefficient, and swirl angle -- are not well correlated with observed vortex formations.

Air Ingestion -- Measured levels of air ingestion, even with air core vortices, were generally less than 2 percent. Maximum values of air ingestion with deliberately induced swirl and blockage conditions were less than 7 percent for horizontal inlets and 12 percent for vertical inlets; these high levels always occurred for high flow and low submergence (F generally greater than 1.0). For submergences of 8 feet or higher, none of the configurations tested indicated air-drawing vortices ingesting more than 1 percent over the entire flow range even with severe flow perturbations.

Swirl (measured 14 diameters from suction inlet) -- Flow swirl within the intake pipes, with or without flow perturbations, was very low. In almost all cases, the swirl angle was less than 4°, an acceptable value for RHR and CSS pumps. The maximum value for severely perturbed flows was about 8° and occurred during the screen blockage test series.

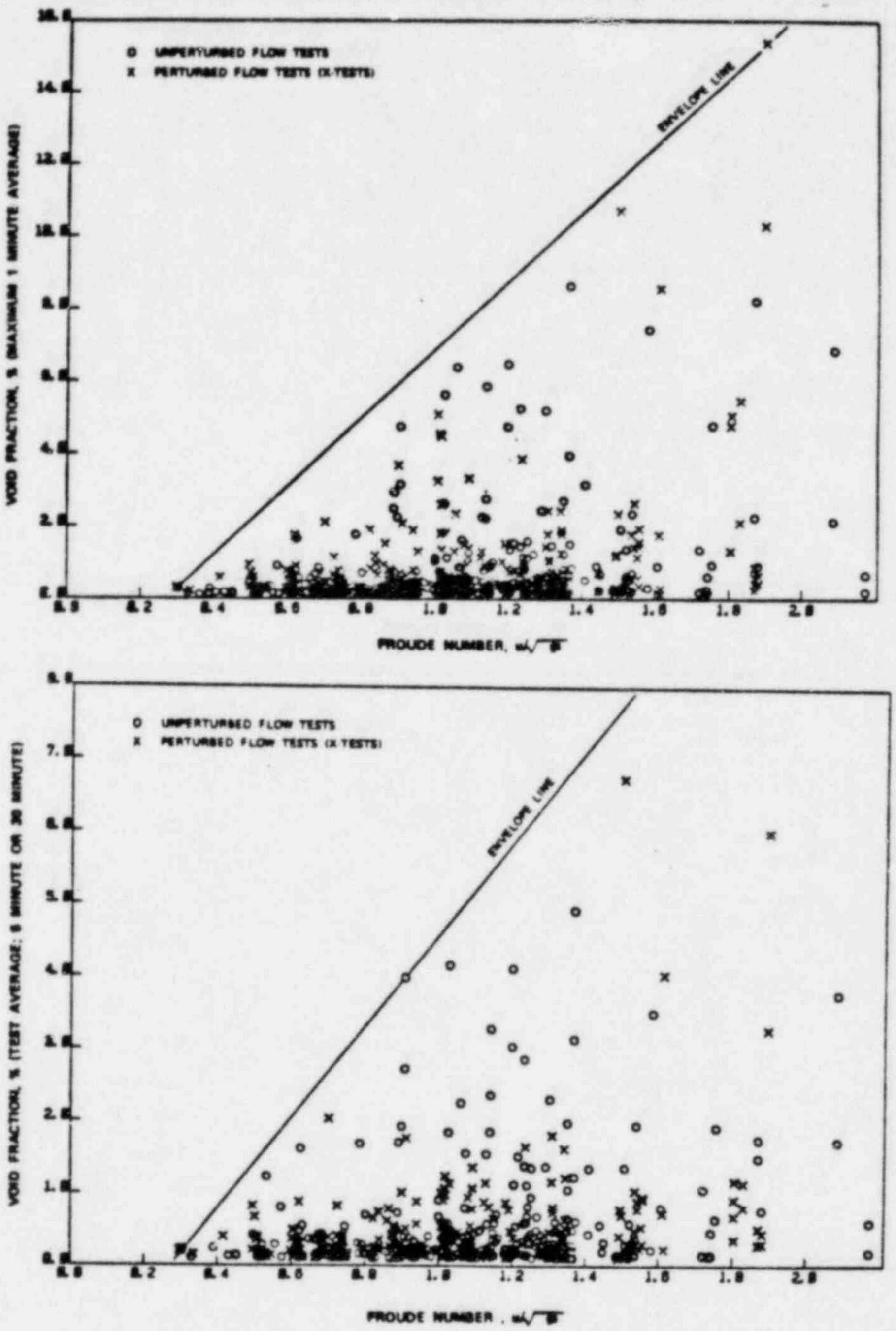


Figure 3.11. Void Fraction (% by Volume) as a Function of Froude Number; Horizontal Outlet Configuration. Only data points indicating nonzero void fraction are plotted.

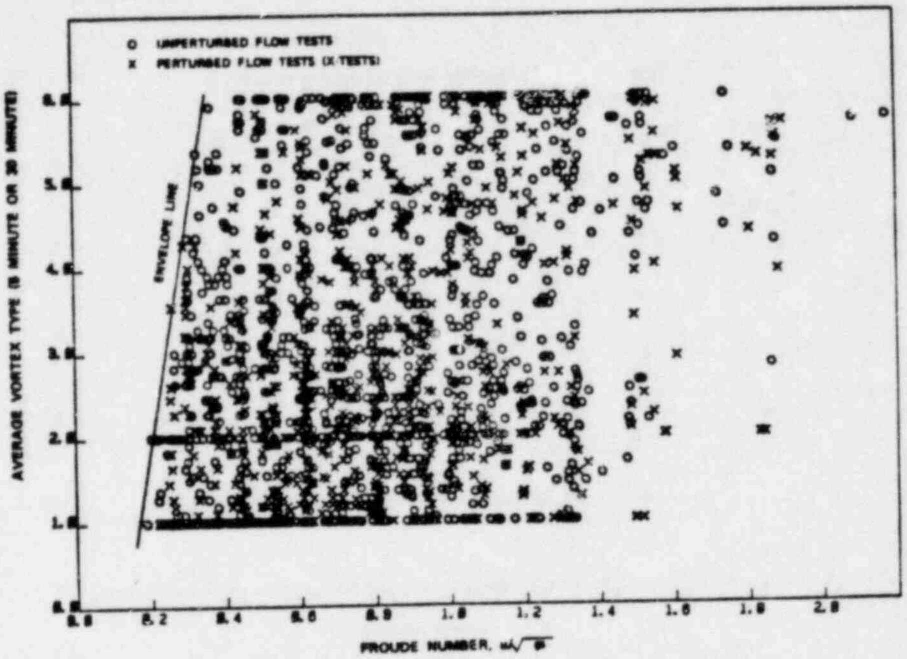


Figure 3.12. Surface Vortex Type as a Function of Froude Number; Horizontal Outlet Configuration.

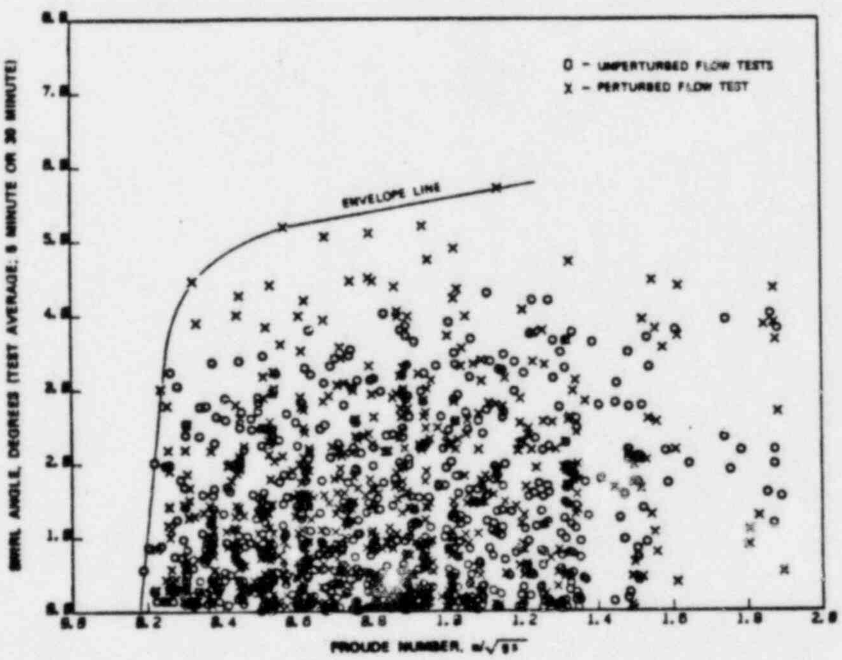


Figure 3.13. Swirl as a Function Froude Number; Horizontal Outlet Configuration.

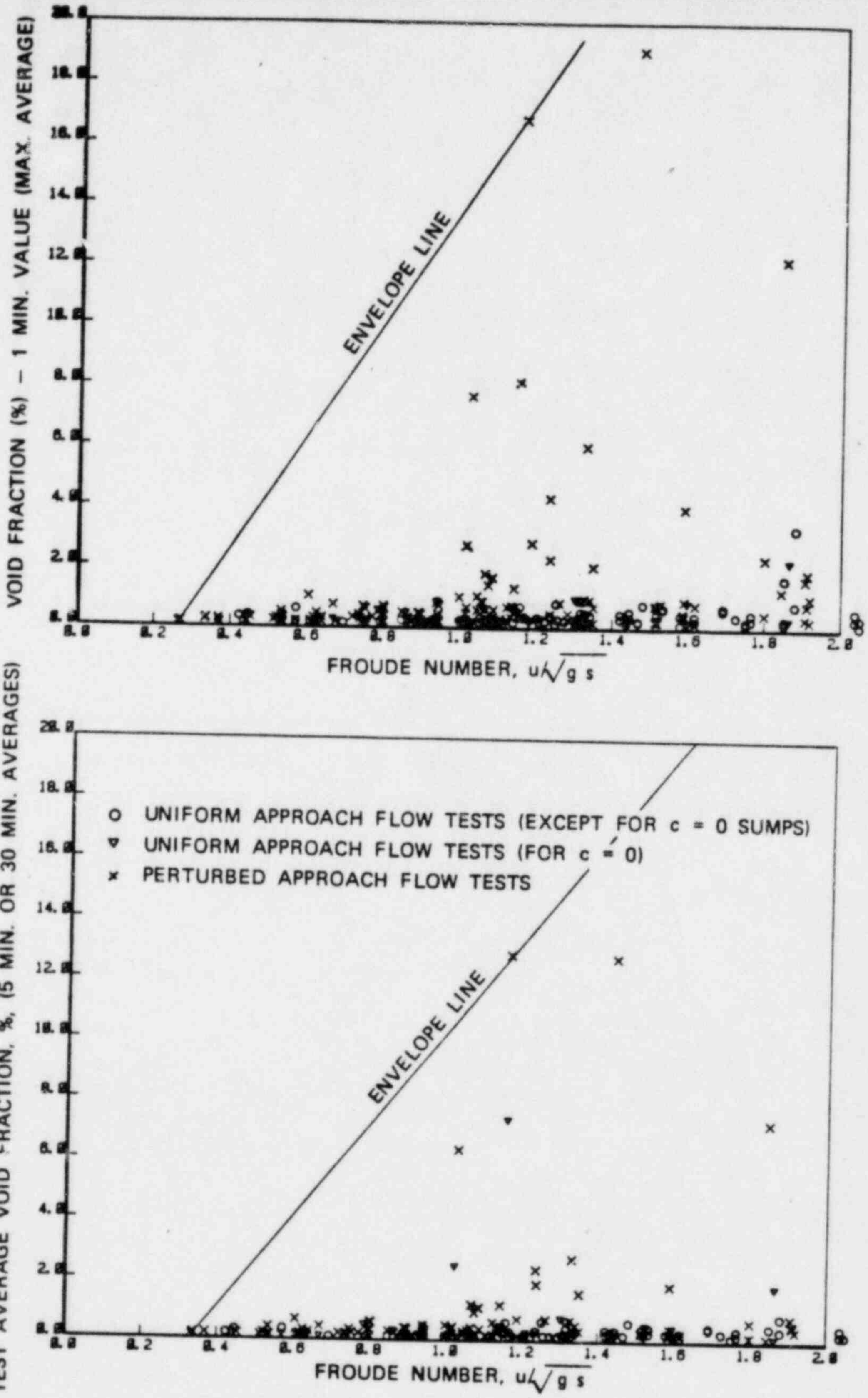


Figure 3.14. Void Fraction Data for Various Froude Numbers; Vertical Outlet Configuration. Only data for nonzero void fraction plotted.

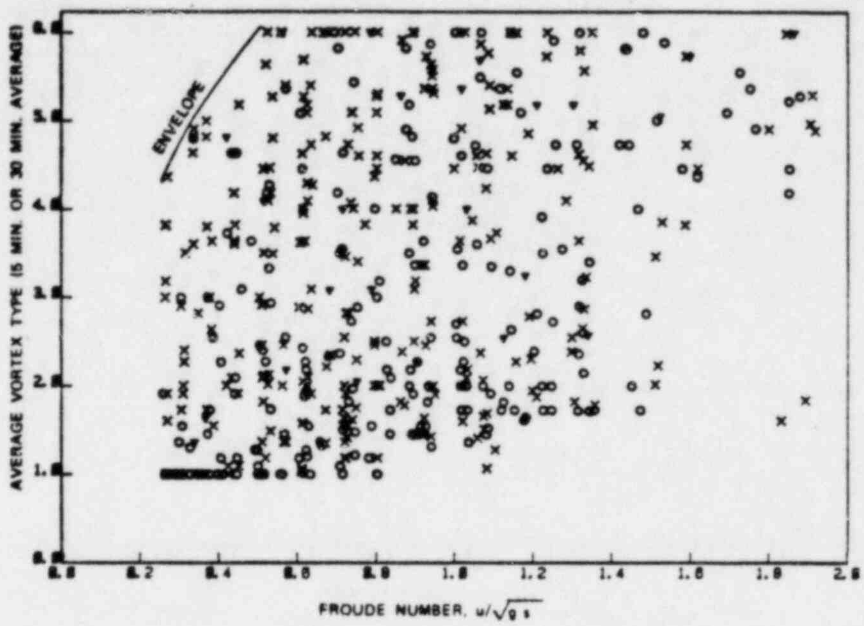


Figure 3.15. Surface Vortex Type as a Function of Froude number; Vertical Outlet Configuration.

