NUREG/CR-2761
ARL-49-82
SAND82-7065

Results of Vortex Suppressor Tests, Single Outlet Sump Tests and Miscellaneous Sensitivity Tests

Containment Sump Reliability Studies
Generic Task A-43

Prepared by M. Padmanabhan/ARL

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Prepared for
U.S. Nuclear Regulatory
Commission

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Manuscript Completed: March 1982
Date Published: September 1982

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Prepared for
Division of Safety Technology
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN A1237

ACKNOWLEDGEMENTS

This extensive research program was funded by the U.S. Department of Energy (DOE), and their support is sincerely appreciated. The scope of work was developed and significant technical contributions were made by personnel from the U.S. Nuclear Regulatory Commission (NRC), and the Sandia National Laboratories (Sandia), and the efforts of these organizations are gratefully acknowledged. Particular thanks are due to Mr. Andrew Millunzi of the DOE, Mr. Aleck Serkiz of the NRC, and Messrs. Peter Strom and Gilbert Weigand of Sandia for their efforts and valuable contributions in making the program effective.

The help provided by all members of the staff at the Alden Research Laboratory associated with this research project is gratefully acknowledged. Special mention must be made of the technical contributions of Professor George Hecker, data analyses by Dr. Shih-kuan Hsu, and the actual conduct of the experiments by Messrs. John Noreika and Russell Dube.

ABSTRACT

Full scale tests of flow conditions in Containment Recirculation Sumps for nuclear power stations were conducted at the Alden Research Laboratory (ARL) of Worcester Polytechnic Institute (WPI) for the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC), on a contract from Sandia National Laboratories (Sandia) to provide sump hydraulic design and performance data for use in resolving the Unresolved Safety Issue, A-43, "Containment Sump Performance".

This document is a report of the results of investigations conducted as a part of Phase II of the test program, including: (a) vortex suppressor tests to study in detail the hydraulic behavior of two commonly used suppressors; namely, cubic cage and horizontal floor grating; (b) single outlet sump tests to ascertain the hydraulic performance of single outlet sumps compared to double outlet sumps; and (c) tests to study the effects on the hydraulic performance of a solid partition wall in a double outlet sump, pump overspeed (i.e., higher flow), outlet pipe diameter, and bellmouth entrances.

The results mainly indicated that: (i) both cubic cage and horizontal grating suppressors were effective in reducing air-ingestion in the suction pipes to zero or near zero, reduced the pipe swirl to some extent, and did not significantly increase inlet losses; (ii) for Froude numbers less than 0.8, with or without any perturbation to the approach flow, both of the single outlet sumps tested indicated no significant air-withdrawals due to vortices, while pipe swirl angles and inlet loss coefficients were found to be similar to those obtained for the double horizontal outlet sumps previously tested; (iii) no significant differences in average vortex types, air-withdrawals and inlet loss coefficients were observed for double suction sumps with solid partition walls (compared to sumps without partition walls), but sumps with partition walls showed lower pipe swirl; (iv) pump overspeed tests (up to 30% higher than normal operating flows) conducted at nearly uniform approach flows indicated no significant increases in any of the variables of concern; (v) for sumps of the same size at the same Froude numbers (not the same flow and submergence), the outlet pipe diameter did not have any significant influence on air-withdrawals, while pipe flow swirl angle and inlet loss coefficient were found to be higher for larger pipe size, irrespective of Froude numbers; and (vi) bellmouth entrances helped reduce inlet loss coefficients but not the average vortex types, air-withdrawals, and pipe flow swirl.

Test data on single and double outlet sumps were used for an envelope analysis so as to derive appropriate maximum bounding values for average vortex types, air-withdrawals, pipe swirl, and inlet loss coefficients versus Froude number. These bounding values are compared with the bounding values of the Phase I tests [1]. In general, single outlet sumps indicated higher air-withdrawals as shown by void fraction envelope lines. Common envelope lines for both single and double outlet sumps were found appropriate for average vortex types, swirl angles, and inlet loss coefficients. These envelope lines indicated higher bounding values compared to Phase I test envelopes. Results of the envelope analysis and an evaluation of other results reported on herein, would provide a data base for use in the preparation of sump design and in their evaluation, and thereby assists in the resolution of the Unresolved Safety Issue, A-43 "Containment Sump Performance".

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EXECUTIVE SUMMARY

As a part of the overall full scale tests of hydraulic performance of containment recirculation sumps for nuclear power stations, various special items were investigated and are discussed in this report; namely, vortex suppressors, single outlet sump configurations, double outlet sumps with partition walls, sumps with different pipe diameters, and sump performance at higher flows due to pump overspeed and bellmouth entrance effects. These studies were conducted at the Alden Research Laboratory (ARL) of Worcester Polytechnic Institute (WPI) for the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC) on a contract from Sandia National Laboratories (Sandia). The overall ARL program is designed to provide sump hydraulic design and performance data for use in resolving the Unresolved Safety Issue, Task A-43, "Containment Emergency Sump Performance".

The objectives of these particular investigations are: (a) to examine the effectiveness and behavior of commonly used vortex suppression devices; (b) to ascertain the hydraulic performance of single outlet sump configurations in comparision with double outlet sumps; (c) to assess any effects of solid partition walls on the hydraulic performance of double outlet sumps; (d) to examine any influence of outlet pipe diameter on sump performance; (e) to ascertain sump performance at higher than normal design flows due to pump overspeed; and (f) to verify any effect of a bellmouth entrance towards improving the hydraulic performance of a sump.

Test details and principal findings are summarized separately for each of the above items in the following paragraphs.

Vortex Suppressors

Two types of commonly used vortex suppressors; namely, cubic cage shaped suppressors made of floor grating and single layer horizontally laid floor grating over the entire sump area, were tested in a selected sump configuration with adverse screen blockages which produced strong vortexing and air-entrainment without the suppressors.

Cages of cubes 3 ft and 4 ft on a side and the tested horizontal floor grating were both found to be effective in suppressing vortices and reducing air-ingestion to zero. Tests on a cage suppressor less than 3 ft on a side indicated existence of air-core vortices for certain flows and submergences, even though air-withdrawals were found reduced to insignificant levels. Both type of suppressors also reduced pipe swirl and did not cause any significant increases in inlet losses.

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 sump 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 with perturbed approach flow indicated significantly high air-withdrawals, especially for the smaller sized sump. Measured swirl values for the pipe flows were insignificant for both the tested sumps, being in the range of 2 to 3 degrees even with approach flow perturbations. The inlet loss coefficients for both sump configurations were in the expected ranges for such protruding outlet, 0.8 ±0.2.