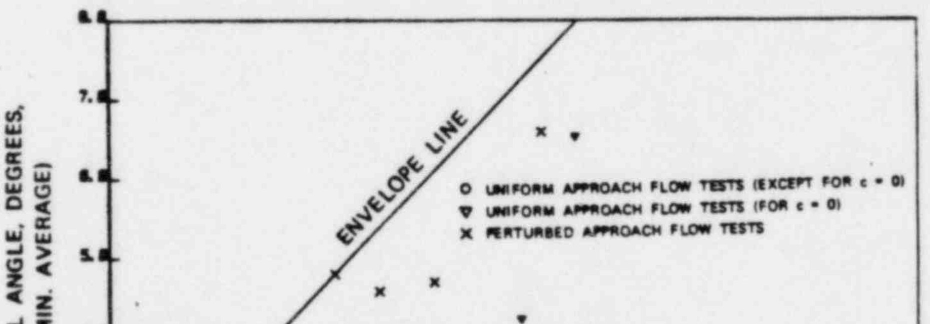


Figure 3.16. Swirl as a Function of Froude Number; Vertical Outlet Configuration.

Sump Head Losses -- Suction pipe intake pressure loss coefficient for most of the tests, with and without flow perturbations, was in the range of 0.8 ± 0.2 and agreed with recommended hydraulic handbook values.

3.4.3. Sump Performance During Accident Conditions (Perturbed Flow)

Screen Blockage -- Screen blockages up to 75 percent of the sump screen resulted in air ingestion levels similar to those noted under "Air Ingestion" above.

Nonuniform Approach Flow Distributions -- Nonuniform approach flows, particularly streaming flow, generally increased surface vortexing and the associated void fraction.

Drain and Break Flow -- Drain and breakflow effects were generally found not to cause any additional air-ingestion. They reduced vortexing severities by surface wave action.

Obstructions -- Obstructions (2 ft or less in cross-section) had no influence on vortexing, air withdrawals, swirl, or inlet losses.

Transients -- Under transient, start-up conditions, momentary vortices were strong, but no air-core vortices giving withdrawals exceeding 5 percent void fraction (1 minute average) were observed.

3.4.4 Geometric and Design Effects (Unperturbed Flow Tests)

In general, no consistent trends applicable for the entire range of tests were observed in the data between the hydraulic response of the sump (air withdrawal, swirl, etc.) and secondary geometric parameters. However, for some ranges of flow and submergences, the following observations are applicable:

- Greater depth from containment floor to the pipe centerline reduces surface vortexing and swirl.
- Lower approach flow depths with higher approach velocities may cause increased turbulence levels serving to dissipate surface vortexing.
- There is no advantage in extending the suction pipe beyond 1 pipe diameter from the wall.
- Suction pipe inlets located with less distance to the sump wall and greater pipe spacing reduces vortexing and swirl.

3.4.5 Design or Operational Items of Special Concern in ECCS Sumps

Vertical Outlets -- Comparison of vertical outlet data to corresponding horizontal outlet data showed some, but no major differences, in hydraulic performance of vertical outlet sumps and horizontal outlet sumps of the same geometry and flow conditions: average vortex types agreed within $\pm$ 1; air withdrawals were somewhat higher for vertical outlet sumps, usually within 1 percent (30 minute averages) and 4 percent (1 and 5 minute averages); swirl angles differed only within $\pm$ 1 degree. As in the case with horizontal outlets where sump performance was best with pipe projections close to the wall, vertical pipe outlets with perturbations performed best when placed close to the wall rather than at the center of the sump.

Cover Plate -- A solid top cover plate over the sump was effective in suppressing vortices as long as the cover plate was submerged and proper venting of air from underneath was provided. No air-drawing vortices were observed for the submerged cover plate tests, and no significant changes in swirl or loss coefficients occurred.

Elevated Water Temperature --Changing water temperature over the range from 40°F to 167°F had no significant effect on horizontal outlet sump performance parameters.

Vortex Suppressors

Cage shaped vortex suppressors made of floor grating to form cubes 3 and 4 ft on a side, and single layer horizontal floor grating over the entire sump area, were both found to be effective in suppressing vortices and reducing air-ingestion to zero. These suppressors were tested using 12-inch outlet pipes, and with the water levels ranging from 0.5 to 6.5 ft above the top of the suppressors. Adverse screen blockages were used in conjunction with sump configurations which produced considerable air-ingestion and strong vortexing without the suppressors; thus, suppressors' effectiveness were tested when hydraulic conditions were least desirable. The suppressors also reduced pipe swirl and did not cause any significant increase in inlet losses. Both the cage shaped grating suppressors as well as the horizontal floor grates were made of standard 1.5 inch floor grates.

Tests on a cage shaped suppressor less than 3 ft on a side indicated the existence of air-core vortices for certain ranges of flows and submergences, even though air-withdrawals were found reduced to insignificant levels.

Either properly sized cage shaped suppressors made of floor grating, or floor grating over the entire sump area, may therefore be used to reduce air-ingestion to zero in cases where the sump design and/or approach flow creates otherwise undesirable vortexing and air-ingestion.

Single Outlets

Two sump configurations (4 ft x 4 ft and 7 ft x 5 ft in plan, both 4.5 ft deep; 12 inch outlets) were tested under unperturbed (uniform) and perturbed approach flows with screen blockages up to 75 percent of the screen area. For both the configurations, unperturbed flow tests indicated air-withdrawals were always less than 1 percent by volume for the entire range of tested flows and submergences ($F = 0.3$ to 1.6). Even with perturbed flows, zero or near zero air-withdrawals were measured in both sumps for Froude numbers less than 0.8, suggesting insignificant vortexing problems. For Froude numbers above 0.8, a few tests indicated significantly high air-withdrawal (up to 17.4 percent air by volume; 1 minute average) especially for the smaller sized sump. Measured swirl values in the pipes were insignificant for both the tested sumps, being in the range of 2 to 3 degrees even with flow perturbations. The inlet loss coefficients for both sump configurations were in the expected ranges for such protruding outlets, 0.8 ± 0.2.

Dual-Outlet Sumps With Solid Partition Walls

Four dual-outlet sump configurations (one 20 ft x 10 ft sump with 24 inch diameter outlets and three 8 ft x 10 ft sumps with 24 inch, 12 inch and 6 inch outlets, respectively) were tested with solid partition walls in the sumps between the pipe outlets and with only one outlet operational. None of the tests indicated any significant increases in vortexing, air-withdrawls, swirl, or inlet losses compared to dual pipe operation without partition walls. Thus, providing a partition wall in a sump should not cause any additional problems when only one pipe is operating.

Bellmouths at Pipe Entrance

Limited tests on a sump configuration were conducted with and without a bellmouth attachment to the 12 inch outlets. Adding bellmouths at the pipe entrances did not show any significant changes in the vortex types, air-withdrawals, and pipe swirl compared to those which otherwise existed under the same hydraulic conditions. Up to about 40 percent reduction in inlet losses was noticed with the addition of a bellmouth.

BWR Suction Pipe Inlets

The hydraulic performance of three representative BWR Residual Heat Removal System suction inlet configurations; namely, Mark I, Mark II, and Mark III designs, were investigated over a Froude number range of from about 0.2 to 1.1 under both unperturbed (uniform) and perturbed approach flow conditions. Zero air-withdrawal was measured for both configurations at Froude numbers equal to or less than 0.8 under all tests approach flows. At a Froude number above 0.8, under perturbed approach flows, the Mark I design (single inlet with conical strainer) allowed air-core vortices drawing up to 4 percent air by volume (1 minute average), while the Mark II and Mark III design (which had a "tee" inlet with conical strainers on each end) showed air-withdrawls only up to 0.5 percent by volume (1 minute average). Swirl levels in the pipe were found to be about 0 to 3 degrees for the Mark I design and 2 to 7 degrees for Mark II and Mark III design. The inlet loss coefficient, including entrance and strainer losses (and "tee losses," if applicable), was determined to be about 1.0 for Mark I design and 1.7 for Mark II and Mark III designs, expressed in terms of suction pipe velocity head.

Scale Model Tests

To evaluate the use of reduced scale hydraulic models to determine the performance of containment emergency sumps and to investigate, in particular, possible scale effects in modeling the hydraulic phenomenon of concern, a test program involving two reduced scale models (1:2 and 1:4) of a full size sump (1:1) was undertaken (Reference 22).

The test results show that the hydraulic models predicted the hydraulic performance of the full sized sump; namely, vortexing, air-ingestion from free surface vortices, pipe flow swirl, and the inlet loss coefficient. No scale effects on vortexing or air-withdrawals were apparent within the tested range for both models. However, an accurate prediction of pipe flow swirl and inlet loss coefficient was found to require that the approach flow Reynolds number and the pipe Reynolds number be above certain limits.

Based on these results, it is concluded that properly designed and operated reduced scale hydraulic models of geometric scales 1:4 or larger could be used to properly evaluate the hydraulic performance of a sump design. Evaluations of sump hydraulic model studies conducted in the past can be derived from this series of tests.

Pump Overspeed Tests

Two 8 x 10 x 4.5 ft sumps (one with horizontal outlets; one with vertical outlets) were tested at higher flow rates to simulate pump overspeed or run-out (to Froude number = 1.6) conditions. No strong air-core vortices were observed with air-withdrawals greater than 1 percent (1 min or 30 min averages).

Maximum recorded pipe swirl angle was 0.9° (at 14.5 pipe diameters from entrance); inlet loss coefficients averaged 0.8 (Reference 23)

4.0 INDEPENDENT PROGRAM REVIEWS

Program reviews were conducted before and during key phases of the work reported in Chapter 3. These reviews were performed for the purpose of soliciting comments and technical concerns about the program's direction and goals from experts not connected with the implementation and execution of TAP A-43. The reviewers were selected from among the foremost authorities in each of the areas reviewed. Two reviews were held; they were

- sump hydraulic performance
- insulation debris calculational methods effects

4.1 Sump Performance Review

The review consisted of two panel meetings.* The primary purpose of the first meeting, held March 17, 1981, was to introduce in detail the program plan and initial test results. The second meeting, held June 4, 1981, was primarily for reviewer response and comment.† Additionally, at both meetings the reviewers were provided with preliminary program redirections, and were requested to comment on results to date and give an analysis of the proposed future program plan. Overall, the reviewers approved of the program, the experimental test plan, its conduct, and data analysis. They concluded that the program and its directions were appropriate for resolving the sump performance issues.

In direct response to reviewer comments, the temperature tests were performed immediately following the first 25 configurations, and, therefore, earlier in the program than originally planned.

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*Meetings were held on March 17, 1981, at Germantown, Maryland, and June 4, 1981, at Alden Research Laboratory of WPI, Holden, Massachusetts. Review attendees and their affiliations were as given below: P. Tullis/Utah State University; D. Simons/Simons, Li and Associates; R. Gardiner/Western Canada Hydraulic Laboratories; D. Canup/Duke Power Company; W. Butler/U.S. Nuclear Regulatory Commission; S. Vigander/Tennessee Valley Authority (TVA); J. Kennedy/University of Iowa; R. Letendre/Combustion Engineering, Inc. R. Letendre did not attend the meeting of June 4, 1981.

†Formal written response and comments were requested at the close of the second meeting. These responses are available through the Office of Light Water Safety Research, Department of Energy, Washington, DC.

Divergent opinions emerged during the review concerning the potential for pump performance degradation when the fluid temperature was near saturation. Some concerns were expressed regarding the possibility of degraded pump performance due to cavitation or the release of dissolved air into the water in the suction lines leading to the pumps. Other opinions suggested that pump performance should be satisfactory at coolant temperatures near saturation, because the solubility of air in water is low near saturation and, provided cavitation were not occurring in the pump, any voids would collapse due to the static pressure increase with depth in the sump. These collapsing bubbles would then form a turbulent environment and inhibit surface vortex activity. The pump issues raised by the reviewers, although not pertinent to the sump hydraulics program, are a part of USI A-43 and have been addressed and resolved (see Section 3.2).

The experimental research program did not examine the effects on sump systems of temperatures near saturation. Temperature effects were examined to the limits of the capacity of the experimental facility (about 165°F). However, up to that limit, no temperature effects on sump system performance were detected.

An area of general peer review group agreement was that sump system performance, with respect to air entrainment, could be improved in most sump configurations by the addition of a vortex suppression device(s). One reviewer, however, commented that such a device(s) might be removed during some phase of reactor operations and not be replaced. Such a possibility, in his judgment, was sufficient justification for an experimental research program that would allow the development of adequate sump design guidelines that were based upon justifiable physical criteria (in the absence of vortex suppressors). The results of the studies provided in Section 3.4 confirm the usefulness of vortex suppressors in the improvement of sump system performance and, further, provide hydraulic results for developing acceptable sump design guidelines.

The adequacy of recirculation sump pumps for performing reliably when air/water mixtures are present and the long-term cooling function required of the ECCS were matters of some concern to the review group. These concerns have been resolved by the development of sump design guidelines which take into account pump performance specifications.

4.2 Insulation Debris Effects Review

The purpose of this review was to determine the adequacy of methods (described in Section 3.2 and in detail in Reference 5) to conservatively estimate quantities of insulation debris that might be produced in containment, its transport and its potential for sump screen blockage.

The review was conducted in two phases. In the initial phase, a draft report describing the methods was provided to peer panel and other reviewers* to solicit their comments.

Reviewers provided highly useful criticisms and comments with recommendations for improvements in the physical basis and rigor of the development.

As a consequence of the reviews, the draft document was modified to accommodate the comments of the reviewers. The modified document was then transmitted to the reviewers who were then requested to prepare comments for a formal peer panel review, the second phase of the review process.

Formal peer panel review took place at NRC Headquarters on March 31, 1982. Panelists Kennedy and Canup were unable to attend the meeting. A number of attendees, in addition to peer panel members, participated in the review.† Questions that were raised during the meeting and their disposition are given below:

1. It was observed that under some circumstances, the amount of debris generated with the potential to migrate to the sump could be greater than that estimated in the draft report. It was resolved by determining that the report would require the selection of those pipe break locations and jet targets that would generate the maximum of potentially transportable debris without regard to initial blowdown and transport direction.

2. Questions were raised about a) the applicability of the jet model used in the debris generation portion of the report, b) the assumption of uniform distribution of debris across the face of the jet and, c) the use of a 0.5 psi stagnation pressure cut-off for debris generation. Resolution of 2.a)

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*Peer panel reviewers were: R. Gardiner/Western Canada Hydraulic Laboratories; D. Simons/Simons, Li & Associates, Inc.; D. Canup/Duke Power Company; R. Mango/Combustion Engineering, Inc.; P. Tullis/Utah State University; J. Kennedy/University of Iowa; W. Butler/U.S. Nuclear Regulatory Commission; and S. Vigander/Tennessee Valley Authority. Other reviewers included G. Weigand/Sandia and R. Bosnak, G. Mazetis, and T. Speis/U.S. Nuclear Regulatory Commission. Their written review comments are available through The Division of Safety Technology, U.S. Nuclear Regulatory Commission, Washington, DC.