Double Outlet Sumps with Solid Partition Walls

Four double outlet sump configurations (a 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 large increases in vortexing, air-withdrawals, swirl angle, or inlet losses compared to dual pipe operation without partition walls. Thus, providing a partition wall in a sump should not cause any additional hydraulic problems when only one outlet pipe is operating.

Pipe Diameter Effects

An 8 ft x 10 ft sump; 4.5 ft deep with horizontal double outlets, was tested with 6 inch, 12 inch, and 24 inch outlet pipes over a range of flows and submergences. Higher flows were tested for larger pipe sizes to achieve a common range of Froude numbers.

The results indicated that at a given flow and submergence, with larger pipe diameters, the pipe flow velocity and hence the Froude number were lowered. This was found to reduce vortexing and air-withdrawals compared to the results with smaller outlet pipes. Even at the same Froude numbers (unequal flow and submergence) larger pipe diameters showed no significant increase in air-withdrawals.

Irrespective of Froude number, relatively higher pipe flow swirl angles were measured for 24 inch outlets compared to 12 and 6 inch outlets, persumably due to a varying influence from submerged vortices. Even though inlet loss coefficients were higher for 24 inch diameter pipes, the actual values of inlet losses (in feet) were smaller for a given flow and submergence because of much lower velocities in the 24 inch pipe.

Pump Overspeed

In an 8 ft x 10 ft sump; 4.5 deep with 12 inch double outlets (both horizontal and vertical orientations), tests with flows up to 8000 gpm per pipe were conducted. No significant increases in air-withdrawals due to vortices, average vortex types, pipe flow swirl angles or inlet loss coefficients were observed compared to tests with up to 6000 gpm (normal expected design flows) conducted earlier under Phase I [1].

Bellmouths at Pipe Entrance

Limited tests on a sump configuration were conducted with and without a bellmouth attached to the 12 inch outlet pipes. Adding bellmouths at the pipe entrances did not produce any significant changes in the vortex types, air-withdrawals, and pipe swirl compared to those which otherwise existed under the same hydraulic conditions. A reduction in inlet losses of up to about 40% was measured with the addition of a bellmouth.

Application to Unresolved Safety Issue A-43

The data gathered from these investigations are used: (a) to obtain maximum bounding envelopes on air-withdrawals, pipe flow swirl, and inlet loss coefficients, and to thereby prescribe limits on the intake Froude number, (or pipe velocity and submergence) for both single and double outlet sumps; (b) to develop guidelines on the use and design of vortex suppressors; (c) to judge any effects of outlet pipe diameter on hydraulic sump performance; and (d) to evaluate the limited benefits due to bellmouth entrances. All these factors contribute to the resolution of the Unresolved Safety Issue, A-43, "Containment Emergency Sump Performance".

1.0 INTRODUCTION

In the event of a loss of coolant accident (LOCA) in a nuclear power station, the emergency core cooling system (ECCS) and containment spray systems (CSS) would be activated to supply coolant to the reactor core and vessel to dissipate the decay heat and to the CSS to reduce containment pressure. At first, these systems draw water from a large supply tank. Later, they are switched to a recirculating mode drawing water that has accumulated in the containment through a sump designated herein as ECCS sump or containment sump. The systems are expected to operate for extended periods of time in this mode. ECCS sumps are provided in the containment to collect water and supply it to the ECCS pumps, to screen out debris, and to provide sufficient suction head for pumps. Hence, they form a key flow link in providing coolant to the reactor and in providing control of the containment environment during recirculation mode.

A few years ago, the hydraulic performance of the ECCS sumps started to receive renewed attention as an important component of the residual heat removal system in nuclear power stations. Ingestion of air from free surface vortices or break jets impinging near the sump, swirling flow in the pump suction lines and excessive pressure losses leading to insufficient net positive section head can result in degraded recirculation system performance. Considering these aspects, the hydraulic performance of ECCS sumps was designated by the U.S. Nuclear Regulatory Commission (NRC) as an unresolved safety issue, A-43.

The Alden Research Laboratory (ARL) of Worcester Polytechnic Institute (WPI) was contracted by the Sandia National Laboratories (Sandia) on behalf of the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC) to conduct full scale experimental research investigations for the Resolution of Unresolved Safety Issues, Generic Task A-43, ECCS Sump Reliability. The investigations were conducted in two phases and this report covers a major portion of the second phase (Phase II). The results of Phase I and other portions of Phase II are available in other reports, [1, 2, 3].

The test program covered in this report can be divided into six items as described in the following paragraphs:

a. Vortex Suppressor Tests

Cages made up of standard floor gratings fitted to the pipe inlets and one or more layers of horizontal floor gratings laid over the whole sump area below the operating water levels are the two commonly used vortex suppression devices installed in many existing ECCS sumps and proved to be effective through model studies [4, 5, 6]. Vortex suppressor tests were designed to investigate these two types of devices in detail to ascertain the effects of cage size or horizontal grating location with respect to water surface on the suppressing action and any need of multi-layer cages or gratings.

b. Single Outlet Sump Tests

Separate sumps for the decay heat removal and coolant spray systems are provided in some plants [7, 8] and in order to ascertain their performance, two configurations (4 ft x 4 ft x 4.5 ft and 7 ft x 5 ft x 4.5 ft sumps; 12 inch horizontal outlet) of single outlet sumps were tested. Such sumps are designed in practice so that each sump will be a separate floor depression with a single outlet, but the sumps may have a common screen and grating. The two configurations were tested with approximately uniform approach flows and also with two selected screen blockages (up to 75% blocked) with the idea of obtaining vortex type, swirl, air-withdrawal and loss coefficient data over the test flows and submergences, and to compare these with data from other sumps with two outlet pipes.

c. Tests in Double Outlet Sumps with Partition Walls

In some existing or planned ECCS sumps, the two outlet pipes in a sump are separated by a solid partition wall [9], and a few tests were included to obtain data on a few such sumps for a single pipe operation.

d. Tests at Higher Flows (Pump Overspeed)

Due to pump overspeed or other reasons, a containment sump may be subjected to operation at higher than normal flows. One sump configuration with horizontal outlets and the other with vertical outlets were tested at higher flows, up to about 8000 gpm.

e. Tests to Ascertain Pipe Diameter Effects

As a continuation of sensitivity tests undertaken under the Phase I test program [1], tests were conducted to ascertain whether pipe diameter itself has any influence on sump performance at the same Froude number. The three pipe diameters, 24 inches, 12 inches, and 6 inches were tested in the same sump configurations.

f. Tests with Bellmouth Entrance

In practice, suction pipe entrances inside the sumps are sometimes provided with a bellmouth or an expansion piece which is expected to improve the flow patterns at the entrance. Tests on a selected sump configuration were repeated with a bellmouth attached at the pipe entrance to examine the effects of the bell on the hydraulic performance of the sump.

The test plan is described in Chapter 2; Chapter 3 provides a key findings summary. Test facility description, measurement techniques, and data acquisition methods have been detailed in earlier reports [1, 2, 10]; however, Appendix A, which briefly covers these items, is provided for reader convenience. The detailed data and discussion thereof is contained in Chapter 4.

2.0 TEST PLAN

The test program covered in this report can be divided into six items:

1. Vortex suppressor tests,
2. Single outlet sump tests,
3. Tests on double outlet sumps with solid partition walls,
4. Pump overspeed tests,
5. Sensitivity tests to ascertain effect of pipe diameter on sump performance, and
6. Sensitivity tests to ascertain effect of bellmouth entrance on sump performance.

Table 1 shows the details of the sump geometries used for each of the above items, with Figure 1 indicating the definition of the geometric variables. Table 2 shows test details including flows and submergences used. It may be noted that all tests were of 30 minute duration (data acquisition time). Details of the tests for each item listed in the above paragraph are included in the following sections. Appendix B gives the total test plan of the entire program of Containment Sump Reliability Studies conducted at ARL.

2.1 Vortex Suppressor Tests

Cages made up of standard floor gratings fitted to the pipe inlets and one or more layers of horizontal floor gratings laid over the whole sump area below the operating water levels are the two tested vortex suppression devices.

Each of the suppressors was tested in an 8 ft x 10 ft x 14.5 ft sump with horizontal 12 inch diameter outlet pipes and in an 8 ft x 10 ft x 4.5 ft sump with vertical 12 inch diameter outlet sumps with both pipes operating and also with single pipe operating for a case with solid partition walls in the depressed sump. The sump screens were partially blocked (about 75%) per scheme 5 or 8 (Figure 2), selected based on earlier test results [1] so that strong vortexing and/or swirl existed before the suppressor was installed. The sizes and orientations of the suppressors are discussed below.

a. Cage Type Suppressors

Figure 3 shows the details of the three single cage arrangements (C1, C2, and C3) involving different cage sizes. The cages were made of 1.5 inch standard floor gratings (1.5 inch deep bars at 1 inch c/c). Two more cage arrangements involving two-layer cages (one above the other) were also tested for one selected screen blockage to evaluate any added improvement, and their arrangements (C4 and C5) are explained in the table included in Figure 3.

TABLE 1

Details of Sump Geometry

Configuration Number	Pipe** Orientation	Type of Test	Geometric Variable, ft*										Remarks
			L	B	d	b	e_x	g	f	c	x	e_y	
34	H	Solid partition wall	20	10	2	3	2	1	16	3	7.5	2	One pipe operation
35	H	24" outlet tests	8	10	2	3	2	1	4	3	7.5	2	Both pipes operating
36	H	Solid partition wall	8	10	2	3	2	1	4	3	7.5	2	One pipe operation
37	H	Solid partition wall	8	10	1	3	2	1	4	1.5	7.5	1	One pipe operation
38	H	Solid partition wall	8	10	0.5	3	2	1	4	0.75	7.5	0.5	One pipe operation
39	H	Single outlet	4	4	1	3	2	1	-	1.5	7.5	1	---
40	H	Single outlet	7	5	1	3	3.5	1	-	1.5	7.5	1	---
41	H	Vortex suppressor	8	10	1	3	2	1	4	1.5	7.5	1	Cage type and horizontal grate type suppressors
42	V	Vortex suppressor	8	10	1	3	2	1	4	1.5	7.5	5	Horizontal grate type suppressors
43	H	Pump overspeed	8	10	1	3	2	1	4	1.5	7.5	1	Higher than normal flows
44	V	Pump overspeed	8	10	1	3	2	1	4	1.5	7.5	5	Higher than normal flows
45	H	Vortex suppressor	8	10	1	3	2	1	4	1.5	7.5	1	One pipe operating with solid partition
46	V	Vortex suppressor	8	10	1	3	2	1	4	1.5	7.5	5	One pipe operating with solid partition

*See Figure 1; a = 6 ft

**H = horizontal; V = vertical

TABLE 2

Test Details *

Configuration Number	Details
34	20 ft x 10 ft sump; b = 3 ft; 24 inch Outlets Single pipe operating (solid partition wall) a. Unperturbed flow tests b. Limited perturbed tests
35	8 ft x 10 ft sump; b = 3 ft; 24 inch Outlets Both pipes operating a. Unperturbed flow tests b. Limited perturbed flow tests
36	8 ft x 10 ft sump; b = 3 ft; 24 inch Outlets Single pipe operating (solid partition wall) a. Unperturbed flow tests b. Limited flow perturbed tests
37	8 ft x 10 ft sump; b = 3 ft; 24 inch Outlets Single pipe operating (solid partition wall) a. Unperturbed flow tests b. Limited flow perturbed tests
38	8 ft x 10 ft sump; b = 3 ft; 6 inch Outlets Single pipe operating (solid partition wall) a. Unperturbed flow tests b. Limited perturbed flow tests
39	4 ft x 4 ft sump; b = 3 ft; 12 inch Outlet Single outlet sump a. Unperturbed flow tests b. Limited perturbed flow tests

* See note at the end for flows and submergences.

TABLE 2
(Continued)

Configuration Number	Details
40	7 ft x 5 ft sump; b = 3 ft; 12 inch Outlet Single outlet sump a. Unperturbed flow tests b. Limited perturbed flow tests
41 and 42	Vortex Suppressor tests*

A. Horizontal Grid Suppressors: 8 ft x 10 ft sump; b = 3 ft; 12 inch outlets; Horizontal and Vertical

	Number of Arrangements			
	Vertical Outlet**		Horizontal Outlet	
Combination:	a	b	a	b
(i) Elevation of Grid (gratings)	3	1	3	1
(ii) Layer Arrangements	1	2	1	2
(iii) Submergences+	2	2	2	2
(iv) Test/Submergences++	4	4	4	4

B. Cage Suppressors: 8 ft x 10 ft sump; b = 3 ft; 12 inch outlets; Horizontal and Vertical

	Number of Arrangements			
	Vertical Outlet		Horizontal Outlet	
Combination:	a	b	a	b
(i) Cage Sizes***	3	1	3	1
(ii) Layer Arrangements	1	2	1	2
(iii) Submergences+	2	2	2	2
(iv) Test/Submergences++	4	4	4	4

* Screen blockages to generate a strong air-drawing vortex will be set up prior to tests.