†Other attendees were: S. Hanauer/NRC; K. Kniel/NRC; C. Liang/NRC; P. Norian/NRC; F. Orr/NRC; A. Serkiz/NRC; J. Shapaker/NRC; G. Hecker/Alden Research Laboratory; E. Gahan/Burns and Roe; J. Wysacki/Burns and Roe; W. Swift/Creare, Inc.; P. Strom/Sandia; and G. Weigand/Sandia.

was arrived at by agreement that a modified Moody jet model (Reference 17) would be allowed to model the jet. It was agreed that the stripping of all insulation from plant and piping within the crane wall and within the jet represented a conservative treatment of insulation debris generation.

Discussions on Item 2.b) concluded that a definite probability existed that debris distribution across the face of the jet would not be uniform. It was agreed that a distribution of debris across the jet face would be provided that would represent the geometric distribution of insulation targeted by the jet in the containment. In addition, because of uncertainties in jet transport to walls, it was agreed that the quantities of debris estimated to exit through crane wall openings would be doubled over those quantities which would have been calculated in the draft report.

The use of a 0.5 psi stagnation pressure cut-off (Item 2.c)), for insulation damage was questioned by a number of reviewers. Technical views were put forward by a Sandia staff member on the expected performance of jets under LOCA conditions. He stated that centerline stagnation pressures above 15 psig could be expected for at least five diameters downstream of high energy, high pressure breaks. An AEC report (The Effects of Atomic Weapons, G. Glasstone, ed.) was cited by Burns and Roe as the origin of the cut-off estimate for debris generation. Alden Research Laboratory reported on preliminary experiments at ARL that have shown that little insulation damage occurred to fibrous insulation assemblies up to 6.5 psi water jet pressures. It was agreed that the 0.5 psi stagnation pressure represented a conservative treatment for the onset of insulation debris generation. It was further agreed that the assumption that all insulation within the jet cone would be transformed to insulation debris was conservative. The last assumption was chosen to represent the volume within which insulation debris would be generated under the treatment provided in Reference 5. The results of work performed subsequently on the issues are provided in Section 5.3 of this report.

3. Discussions were held on the physical accuracy of the model in representing pipe whip, pipe impact, the direction of motion of dislodged insulation and its trajectory. It was first pointed out that the quantities of insulation generated by this mechanism would amount to 10 percent or less of that generated by jet forces. It was further pointed out that the treatment in the report was designed to conservatively scope the problem, as opposed to providing detailed descriptions of system dynamics. It was agreed that the use of the treatment in the report would conservatively estimate the quantities of insulation debris produced by a minor contributor to debris production and, as such, was satisfactory.

4. Questions were raised on the treatment of long term transport following blowdown. These questions related to:

   a) recirculation flow velocities within containment,

   b) hydraulic lift provided to sunken debris,

   c) drawdown of floating debris onto less than fully submerged sump screens (ice-jam effect) and,

   d) transport mechanisms of sunken debris, such as tumbling and sliding.

   In the resolution of 4. a), agreement was reached to account for obstructions in flow paths and subsequent flow expansion.

   Agreement was reached on Item 4. b) horizontally oriented if lift were to be approximated by drag for horizontal debris, zero for vertically oriented debris and disregarded for tumbling debris.

   Item 4. c), was recognized as a potentially important mechanism for screen blockage. It will be treated by established methods available in the literature.

   Tumbling and other transport mechanisms, as noted under Item 4. d), could significantly affect the movement of debris towards screens. Panelists agreed to treatments which they considered to be conservative in dealing with debris movement via these mechanisms.

5. Arguments were raised that a period of debris transport intermediate to short term transport and long term transport (as defined here) might exist. It was postulated that transport during such an interim period might seriously affect potential sump blockage. Inasmuch as the report assumes that all floating debris reaches the sump, such an interim migration period would not affect the consequences of such transport. With respect to debris of density equal to or greater than unity and its transport, discussions brought out that the likelihood of a significant effect during such an interim period would be minor, flow patterns would show no preferential transport toward the sump and entrainment would be higher in the recirculation mode than in the interim period.

6. An issue that failed to be resolved was the behavior of fibrous insulation in its migration toward a sump and the potential for blockage by such material. As an issue, this problem has been indicated to exist at only a few plants and is, consequently, plant specific. Nevertheless, it was an open issue at the time of the meetings. Following the meetings,

experimental studies were conducted at Alden Research Laboratory to estimate stagnation pressures required for the onset of debris generation for nonencapsulated mineral wool and fiberglass insulations (Reference 6), the transport characteristics of such debris and the pressure losses at sump screens caused by the accumulation of fibrous debris on screens (Reference 7). These findings are reflected in the findings provided in Section 5.3 of this report.

All panelists, excepting S. Vigander of TVA, concluded that the use of the methods discussed would result in conservative estimates of sump screen blockage. Vigander commented that while he was of the opinion that the treatment would yield conservative, perhaps ultra-conservative, results, he could not with certainty arrive at that conclusion. He suggested that uncertainty analyses be conducted to establish the levels of conservatism (if any) that are provided in the development. Other panelists agreed that quantitative or qualitative error analyses would be desirable, although the needs for such analyses were deemed not to be immediate or pressing.

5.0 SUMMARY OF SUMP PERFORMANCE TECHNICAL FINDINGS

5.1 General Overview

The containment emergency sump should be evaluated to determine design adequacy for providing a reliable water source to the ECCS and CSS pumps during a post-LOCA period. Both sump hydraulic performance under adverse conditions, and potential LOCA-induced insulation debris effects require adequate technical assessment to assure that long-term recirculation can be maintained. Typical technical considerations are shown in Figure 5.1. Each major area of concern--pump performance, sump hydraulics, and debris generation potential--can be assessed separately, but the combined effects of all three areas should then be assessed to determine the overall effect on the NPSH requirements of the pumps. The sections below summarize technical findings and provide concise data sets.

5.2 Sump Hydraulic Performance

Full scale tests show that adequate sump hydraulic performance is principally a function of depth of water (the submergence level of the suction pipe) and the rate of pumping (suction inlet water velocity). These variables can be combined to form a dimensionless quantity defined as the Froude number:

$$\text{Froude number} = V/\sqrt{gs}$$

where

- V = suction pipe mean velocity,
- s = submergence (water depth from surface to suction pipe centerline), and
- g = acceleration due to gravity.

The extent of air ingestion is the principal parameter to be determined. Small amounts of air (i.e., $\lesssim$ 2 percent by volume) can significantly degrade pumping capacity. (References 11, 12, and and 13.) Section 3.4 summarizes the results of full scale hydraulic tests. Figures 3.11 and 3.14 show typical void fraction data as a function of Froude number. References 9, 20, 21, 22 and 24 provide more detailed results from the test program at ARL. Generally, sump design acceptability should be based upon $\lesssim$ 2 percent air ingestion to assure undegraded pump performance.

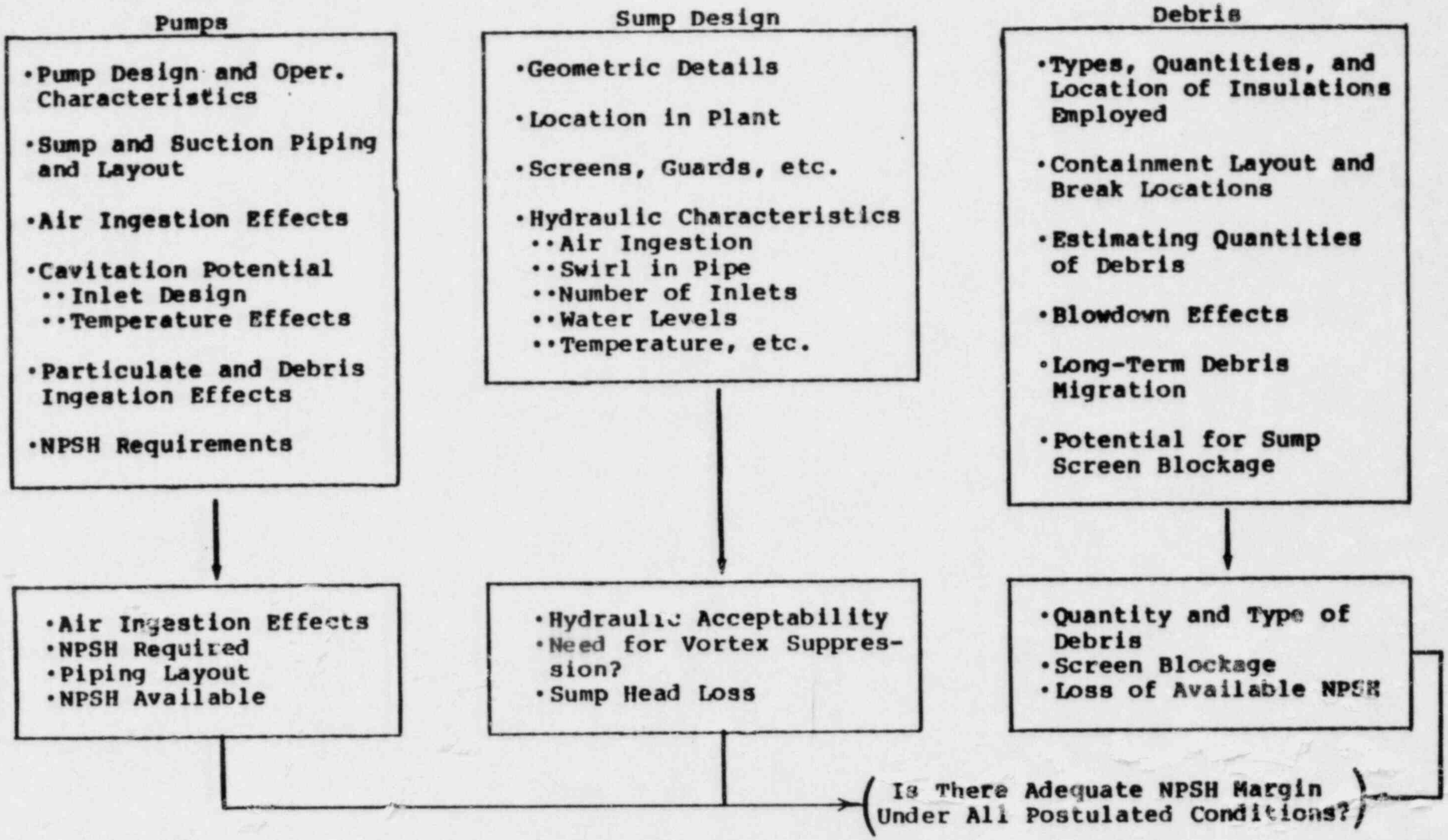


Figure 5.1. Technical Considerations Relevant to Containment Emergency Sump Performance

Sump hydraulic performance can, therefore, be assessed as follows:

1. Table 5.1 provides technical findings for sump designs where negligible (or zero) air ingestion would exist.

2. Sump geometric design and hydraulics performance based on air ingestion levels of < 2 percent can be derived by the use of Tables 5.2, 5.3, and 5.4.

3. The use of vortex suppressors provides a means to achieve zero air ingestion. Vortex suppression devices such as those shown in Table 5.6 have been shown to reduce air ingestion levels to essentially zero.

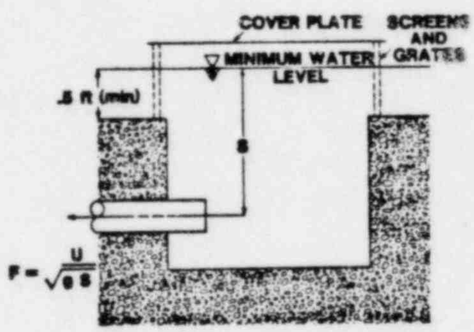
4. Additional information pertinent to screens and grates as would affect hydraulic performance is provided in Table 5.5.

5. Elevated water temperatures have been shown to have negligible effects on sump hydraulic performance through full scale tests conducted to 165°F.

TABLE 5.1

Zero Air Ingestion
Hydraulics Design Findings

Item	Horizontal Outlets		Vertical Outlets	
	Dual	Single	Dual	Single
Minimum Submergence, s (ft)	10		10	
Maximum Froude Number, F	0.25		0.25	
Maximum Pipe Velocity, U(ft/s)	4		4	



Aspect Ratio: 1-5

Minimum Perimeter: $\geq$ 16 ft
B - e_y/d: $\geq$ 3 ft
C/d: $\geq$ 1.5 for Horizontal Outlets, $\leq$ 1 for vertical inlets

Minimum Screen Area: $\geq$ 34 ft^2

TABLE 5.2
Hydraulics Design Findings

Item	Horizontal Outlets		Vertical Outlets	
	Dual	Single	Dual	Single
Minimum Submergence, s (ft)	7.0	8.0	8.0	10
Maximum Froude Number, F	0.53	0.40	0.41	0.33
Maximum Pipe Velocity, U(ft/s)	8.0	6.5	7.0	6.0
Maximum Screen Face Velocity (Blocked and minimum submergence) (ft/s)	3.0	3.0	3.0	3.0
Minimum Water Level (inside screens and grates)	Sufficient to cover 1.5 ft of open screen			
Maximum Approach Flow Velocity (ft/s)	0.36	0.36	0.36	0.36
Sump Loss Coefficient, C_L	1.2	1.2	1.2	1.2
Air Withdrawal, α_s, α_o	-2.47	-4.75	-4.75	-9.35
$\alpha_s = \alpha_o + \alpha_1 \times F$ (% air by Volume) α_1	9.38	18.04	18.69	35.95

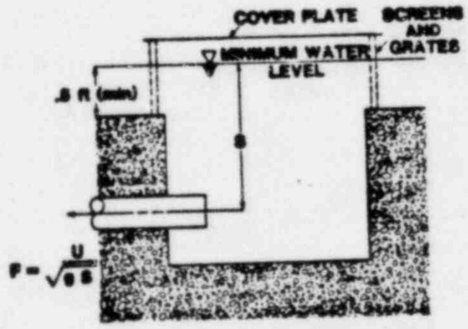
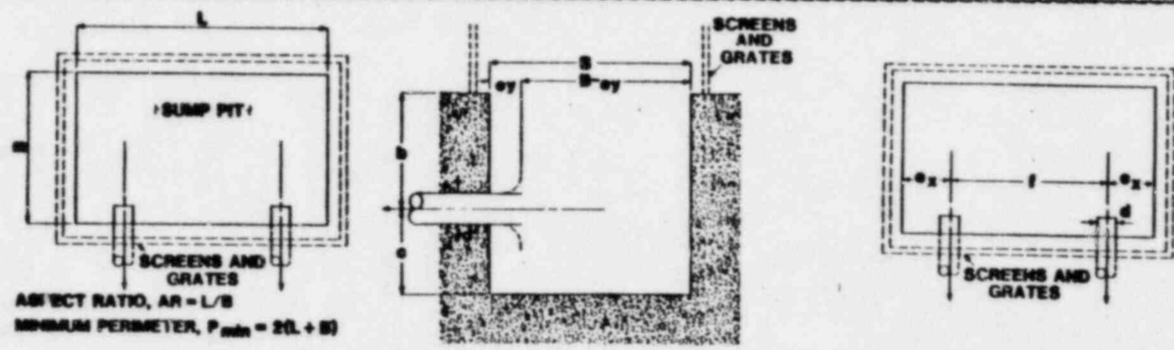