** Outlets at sump center.

*** 4 ft x 4 ft x 4 ft, 3 ft x 3 ft x 3 ft, and 1.5 ft x 1.5 ft x 1.5 ft cages made of gratings.

\+ S = 8 ft and 5 ft.

++ Q = 3000, 4000, 5300, and 6600 gpm/pipe.

TABLE 2
(Continued)

Configuration Number	Details
43 and 44	Pump Over-Speed Tests 8 ft x 10 ft sump; b = 3 ft; 12 inch outlet; Horizontal and Vertical Flow will be increased from 6000 gpm to about 9000 gpm (or the maximum attainable flow) with only <u>one</u> outlet operating. Two submergences will be tested with 3 tests/submergences (6600, 8000, and 9000 gpm/pipe); <u>No</u> perturbations.
45 and 46	Single Pipe Suppression Tests 8 ft x 10 ft sump; b = 3 ft; 12 inch outlet; Horizontal and Vertical (center) Based on the single pipe tests (solid partition wall) with and without perturbations, the flow conditions will be set so that a strong air-core vortex is generated. The best horizontal and cage arrangements as per tests on vortex suppressors conducted earlier, will then be tested for the single pipe operating (2 submergences and 4 test/submergences).

Note: <u>Flows and Submergences</u>

A. Unperturbed Tests

(i) 4 Submergences corresponding to 1, 2, 3, and 5 ft of water above containment floor

(ii) 5 Full Tests/Submergence

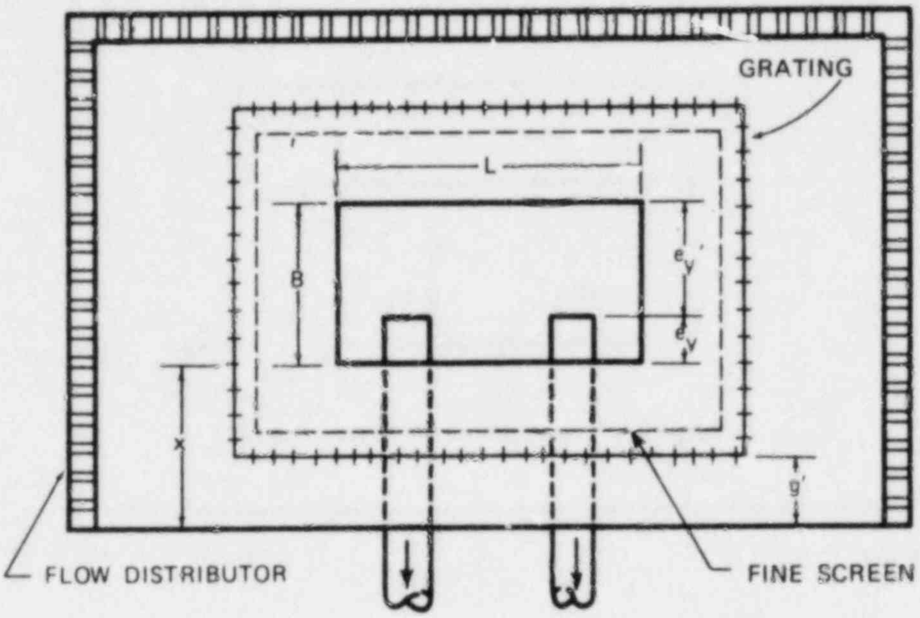
say 4000, 5300, 6600, 8000, and 9000 gpm/pipe for 24 inch pipes
2000, 3000, 4000, 5300, and 6600 gpm/pipe for 12 inch pipes
750, 1000, 1325, 1650, and 2000 gpm/pipe for 6 inch pipes

B. Limited Perturbation Tests

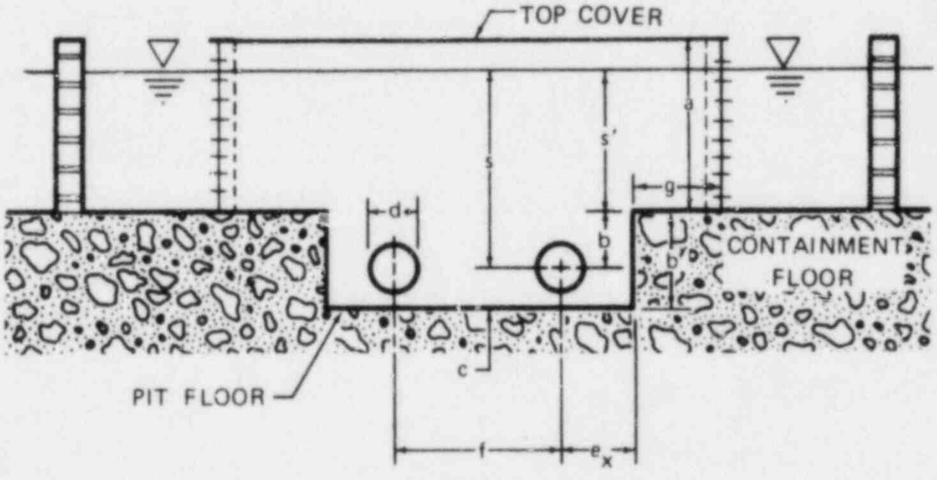
(i) 1 Submergence corresponding to 2 ft of water above containment floor.

(ii) Flows as in item A (ii) above.

(iii) 2 Screen Blockage schemes to be selected from Phase I test results or by trial.