TABLE 5.3

Geometric Design Envelope Findings

		Size and Placement		Inlet Position**						Screens & Grates
		Aspect Ratio	Min. Perimeter	e_y/d	$(B-e_y)/d$	c/d	b/d	f/d	e_x/d	Min. Screen Area (Plane face)
Horizontal Outlets	Dual	1 to 5	36 ft	≥ 0	≥ 3	≥ 1.5	≥ 1	≥ 4	1.5* or > 1.5	75 ft^2
	Single	1 to 5	16 ft	≤ 1				–		35 ft^2
Vertical Outlets	Dual	1 to 5	36 ft	1.5* or > 1.5	≤ 1	≥ 0	≥ 1	≥ 4	1.5* or > 1.5	75 ft^2
	Single	1 to 5	16 ft			≤ 1		–		35 ft^2

Definitions

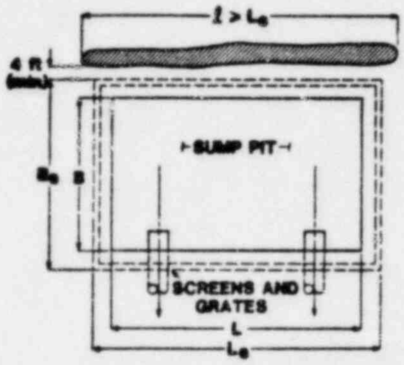


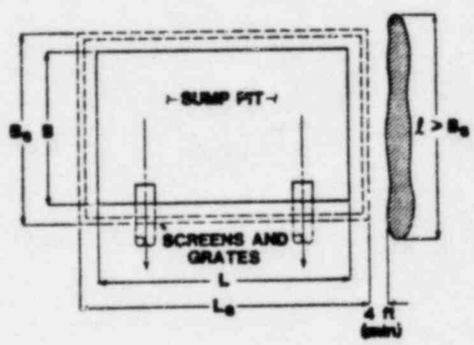
**Preferred location.

*Dimensions are always measured to pipe centerline.

TABLE 5.4

Additional Considerations Related To Sump Size and Placement*





1. Aspect Ratio, see Table 5.1.
2. Minimum Sump Perimeter, see Table 5.1.
3. Sump clearance of 4 ft between the screens/grates and any wall or obstruction of length ℓ equal to or greater than the adjacent screen/grates length (B_s or L_s).
4. A solid wall or large obstruction may form the boundary of the sump on one side only, i.e., the sump must have three (3) sides open to the approach flow.

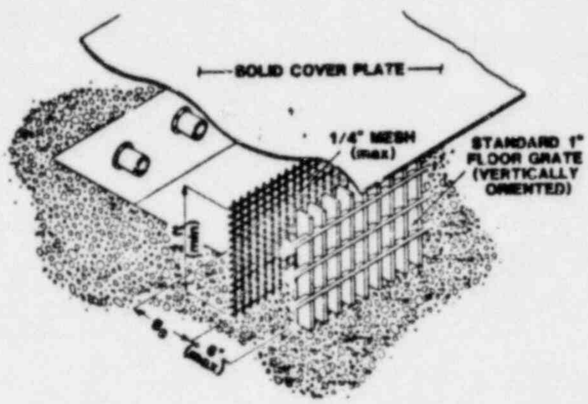
*These additional considerations are provided to ensure that the experimental data boundaries (upon which Tables 5.2 and 5.3 are based) resulting from the experimental studies at Alden Research Laboratory are noted.

TABLE 5.5

Screen, Grate, and Cover Plate Design Findings*

1. Minimum plane face screen area, see Table 5.2.

2. Minimum height of open screen should be 2 feet.



3. Distance from sump side to screens, g_s; g_s may be any reasonable value.

4. Screens should be 1/4 inch mesh or finer.

5. Gratings should be vertically oriented 1 to 1-1/2 inch standard floor grate or equivalent.

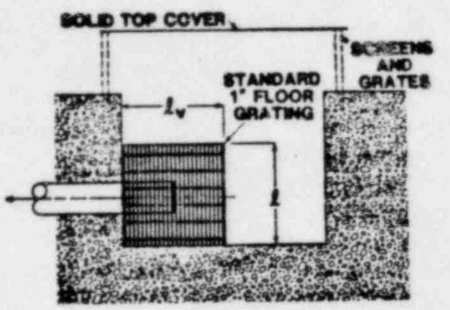
6. The distance between the screens and grates shall be 6 inches or less.

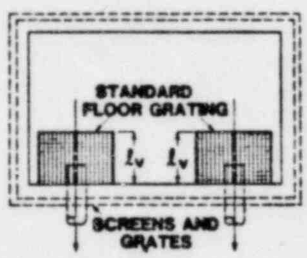
7. A solid cover plate above the sump and extending to the screens and grates is required; the cover plate must be designed to ensure the release of air trapped below the plate (a cover plate located below the minimum water level is preferable).

*These additional details are pertinent to the Alden Research Laboratory's full scale tests and were found to yield satisfactory sump hydraulic performance.

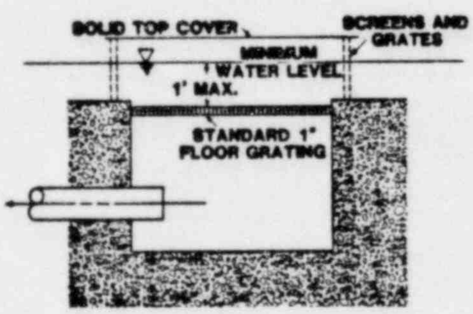
TABLE 5.6

Findings For Selected Vortex Suppression Devices*





1. Cubic arrangement of standard 1-1/2 inch or deeper floor grating (or its equivalent) with a characteristic length, ℓ_v, that is $\geq$ 3 pipe diameters; the top of the cube must be submerged a minimum of 6 inches below the minimum water level. Non-cubic designs, where ℓ_v is $\geq$ 3 pipe diameters for the horizontal upper grate, satisfying the depth and distances to the water minimum water surface given for cubic designs are acceptable.



2. Standard 1-1/2 inch or deeper floor grating (or its equivalent) located horizontally over the entire sump and containment floor inside the screens and located between 3 inches and 12 inches below the minimum water level.

*These types of vortex suppressors were tested at Alden Research Laboratory and have demonstrated the capability to reduce air ingestion to 0%, even under the most adverse conditions simulated.

TABLE 5.7

Debris Assessment Considerations*

CONSIDERATION	EVALUATE
1) Debris Generator (Pipe Breaks & Location as identified in SRP Section 3.6.2)	° Major Pipe Breaks & Location ° Pipe Whip & Pipe Impact ° Break Jet Expansion Envelope (This is the major debris generator)
2) Expanding Jets	° Jet Expansion Envelope ° Piping & Plant Components Targeted (i.e., steam generators) ° Jet Forces on Insulation ° Insulation Which Can Be Destroyed or Dislodged by Blowdown Jets. ° Sump Structure (i.e., screen) Survivability Under Jet Loading
3) Short-Term Debris Transport (transport by blowdown jet forces)	° Jet/Equipment Interaction ° Jet/Crane Wall Interaction ° Sump Location Relative to Expanding Break Jet
4) Long-Term Debris Transport (transport to the sump during the recirculation phase)	° Containment Layout & Sump Location ° Heavy (or "Sinking") Debris ° Floating Debris ° Neutral Buoyancy Debris
5) Screen Blockage Effects (impairment of flow and/or NPSH margin)	° Screen Design ° Sump Location ° Water Level Under Post LOCA Conditions ° Flow Requirements

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Key Elements for Assessment of Debris Effects	° Estimated Amount of Debris That Can Reach Sump ° Screen Blockage ° ΔP Across Blocked Screens

*per debris estimation methods described in Section 3.3

5.3 Debris Assessments

Debris assessments should consider the initiating mechanisms (pipe break locations, orientations, and break jet energy content), evaluation of the amount of debris that might be generated, short- and long-term transport, the potential for sump screen blockage, and head loss that could degrade available NPSH. Table 5.7 outlines key considerations requiring evaluation. Evaluation of potential debris effects requires the following information:

1. Identification of major break locations (per SRP 3.5.2) and jet energy levels.

2. Types, quantities, methods of fabrication and installation, mechanical attachments, and hygroscopic characteristics of the insulation employed on primary and secondary system piping, reactor pressure vessel, and major components (e.g., steam generators, reactor coolant pumps, pressurizer, tanks, etc.) that can become targets of expanding jet(s) identified under Item (1).

3. Containment plan and elevation drawings showing high energy line piping runs, system components, and piping that are sources of insulation debris, structures and system equipment that become obstructions to debris transport, sump location(s), and drawings showing sump design details, including trash rack and screen details, as well as suction piping orientation.

4. Expected recirculation phase water levels and RHR and CSS pump NPSH requirements versus flow rate.

Generic findings regarding debris that might be generated, transported and lodged against sump screens (and the plant specific dependence of these phenomena) are discussed in Section 3.3 and presented in detail in References 5, 6, and 7. The following paragraphs summarize the findings:

1. Break locations, type and size, and break jet targets are major factors to consider in the estimation of potential qualtities of debris generated. The break-jet is a high energy two-phase expansion that is capable of disintegrating insulation and insulation coverings by producing high impingement pressures and large jet loads.

2. Mirror (reflective metallic insulations) and totally encapsulated insulations do not appear to pose screen blockage problems. However, if the sump location can be directly targeted by an expanding break jet, a close examination of possible jet load damage to such insulations and their possible prompt transport to the sump should be made.

3. Low density insulations, such as calcium silicate and unibestos, have closed cell structures and float. They are unlikely to impede flow through sump screens. Partially submerged screens should, however, be evaluated for pull-down of floating debris. Low density hygroscopic insulations that, upon being wetted, have equilibrium densities greater than water require plant specific determinations of screen blockage effects.

4. Nonencapsulated insulations (particularly mineral wool and fiberglass materials) have been shown to present the possibility for high screen blockages (References 5, 7, 14, and 15). These materials, even if deposited in relatively small thickness layers onto sump screens (e.g., on the order of an inch or less), can result in high pressure drops. For those plants employing quantities of nonencapsulated insulations, potential screen blockages should be calculated using the models provided in Reference 5, the experimental information on transport (see Table 5.8) and head losses given in Reference 7 as well as actual plant layouts that include postulated rupture locations (PRLs) and insulation locations. Insulation debris screen thicknesses, t_i, should be estimated as:

$$t_i = \frac{\text{Volume of debris transported}}{\text{Available sump screen area}} .$$

Calculations of pressure drops at required RHR flow can be made using the analytical methods given in Reference 5, the experimental information presented in References 6 and 7, using the flowchart provided in Figure 5.2, and the detailed procedure provided in Appendix B.

5.4 Pump Performance Under Adverse Conditions

The pump industry historically has determined net positive suction head requirements for pumps on the basis of a percentage degradation in performance. The percentage is arbitrary, but generally 1 percent or 3 percent. A 2 percent limit on allowed air ingestion has been set because data show that air ingestion levels exceeding 2 percent can produce significant head degradation. Either the 2 percent limit in air ingestion or the NPSH requirement to limit cavitation may be used independently when the two effects act independently. However, air ingestion levels less than 2 percent will affect NPSH requirements. In determining these combined effects, the effects of air ingestion should be taken into account.

A calculational method for assessing pump inlet conditions is shown in Figure 5.3. For a given sump design, the following procedure can be followed:

1. Determine the static water pressure at the sump suction pipe after debris blockage effects have been evaluated. (See Section 5.3.) Note that the water level in the sump should not be so low that a limiting critical water depth occurs at the sump edge such that flow is restricted into the sump.

2. Assess potential level of sump air ingestion using criteria set forth in Section 5.2.

3. Determine pressure losses between sump suction pipe inlet and pump inlet flange for the required RHR and CSS flows. If the pump inlet is located less than 14 pipe diameters from suction pipe inlet, the effect of sump-induced swirl should be evaluated. (See Section 3.2.3 and References 2 and 8).

4. Calculate the static pressure at the pump inlet flange. Static pressure is equal to containment atmospheric pressure plus the hydrostatic pressure due to pump elevation relative to sump surface level less pressure losses and the dynamic pressure due to velocity. (See Section 3.2.3.) Note that no credit is allowed for containment overpressure per SRP Section 6.2.

5. Calculate the air density at the pump inlet, then calculate the air volume flow rate at the pump inlet, incorporating the density difference from sump suction pipe to the pump.

6. If the calculated air ingestion is found to be less than or equal to 2 percent, proceed to Step 7. If the calculated air ingestion is greater than 2 percent, reassess the sump design and operation per Section 5.1.

7. Calculate the net positive suction head (NPSH) available.

8. If air ingestion is indicated, correct the NPSH requirement from the manufacturer's pump curves by the following relationship:

$$NPSH_{required}(air/water) = NPSH_{required}(water) \times \beta$$

where

$$\beta = 1 + 0.50\ \alpha_p$$

and α_p is the air ingestion rate (in percent by volume) at the pump inlet flange.

9. If NPSH available from Step 7 is greater than the NPSH requirement from Step 8, inlet considerations will be satisfied.

TABLE 5.8

Transportation Tests Results
From Reference 7

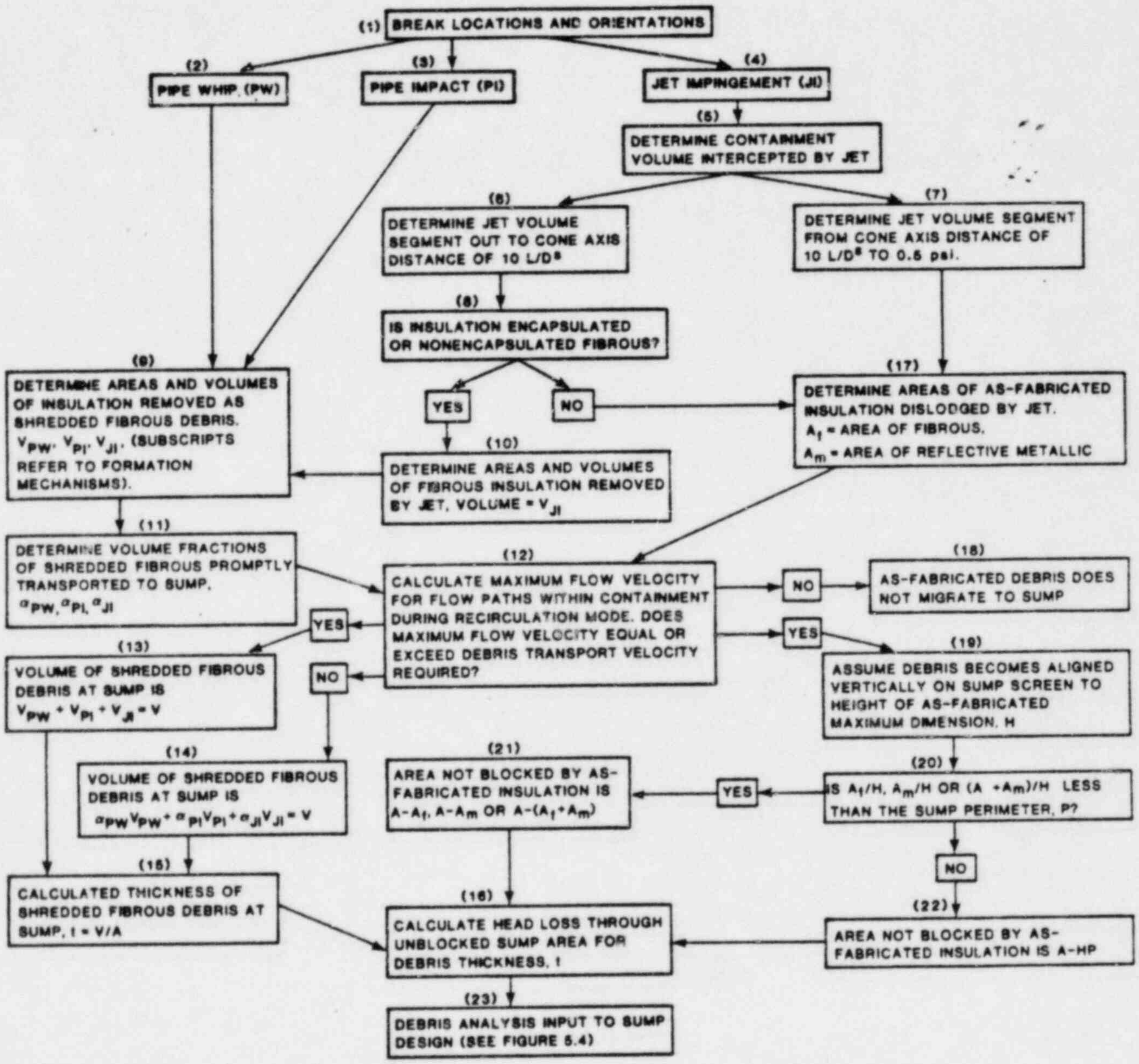
Condition	Pillow Type	V_i (ft/sec)	V_s (ft/sec)	V_v (ft/sec)	ΔH (ft)	$\frac{\Delta H}{\frac{V^2}{2g}}$	Comments
Whole pillows (floating)	1	N/A	N/A	>2.3			
	2	N/A	N/A	N/A			Sunk while against screen
	3	N/A	N/A	N/A			Sunk while against screen
Whole pillows (sunken)	1	1.1	1.1	1.1	0.13		Only one pillow
		0.9	1.1	1.1	0.07		Only one pillow; folded in half on screen
	2	1.2	1.8	2.0	0.44	7.1	
		1.4	1.6	2.4			
	3	1.5	1.7	2.0	0.60	9.7	
		1.1	1.6	1.6	0.33	8.3	Pillows on screens overlap by 2 inches
Pillows with covers removed but included and separated insulation layers (sunken)	1	1.1	1.1	1.1	0.67	35.7	
		0.9	1.5		0.96	27.5	Not all pieces vertical
	2 or 3	1.1	>1.6				
		0.9	1.2	1.2	0.71	31.7	
Pillows with covers and insulation layers in 5 pieces (sunken)	1	1.0	1.9		1.4	25.0	Not all pieces vertical
		1.1	2.0		1.6	25.6	
	2 or 3	1.0	1.4	1.6	0.54	13.6	Significant overlap of pieces on screen
Very small pieces							
4" x 4" x 1"	2 or 3	0.7					
4" x 1" x 1"		0.5					
Shreads (sunken)		0.2					
Metallic reflective sample	N/A	2.6	2.6				
		2.0	>2.3				
Closed cell sample	N/A	2.5	2.5				
		1.1	1.7				

NOTES: V_i = velocity needed to initiate motion of at least one piece of insulation (not including covers when separated from pillows)

V_s = velocity needed to bring all material on screen

V_v = velocity needed to flip all pieces vertically on screen

ΔH = head loss at V_v (or V_s if V_v not given)



V_{PW} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY PIPE WHIP. (FT^3)
V_{PI} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY PIPE IMPACT. (FT^3)
V_{JI} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY JET IMPINGEMENT. (FT^3)
α_{PW} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY PIPE WHIP PROMPTLY TRANSPORTED TO SUMP.
α_{PI} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY PIPE IMPACT PROMPTLY TRANSPORTED TO SUMP.
α_{JI} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY JET IMPINGEMENT PROMPTLY TRANSPORTED TO SUMP.
L/D - RATIO OF PIPE LENGTH TO PIPE DIAMETER.
V - TOTAL VOLUME OF SHREDDED DEBRIS TRANSPORTED TO SUMP SCREEN. (FT^3)
A_f - AREA OF AS-FABRICATED FIBROUS INSULATION DISLODGED BY JET. (FT^3)
A_m - AREA OF AS-FABRICATED REFLECTIVE METALLIC INSULATION DISLODGED BY JET. (FT^2)
A - EFFECTIVE AREA OF SUMP SCREEN. (FT^2)
H - MAXIMUM LINEAR DIMENSION OF AS-FABRICATED INSULATION. (FT)
P - PERIMETER OF EFFECTIVE SUMP SCREEN. (FT)
t - CALCULATED THICKNESS OF SHREDDED DEBRIS MAT ON SUMP SCREEN. (IN)

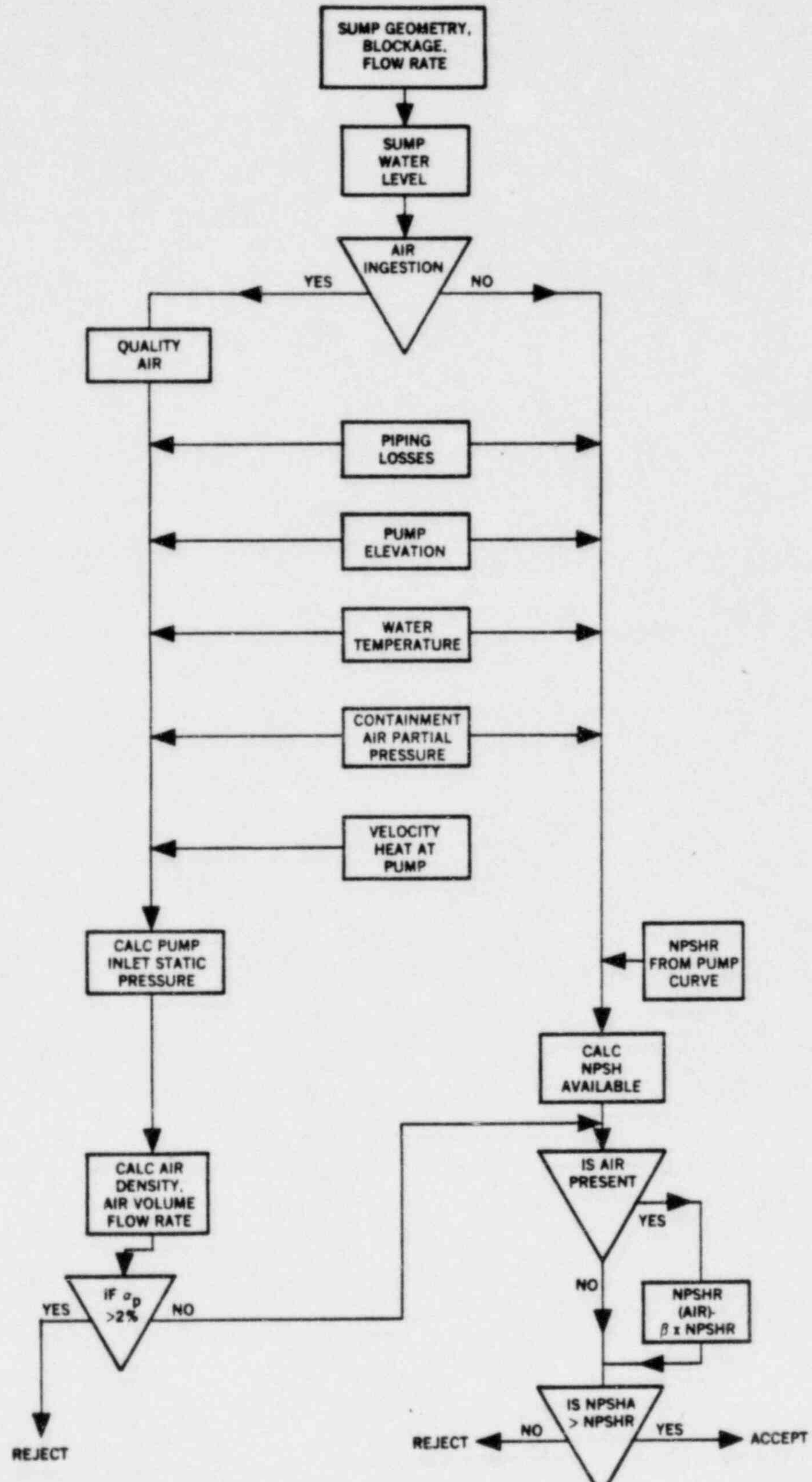
*CALCULATIONAL METHODS ARE AS GIVEN IN REFERENCE 5.

Figure 5.2 Debris Generation, Transport and Sump Blockage Potential

If the above review procedure leads to the conclusion that an inadequate NPSH margin exists, further plant specific discussions need to be undertaken with the applicant for resolution of differences, uncertainties in calculations, plant layout details, etc., for resolution of this finding. The lack of credit for containment overpressure should be recognized as a conservatism which should be assessed on a plant specific basis.

5.5 Combined Effects

The findings from Sections 5.2, 5.3 and 5.4 can be combined in the manner shown in Figure 5.4 to determine overall sump performance.