TOP VIEW



FRONT ELEVATION

FIGURE 1 DEFINITION OF GEOMETRIC VARIABLES

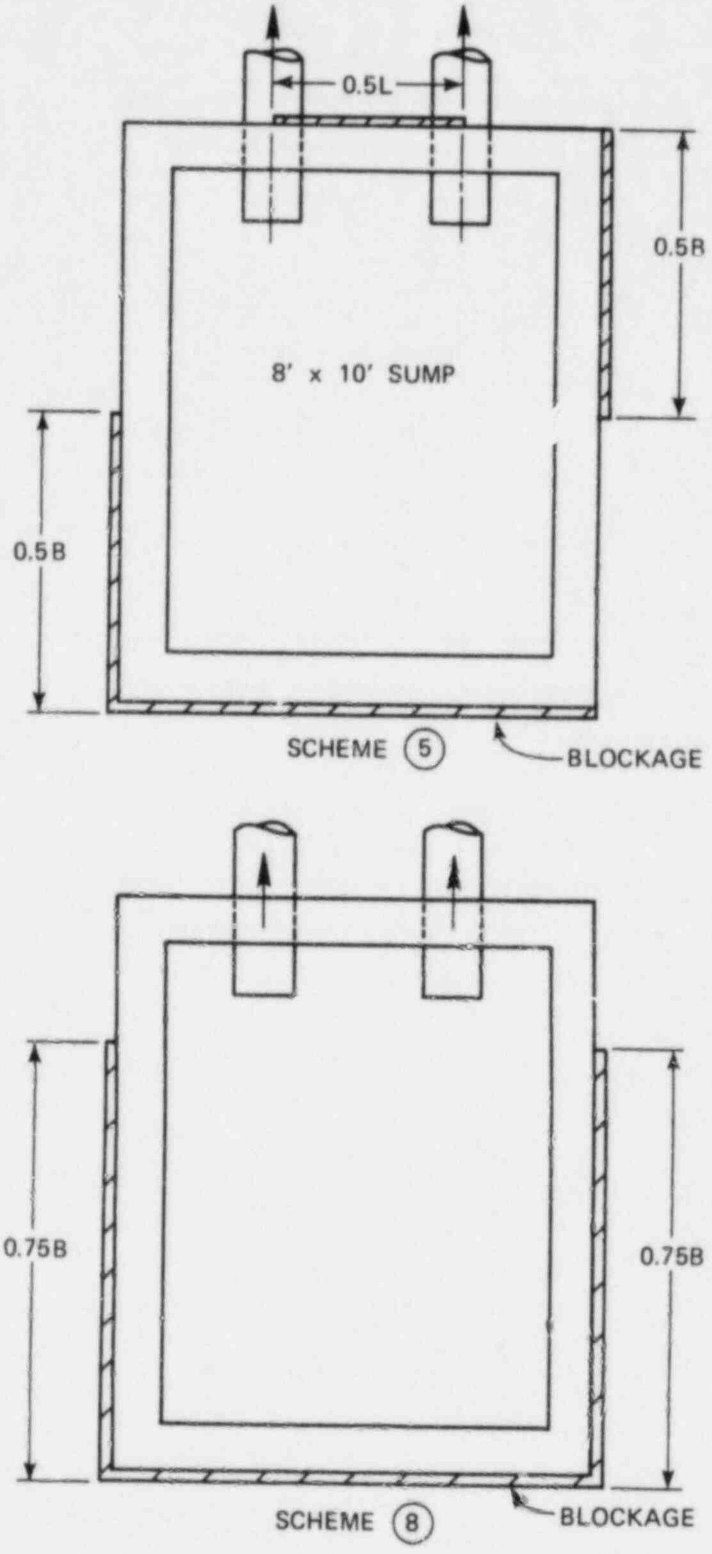
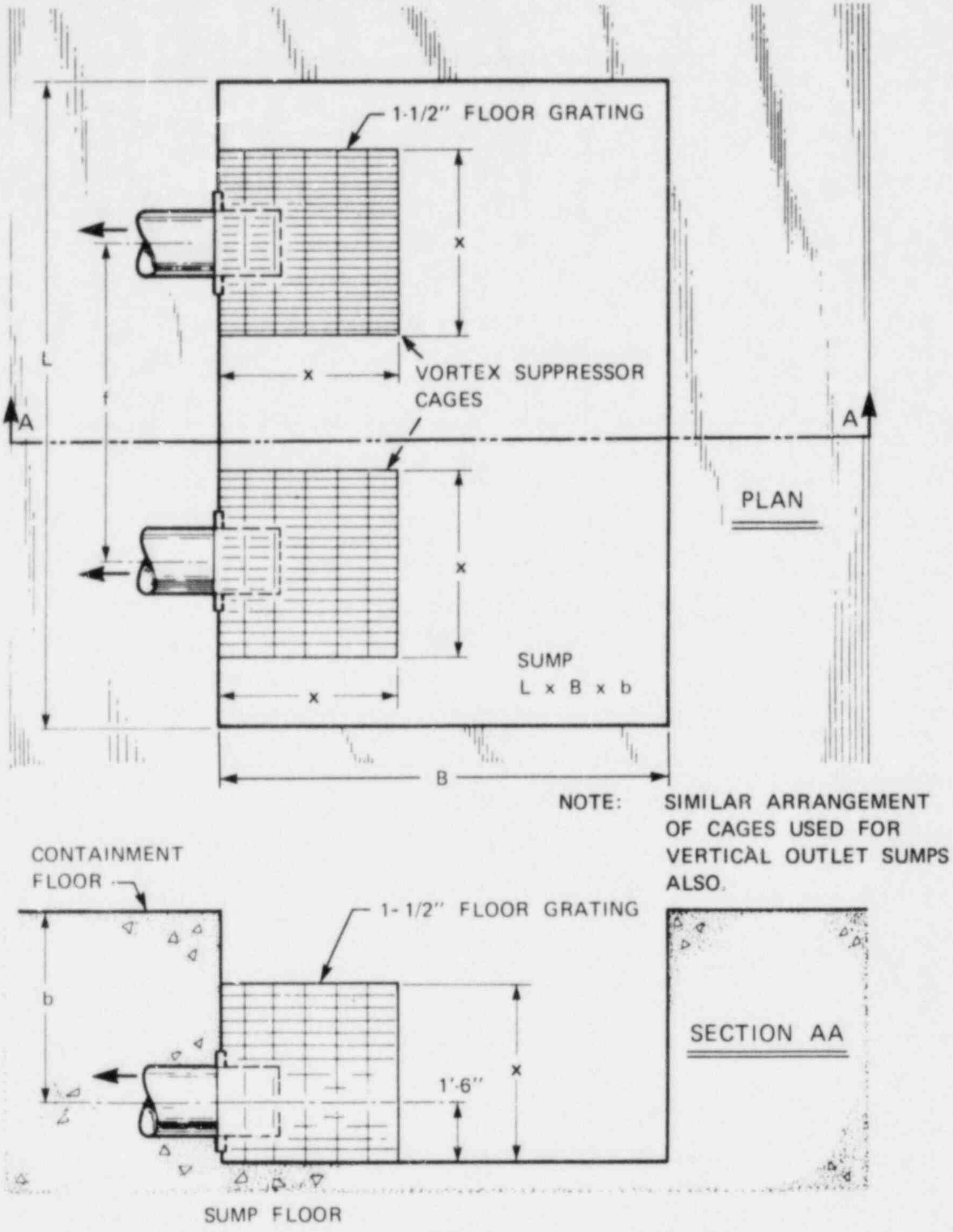


FIGURE 2 SCREEN BLOCKAGE SCHEMES USED FOR VORTEX SUPPRESSOR TESTS



NOTE: SIMILAR ARRANGEMENT OF CAGES USED FOR VERTICAL OUTLET SUMPS ALSO.