FLOW CHART FOR CALCULATION OF PUMP INLET CONDITION

Figure 5.3

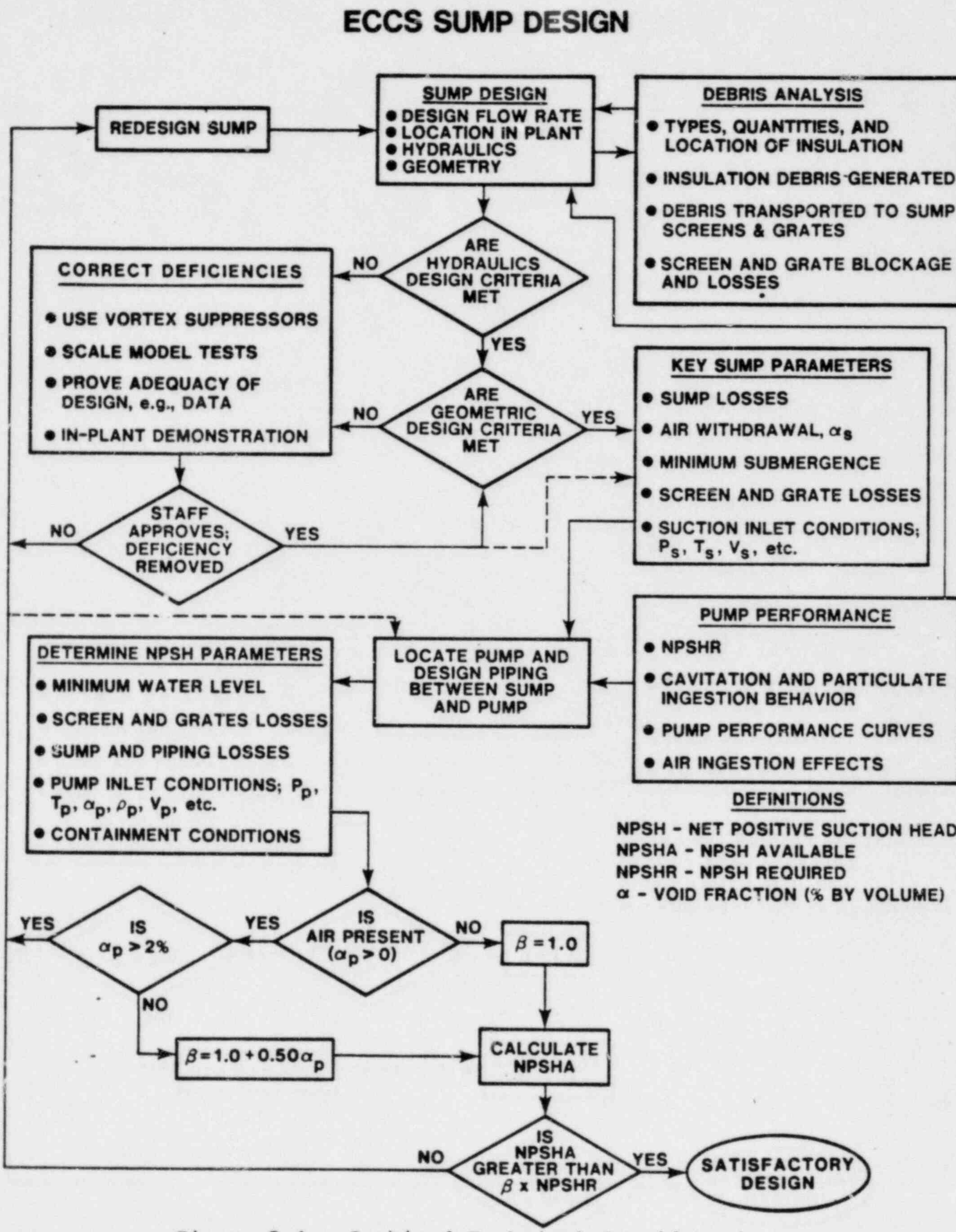


Figure 5.4. Combined Technical Considerations for Sump Performance

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APPENDIX A

PLANT SUMP DESIGNS

AND CONTAINMENT LAYOUTS

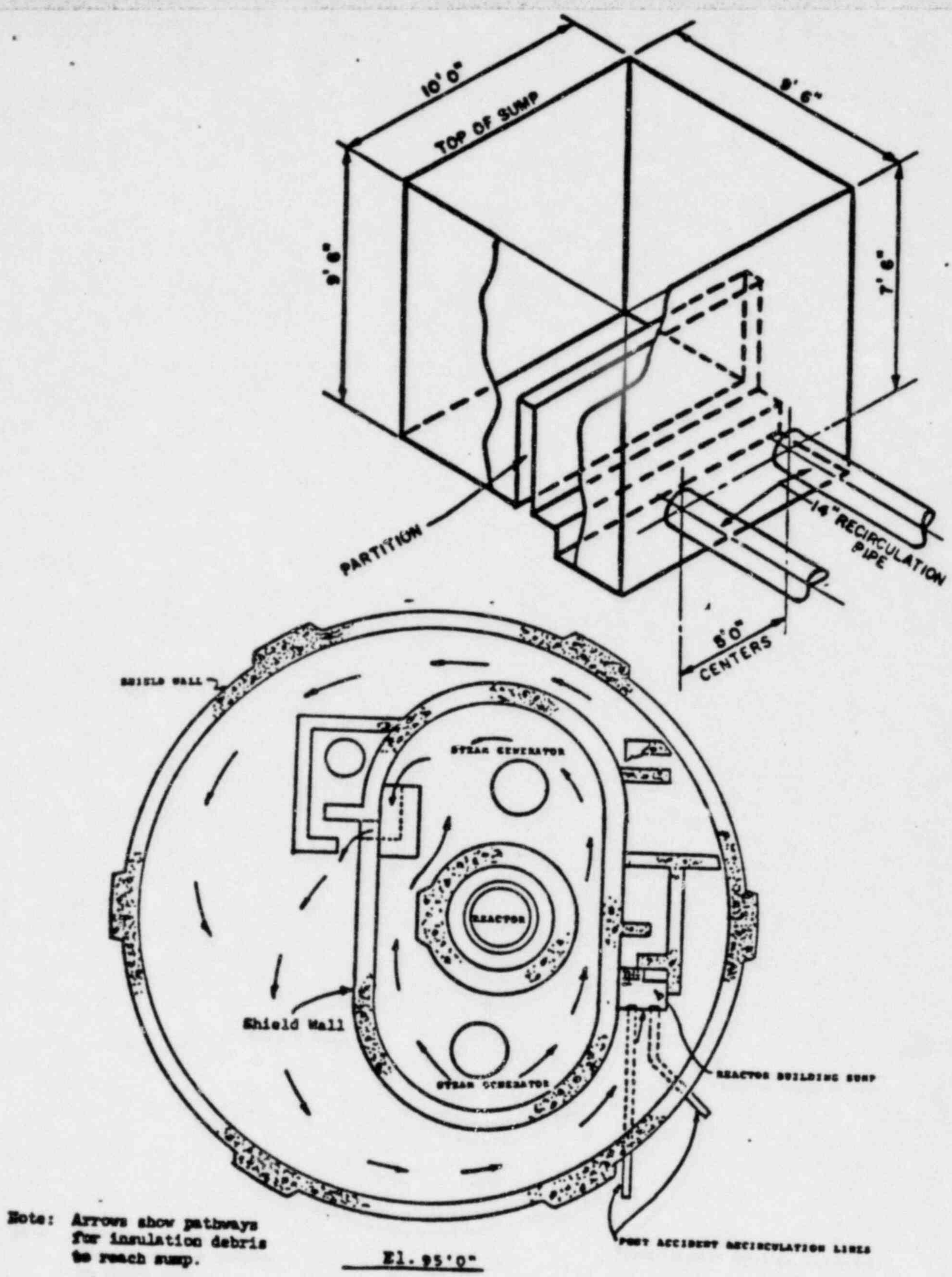


Figure A-1. ECCS Sump and Containment Building Layout, Crystal River Unit 3

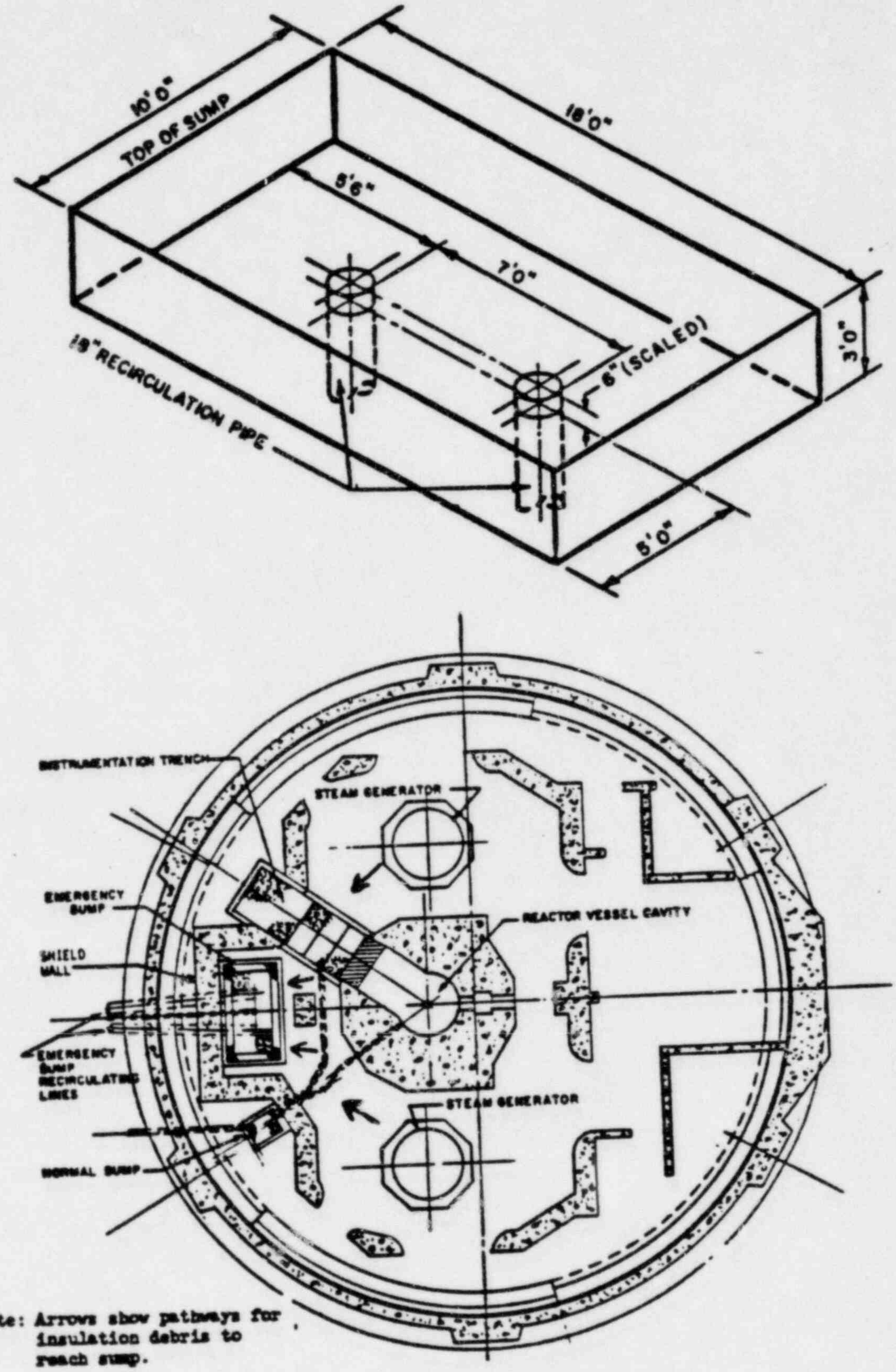


Figure A-2. ECCS Sump and Containment Building Layout, Oconee Unit 3

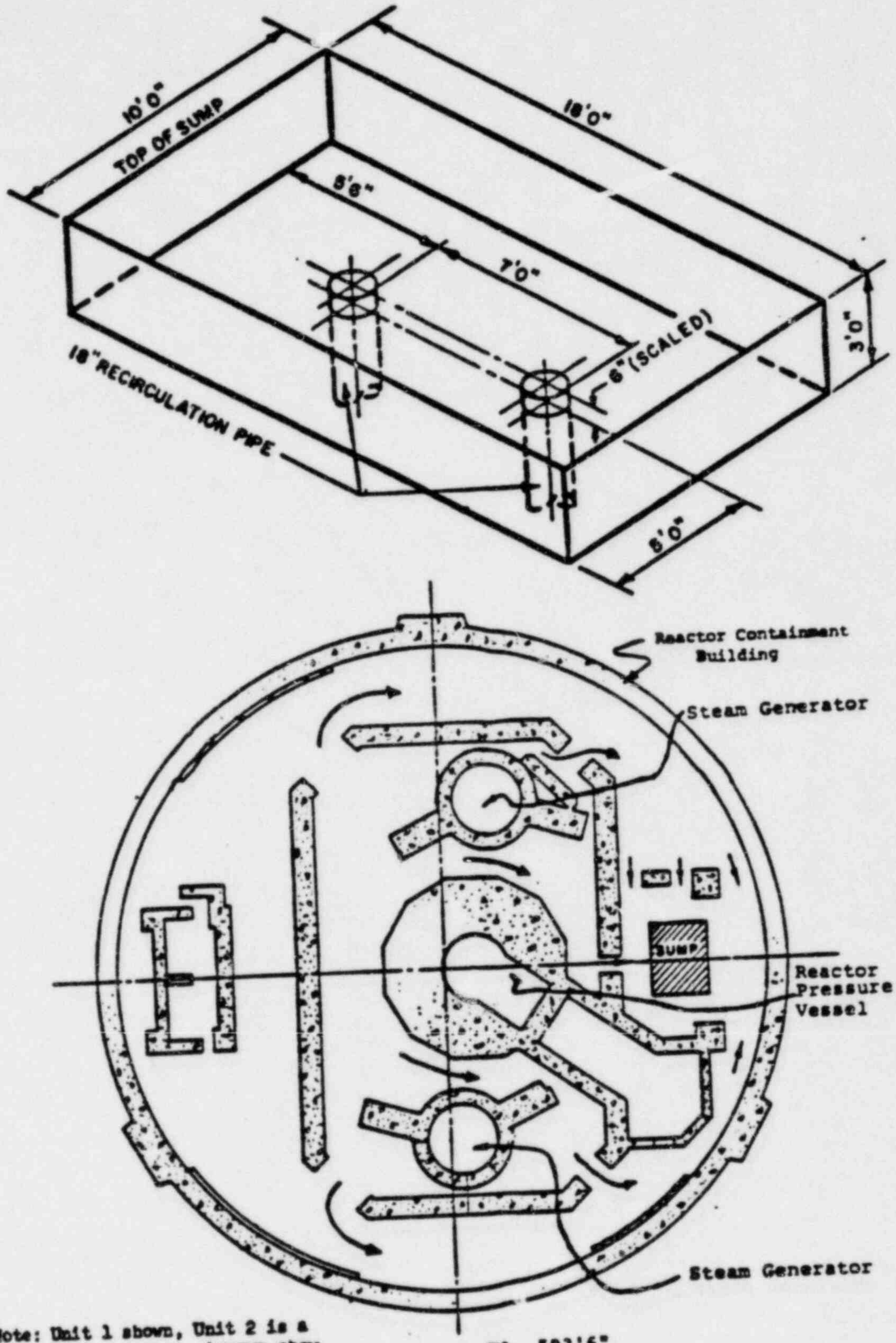


Figure A-3. ECCS Sump and Containment Building Layout, Midland Unit 2

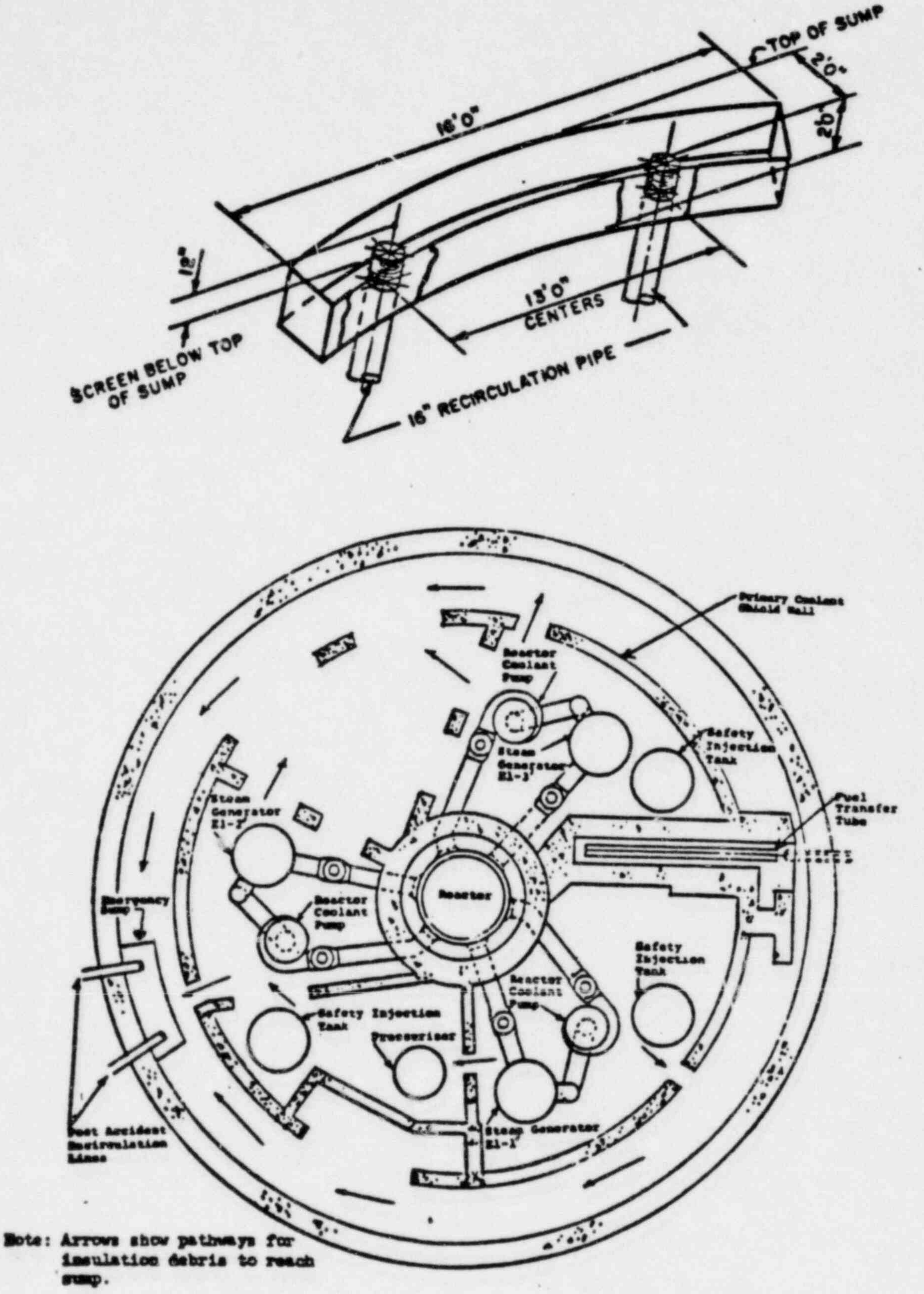
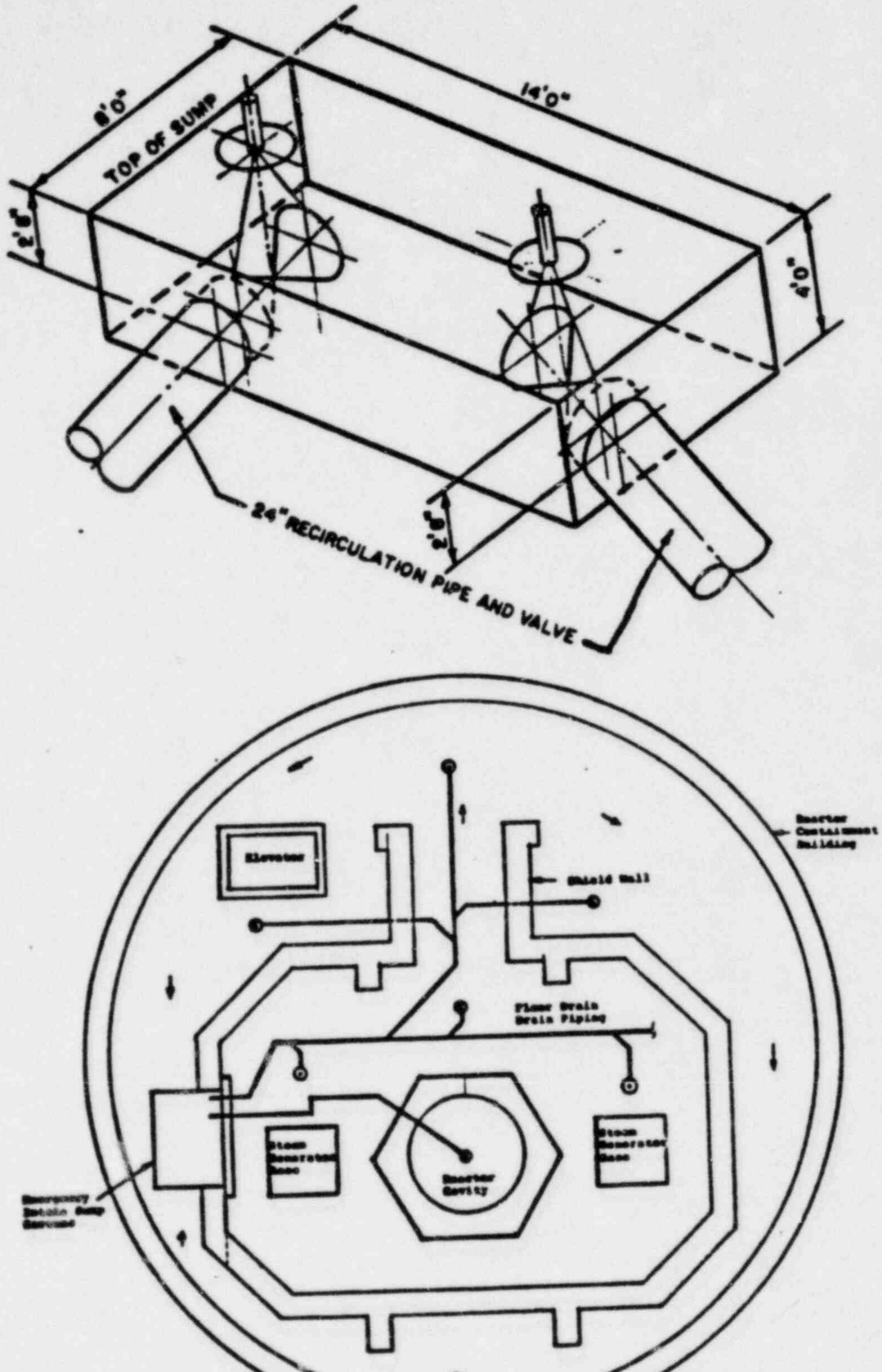


Figure A-4. ECCS Sump and Containment Building Layout, Maine Yankee



Note: Arrows show pathways for insulation debris to reach sump.

Figure A-5. ECCS Sump and Containment Building Layout, Arkansas Unit 2

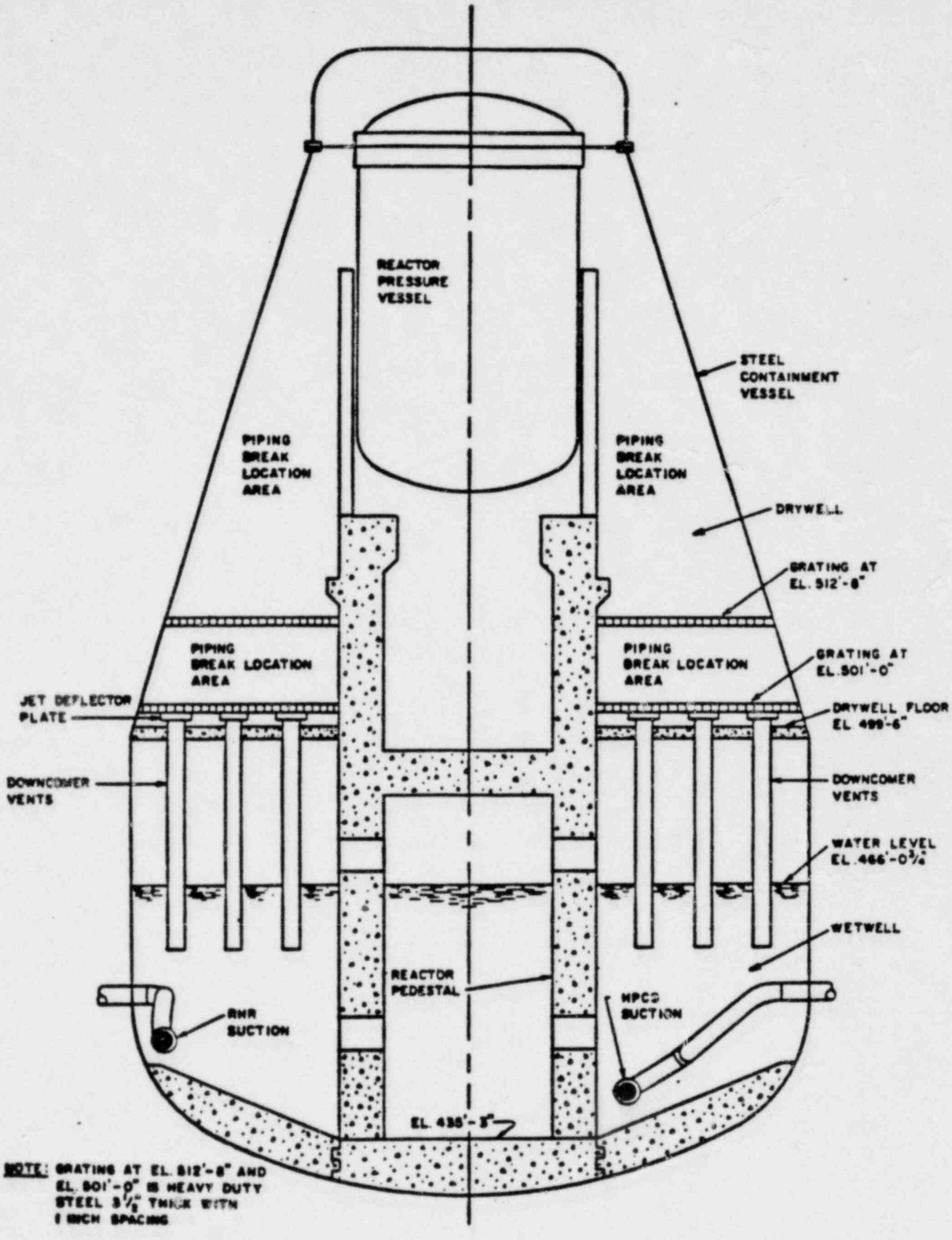


Figure A-6. Primary Containment Vessel, WPPSS Unit 2

APPENDIX B

A Procedure for Estimating Debris Generation, Transport, and Sump Screen Blockage Potential

Generic findings regarding insulation debris generation, its transport, the potential for sump screen blockage by debris and the plant specific dependence of these phenomena are discussed in Section 3.3 of this report and are presented in detail in Reference B-1. References B-2 and B-3 provide supplementary experimental data related to the above issues. A procedure for estimating, in step-wise fashion, debris generation, transport, and screen blockage is described in the following paragraphs and is illustrated in Figure B-1. The analytical methods to be used are those provided in Reference B-1.

1. Pipe break locations and orientations are determined for possible LOCAs in containment (Box 1 of figure).

2. Three mechanisms for debris generation are considered: pipe whip (Box 2), pipe impact (Box 3) and jet impingement (Box 4). Of these, the mechanism that produces the preponderance of debris is jet impingement.

3. The containment volume intercepted by the jet is determined (Box 5).

4. A large break jet can disintegrate insulation at pressures of 20 psi and above (Reference B-2). This is approximately equivalent to an axial distance along the jet centerline of 10 L/Ds from the jet origin (Reference B-4). The volume contained within this cone is to be calculated (Box 6).

5. At axial distances along the jet centerline greater than 10 L/Ds to distances where stagnation pressures of 0.5 psi are caluclated, insulation is assumed to be dislodged in an as-fabricated form within the volume encompassed by the jet. The greater distance corresponds approximately to 0.5 psi as given in Reference B-1, as the lower limit of insulation damage. The volume contained within this jet segment is to be calculated (Box 7).

   Note: The results obtained from this calculation will be used in the determination of as-fabricated insulation dislodged and the calculational procedure proceeds to Box 17.

6. Within the jet volume extending from the jet region to 10 L/Ds (~ 20 psi), determine if encapsulated or nonencapsulated is present (Box 8).

7. If insulation, as described in 6, is present within the volume intercepted by the jet, determine the areas removed and calculate the insulation volumes from the as-fabricated dimensions (Box 10).

8. Determine the volumes of insulation removed by pipe whip, PW, pipe impact, PI, and jet impingement, JI. This material is to be treated as shredded fibrous debris. Volumes are to be determined from as-fabricated dimensions (Box 9).

9. Determine those volumes fractions of shredded fibrous debris that are promptly transported by pipe whip, α_{PW}, pipe impact, α_{PI}, and by jet impingement, α_{JI}, to the sump screen (Box 11).