CAGE ARRANGEMENT	NUMBER OF CAGES	CAGE SIZE x, ft
C1	1	4
C2	1	3
C3	1	1.5
C4	2	1.625' CAGE OVER 1.5' CAGE
C5	2	3' CAGE OVER 1.5' CAGE

FIGURE 3 DETAILS OF CAGE TYPE SUPPRESSOR ARRANGEMENTS

b. Horizontal Grating Suppressors

Horizontal grating suppressors are known to perform better in suppressing a free-surface vortex the closer they are to the water surface. However, in an ECCS sump with a wide range of water levels, it may be important to know whether a single grating will suffice or layers of gratings at different elevations would be required. Hence, a single grating was first tested at different elevations followed by two gratings, each at different elevations. The three single grating arrangements and the two double grating arrangements are shown (numbered H1 to H5) in Figure 4. The gratings were also of 1.5 inch standard floor gratings. The double grating arrangement was tested for only one screen blockage which gave relatively poor (adverse) performance in terms of pipe swirl with a single grating at the lowest tested elevation.

2.2 Single Outlet Sump Tests

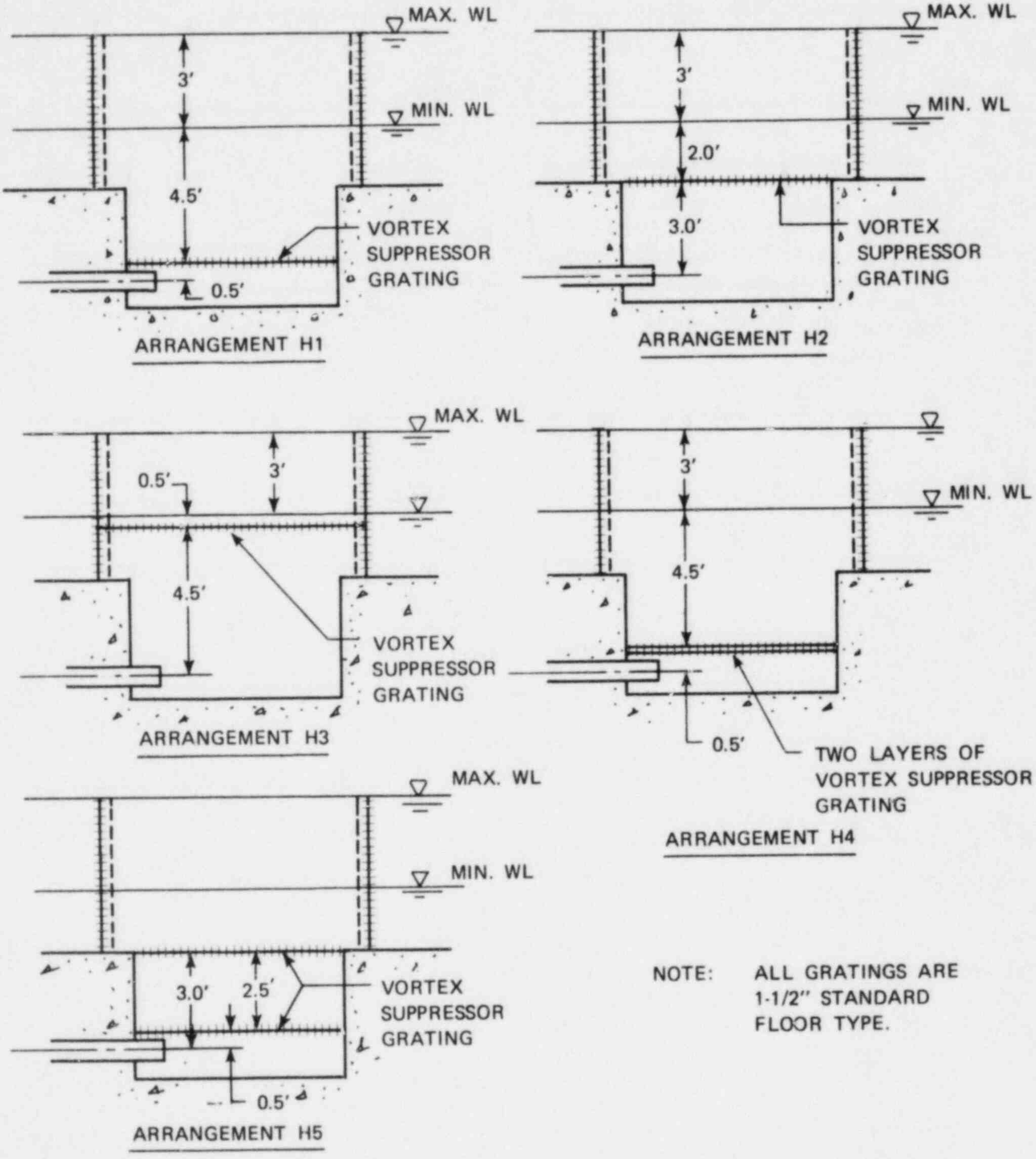
Two configurations (configurations 39 and 40 in Table 1) of single outlet sumps were tested with unperturbed approach flows and also with two selected screen blockages (up to 75% blocked). Data on vortex type, swirl, air-withdrawal and loss coefficient were obtained over the test flows and submergences. Figure 5 shows the screen blockage schemes used for the single outlet tests, derived by trial so as to get the worst vortexing conditions.

2.3 Tests on Double Outlet Sumps with Solid Partition Walls

Four sump configurations; namely, configurations 34 and 36 with horizontal 24 inch outlets, configuration 37 with horizontal 12 inch outlets, and configuration 38 with horizontal 6 inch outlet (Table 1) were tested with a solid partition wall along the center of the sump length, extending from the sump floor to the containment floor elevation. Figure 6 shows a typical arrangement. The sumps were tested with single pipe operating and for unperturbed approach flows as well as for perturbed approach flows with the screen blockage schemes shown in Figure 7.

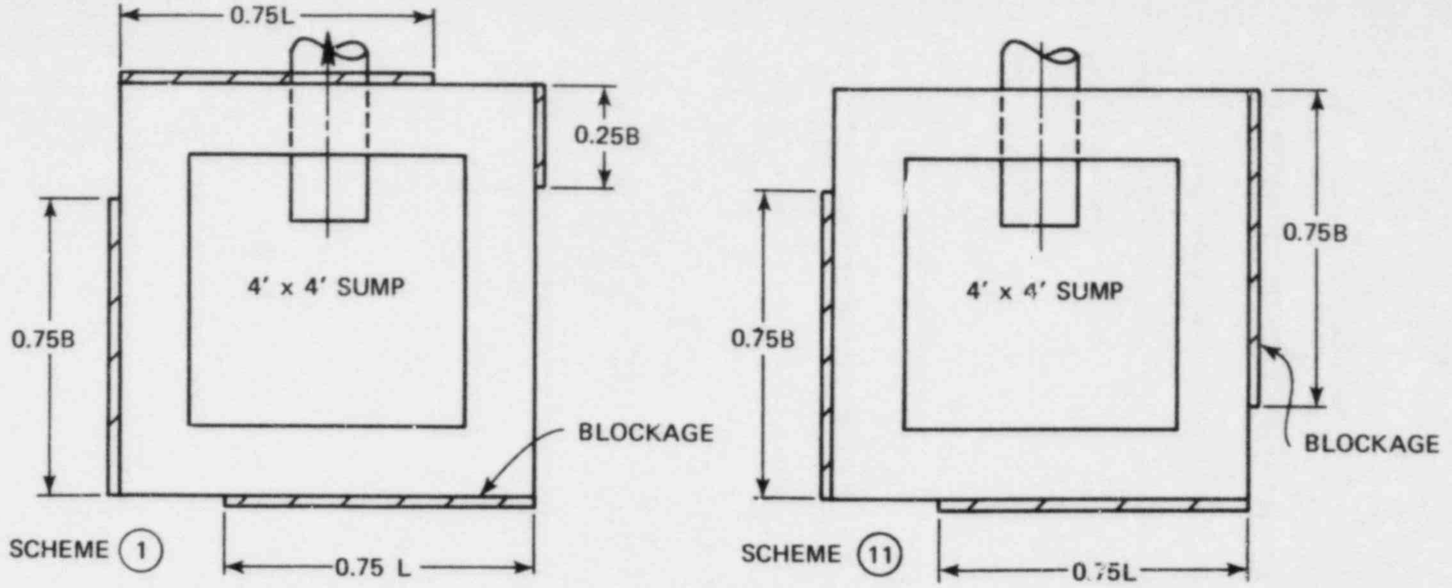
2.4 Pump Overspeed Tests

These tests were conducted so as to test a sump at higher than normal operating flows which would be the case with pump overspeed. The tested configurations were 8 ft x 10 ft in size, 4.5 ft deep with two 12 inch diameter outlets at 4 ft centers, one configuration with horizontal outlets and the other with vertical outlets (configurations 43 and 44 in Table 1). These configurations are the same as configurations 2 or 64 and 58, respectively, of the earlier tests (Appendix B). The tests were conducted with single pipe operation and at the maximum flow attainable in the facility, which was about 7000 to 8000 gpm, for the range of submergences of 4 to 8 ft. These tests were conducted with unperturbed approach flow to the screens.

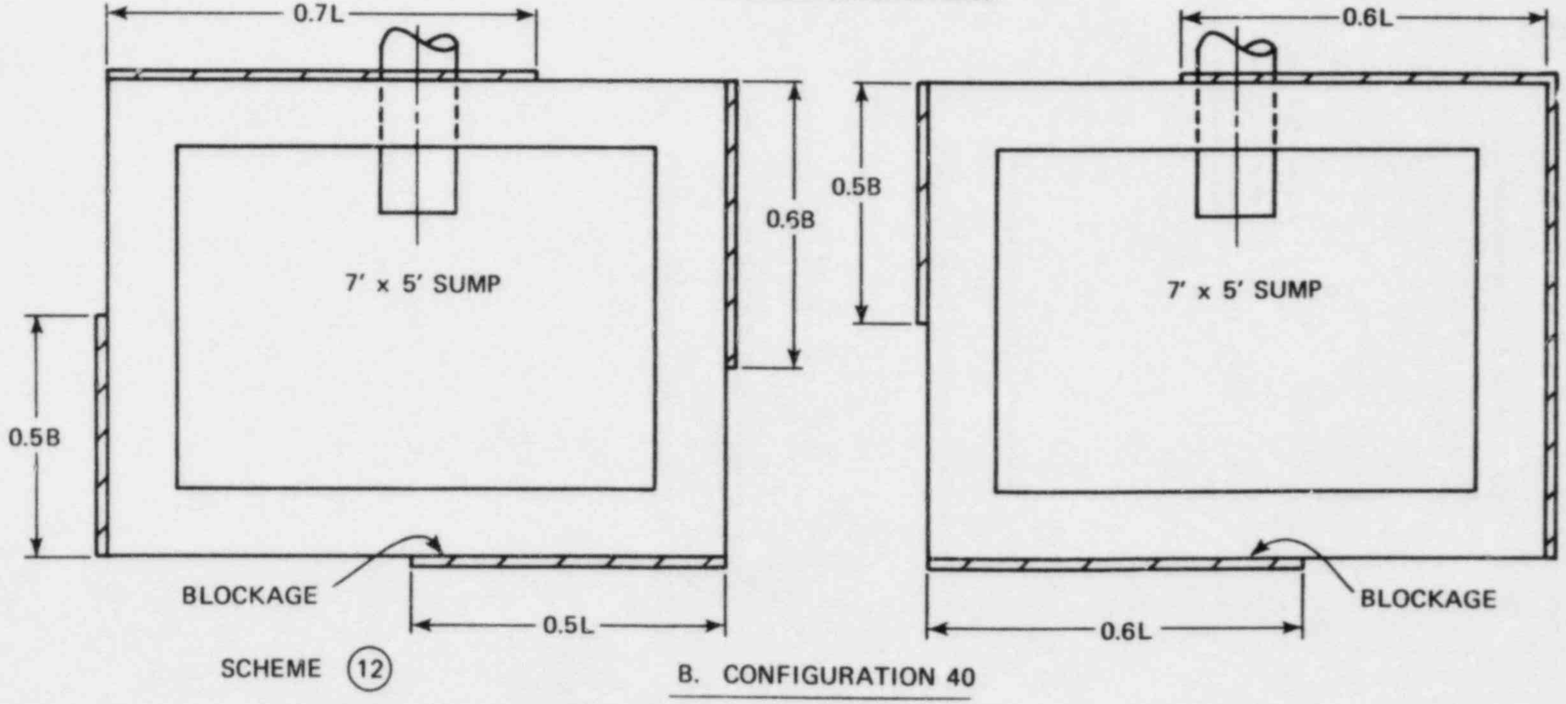


NOTE: ALL GRATINGS ARE 1-1/2" STANDARD FLOOR TYPE.