10. Calculate the maximum flow velocity that exists in the containment under recirculation conditions using the methods provided in Reference B-1. Determine if this flow velocity is sufficient to allow the migration of sunken shredded fibrous debris to migrate to the sump using the transport information given in Table B-1 (Box 12).

11. If the flow velocity calculated from 10, above, is sufficient to cause migration, all the shredded fibrous insulation generated ($V_{PW} + V_{PI} + V_{JI}$) is assumed to migrate to the sump screen (Box 13).

12. If the flow velocity calculated from 10, above, is insufficient to cause migration, prompt transport is the only mechanism for shredded insulation to reach the screen. The volume of this material at the screen is $\alpha_{PW} V_{PW} + \alpha_{PI}V_{PI} + \alpha_{JI}V_{JI}$ (Box 14).

13. Upon the determination of the volume of shredded debris that reaches the screen (either 11 or 12 above apply), the equivalent thickness of shredded debris forming a mat on the sump is calculated. This value is: $t = V/A$, where V is the combined debris volume, determined in either 11 or 12 above, and A is the effective area of the sump screen (Box 15).

Note: Before proceeding to the following step, calculations provided in Boxes 17 through 22 are required.

14. Upon completion of 5 above, the areas of insulation, whether fibrous, A_f, or reflective metallic, A_m, estimated to have been dislodged within the jet volume contained along the axial distance from the source between stagnation pressures of 20 (10 L/Ds) to 0.5 psi. If reflective metallic was contained within the volume to axial distances from the source to 20 psi stagnation pressures, this is to be included in the area of this material dislodged, A_m (Box 17).

15. The maximum containment flow velocity calculated in 10, above, is referred to, as are the flow requirements to allow debris migration (Table B-1) (Box 12).

16. If the maximum containment flow velocity is insufficient for debris to migrate, as-fabricated debris (either fibrous or reflective metallic) does not reach the sump (Box 18).

17. If the maximum containment flow velocity is sufficient to allow the migration of fibrous as-fabricated insulation or both fibrous and reflective metallic insulations, it is assumed that such insulation(s) become vertically aligned along the sump screen face to a height corresponding to the maximum as-fabricated insulation dimension, H (see Reference B-3) (Box 19).

18. If only as-fabricated fibrous material migrates to the screen, determine if its equivalent length, A_f/H, is greater than the sump perimeter, P. If only as-fabricated reflective metallic can migrate to the screen, calculate the equivalent length, A_m/H. If both species can migrate, calculate the equivalent length of both, $(A_f + A_m)/H$ (Box 20).

19. If the equivalent lengths determined in 18 above are less than the equivalent perimeters of the sump screen, P, the area not blocked by as-fabricated insulation is $A - A_f$, or $A - A_m$, or $A - (A_f + A_m)$, where A is the equivalent screen area of the sump (Box 21).

20. If the equivalent lengths calculated in 18 above are greater than the equivalent perimeter of the sump screen, P, the amount of screen blockage by as-fabricated debris can be no more than the area composed of the perimeter, P, multiplied by the maximum as-fabricated height, H, of the insulation (see Reference B-3). The area not blocked by as-fabricated insulation is thus calculated to be A - HP, where A is the equivalent screen area of the sump (Box 22).

21. Using the equivalent shredded fibrous insulation thickness, t, obtained from 13 above, and the unblocked screen area, obtained from 19 or 20 above, determine the head loss through the debris mat from Reference B-3 (Box 16).

22. The head loss calculated in Step 16 serves as debris analysis input to the requirements for sump design, as shown in Figure 5.4 and discussed under Combined Effects in Section 5.5 of this report.

TABLE B-1

Transportation Tests Results
From Reference B-3

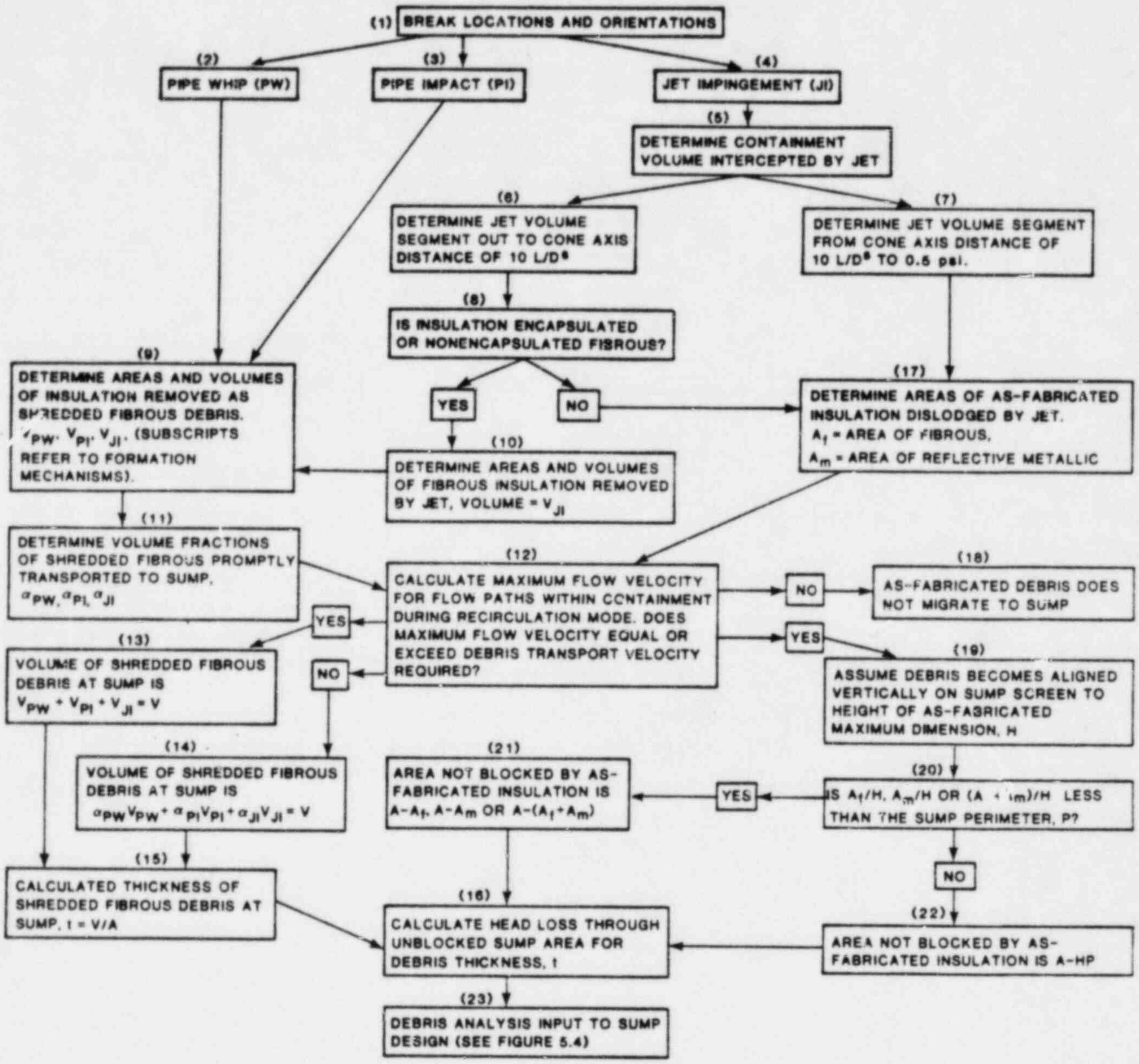
Condition	Pillow Type	V_i (ft/sec)	V_s (ft/sec)	V_v (ft/sec)	ΔH (ft)	$\frac{\Delta H}{\frac{V^2}{2g}}$	Comments
Whole pillows (floating)	1	N/A	N/A	>2.3			
	2	N/A	N/A	N/A			Sunk while against screen
	3	N/A	N/A	N/A			Sunk while against screen
Whole pillows (sunken)	1	1.1	1.1	1.1	0.13		Only one pillow
		0.9	1.1	1.1	0.07		Only one pillow; folded in half on screen
	2	1.2	1.8	2.0	0.44	7.1	
		1.4	1.6	2.4			
	3	1.5	1.7	2.0	0.60	9.7	
		1.1	1.6	1.6	0.33	8.3	Pillows on screens overlap by 2 inches
Pillows with covers removed but included and separated insulation layers (sunken)	1	1.1	1.1	1.1	0.67	35.7	
		0.9	1.5		0.96	27.5	Not all pieces vertical
	2 or 3	1.1	>1.6				
		0.9	1.2	1.2	0.71	31.7	
Pillows with covers and insulation layers in 5 pieces (sunken)	1	1.0	1.9		1.4	25.0	Not all pieces vertical
		1.1	2.0		1.6	25.6	
	2 or 3	1.0	1.4	1.6	0.54	13.6	Significant overlap of pieces on screen
Very small pieces 4" x 4" x 1"	2 or 3	0.7					
4" x 1" x 1"		0.5					
Shreads (sunken)		0.2					
Metallic reflective sample	N/A	2.6	2.6				
		2.0	>2.3				
Closed cell sample	N/A	2.5	2.5				
		1.1	1.7				

NOTES: V_i = velocity needed to initiate motion of at least one piece of insulation (not including covers when separated from pillows)

V_s = velocity needed to bring all material on screen

V_v = velocity needed to flip all pieces vertically on screen

ΔH = head loss at V_v (or V_s if V_v not given)



V_{PW} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY PIPE WHIP. (FT^3)
V_{PI} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY PIPE IMPACT. (FT^3)
V_{JI} - VOLUME OF SHREDDED FIBROUS INSULATION REMOVED BY JET IMPINGEMENT. (FT^3)
α_{PW} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY PIPE WHIP PROMPTLY TRANSPORTED TO SUMP.
α_{PI} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY PIPE IMPACT PROMPTLY TRANSPORTED TO SUMP.
α_{JI} - FRACTION OF VOLUME OF SHREDDED INSULATION CAUSED BY JET IMPINGEMENT PROMPTLY TRANSPORTED TO SUMP.
L/D - RATIO OF PIPE LENGTH TO PIPE DIAMETER.
V - TOTAL VOLUME OF SHREDDED DEBRIS TRANSPORTED TO SUMP SCREEN (FT^3)
A_f - AREA OF AS-FABRICATED FIBROUS INSULATION DISLODGED BY JET. (FT^3)
A_m - AREA OF AS-FABRICATED REFLECTIVE METALLIC INSULATION DISLODGED BY JET. (FT^2)
A - EFFECTIVE AREA OF SUMP SCREEN. (FT^2)
H - MAXIMUM LINEAR DIMENSION OF AS-FABRICATED INSULATION. (FT)
P - PERIMETER OF EFFECTIVE SUMP SCREEN. (FT)
t - CALCULATED THICKNESS OF SHREDDED DEBRIS MAT ON SUMP SCREEN (IN)

Figure B-1. Debris Generation, Transport, and Sump Blockage Potential

Note: Caclulational Methods are as Given in Reference B-1.

References to Apendix B

B-1 Wysocki, J. J. et al., "Methodology for Evaluation of Insulation-Debris," NUREG/CR-2791, Burns and Roe, Inc., Oradell, NJ, (to be published).

B-2 Durgin, W. W. and Noreika, J. F., "Thermal Debris Formation Due to Impingement of High Energy Jet Flow/Preliminary Report," and Addendum, Alden Research Laboratory, Holden, MA, August 1982.

B-3 Brocard, D. N., "Buoyancy, Transport and Head Loss of Fibrous Reactor Insulation," Alden Research Laboratory, draft report, Holden, MA, July 1982.

B-4 Weigand, G. G. and Thompson, S. L., "Break Flow and Two-Phase Jet Load Model," Sandia National Laboratories, Albuquerque, NM. Presented at International Meeting on Thermal Reactor Safety, Chicago, IL, August 1982.

APPENDIX C

Insulation Debris Formation Under Jet Flow Conditions

As discussed in Sections 3.3, 5.3, and Appendix B of this report, it has been assumed that encapsulated and nonencapsulated insulations disintegrate at break jet stagnation pressures of 20 psi and greater. This assumption is based upon observations made at Alden Research Laboratory of water jet damage to three types of nonencapsulated insulations at various stagnation pressures and at two angles of jet impingement (Reference C-1).

The above experiments, carried out at ambient water temperature, revealed that the most damage susceptible of the as-fabricated insulations tested (Type 1, see Table C-1) first began to fail at 20 psi jet pressure and when subjected to a jet impingement at 45° to the normal. As discussed here, the onset of failure consisted of the covering of the as-fabricated blanket starting to pull apart after being subjected to a 2" diameter jet at 20 psi for a 5 minute period. A summary of the damage onset results obtained are provided in Table C-1.

In the use of the assumption of 20 psi as that stagnation pressure where both encapsulated and nonencapsulated insulations disintegrate, the extrapolation of the results obtained from a small jet (2" diameter) used in the referenced experiments to a large jet that might result from a LOCA must be made. It is noted here that the threshold of damage determined experimentally (as opposed to an assumed disintegration into insulation shreds or fibers) has been judged to begin with damage to as-fabricated insulation blanket covers. The pressure loadings on such coverings due to jet impingement may be represented as:

$$F = P \times A \quad \text{(lbs)}$$

where P is the jet stagnation pressure in psi and A is area of jet impact in square inches.

If ρ represents the number of fabric mesh nodes per unit area of fabric, the total number of nodes in area A is:

$$n = \rho \times A \, .$$

The force exerted per node is then

$$F = \frac{P \times A}{\rho \times A} = P/\rho \quad \text{(lbs/node)}$$

and is, consequently, independent of the area covered by the jet.

In the development of a procedure through which estimates may be made of debris generation, transport and potential sump blockage (see Appendix B), it has been assumed that insulation contained within the jet volume where the

Table C-1
Summary of Jet Impingement Experiments
(onset of damage) (Abstracted from Reference C-1)

Insulation Type *	Duration of Jet Impingement (min)	Angle of Jet to Surface (degrees)	Jet Pressure (psi)	Comments
1	5	90	35	side seam ruptured
1	5	45	20	covering starting to pull apart
2	5	90	40	initial rips, small
2	5	45	30	initial rip, 1-1/2"x 3/8"
3	5	90	65	blowout, 8" dia. hole
3	5	45	45	small rip

Type 1: 4" mineral wool or refractory mineral fiber (6 lb. density) covered with Uniroyal #6555 asbestos cloth coated with 1/2 mil. Mylar.

Type 2: 4" Burlglass 1200, or 4 layers of 1" thick Filomat D (fiberglass), inner covering of knitted stainless steel mesh, outer covering of Alpha Maritex silicone aluminum cloth, product #2619.

Type 3: Same insulation materials as Type 2. Inner and outer covering of 18 ounce Alpha Maritex cloth, product #7371.

stagnation pressure is equal to or greater than 20 psi is disintegrated. This has been based upon the observations of threshold damage discussed above. This value of 20 psi has been related to nondimensional units (10 L/Ds) from a pipe break in a fully pressurized PWR. These nondimensional units have been used in the procedure and flow chart provided in Appendix B. In Figure C-1, the relationship of pressure to centerline distance in L/Ds from a pipe break at an initial pipe pressure of 150 bars (~ 2200 psi) is given. It may be observed that approximately 7.0 L/Ds corresponds to 20 psi. The assumption of insulation disintegration within a jet volume extended from the jet origin to 10 L/D^S distance is thus considered conservative.

The assumption is made that 0.5 psi represents the lower limit to which insulation damage (intact insulation dislodged) can occur. This value of 0.5 psi stagnation pressure is given in Reference C-3 and is considered to be conservative.

The assumptions present in this report regarding debris generation are thus considered conservative for the following reasons:

1. Complete insulation disintegration is assumed within jet volumes where stagnation pressures equal or exceed 20 psi. Such stagnation pressures (20 psi) have been observed to be those for the threshold of damage to the covers of the most damage susceptible as-fabricated insulations.

2. The duration of jet impingement during jet damage experiments lasted approximately twice that required for large LOCA blowdown (i.e., 5 min. versus approximately 2 min.).

3. At constant stagnation pressure, the load exerted on unit node of insulation cover is independent of jet impingement area.

4. The nondimensional axial distance along a jet (of initial pressure ~ 2200 psi) to a stagnation pressure of 20 psi is assumed, for conservatism to be 10 L/Ds.

5. Insulation, in as-fabricated form, is assumed to be dislodged at stagnation pressure between 20 psi (10 L/Ds) and 0.5 psi.

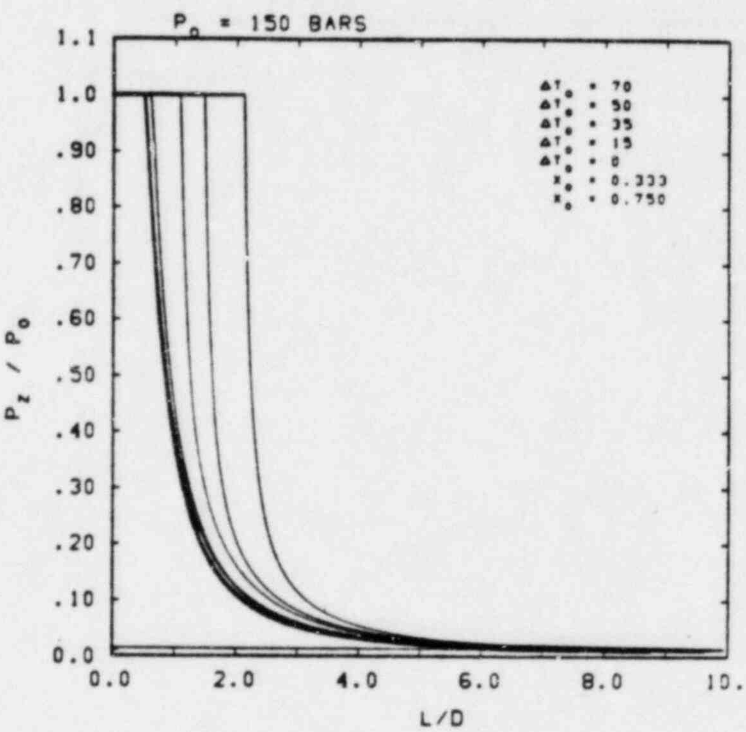


Figure C-1. Centerline target pressure distributions. Reproduced from Reference C-2. Note: Lower horizontal line represents a stagnation pressure of 20 psi. The intercept is at approximately 7.0 L/Ds.

References to Appendix C

C-1 Durgin, W. W. and Noreika, J. F., "Thermal Debris Formation Due to Impingement of High Energy Jet Flow/Preliminary Report" and Addendum, Alden Research Laboratory, Holden, MA, August 1982.

C-2 Weigand, G. G. and Thompson, S. L. "Break Flow and Two-Phase Jet Load Model," Sandia National Laboratories, Albuquerque, NM. Presented at International Meeting on Thermal Reactor Safety, Chicago, IL August 1982.

C-3 Wysocki, J. J., et al., "Methodology for Evaluation of Insulation Debris," NUREG/CR-2791, Burns and Roe, Inc., Oradell, NJ. (To be published.)