FIGURE 4 DETAILS OF HORIZONTAL GRATING TYPE VORTEX SUPPRESSOR ARRANGEMENTS



A. CONFIGURATION 39



B. CONFIGURATION 40

FIGURE 5 SCREEN BLOCKAGE SCHEMES TESTED FOR SINGLE OUTLET SUMPS

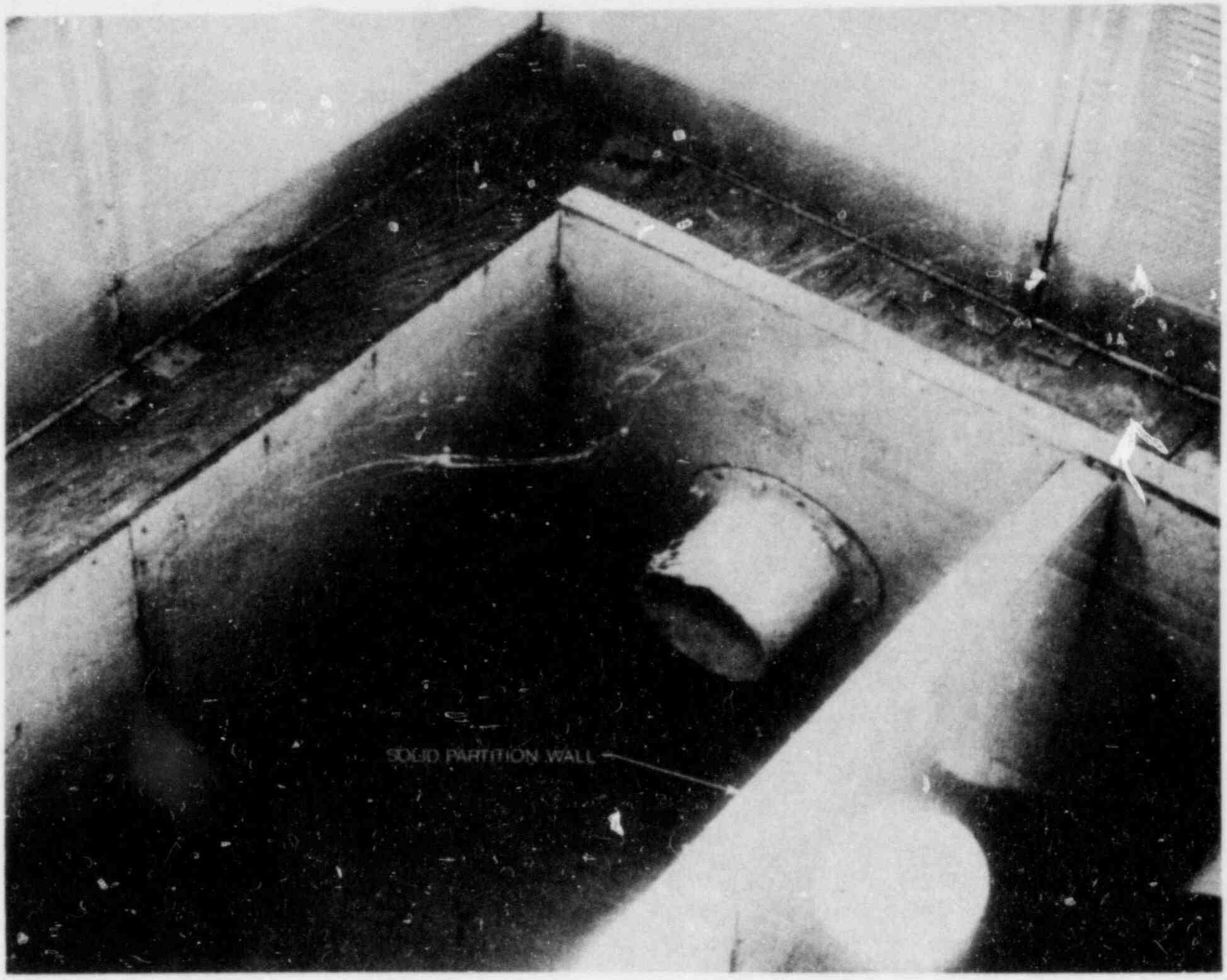
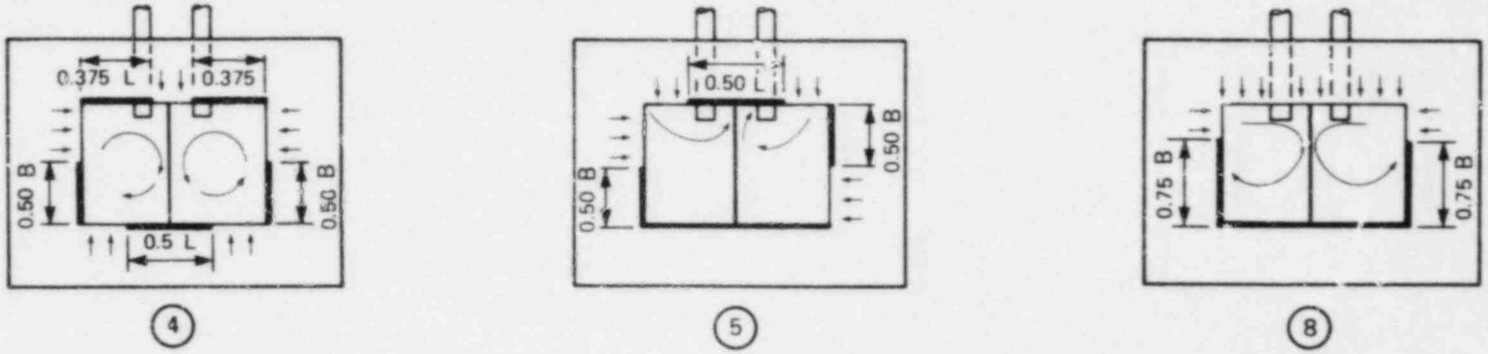


FIGURE 6 A TYPICAL HORIZONTAL OUTLET SUMP WITH A SOLID PARTITION WALL



④ ⑤ ⑧

SCREEN BLOCKAGE

B = WIDTH OF SCREENS
L = LENGTH OF SCREENS

CONFIGURATION NO.	BLOCKAGE SCHEMES
34	4 and 8
36	4 and 8
37	4 and 8
38	5 and 8

FIGURE 7 SCREEN BLOCKAGE SCHEMES USED FOR SOLID PARTITION WALL SUMP TESTS

2.5 Sensitivity Tests - Effect of Pipe Diameters

The three pipe diameters tested were 24 inches, 12 inches, and 6 inches and the sump configurations (8 ft x 10 ft sumps; 3 ft to pipe center from containment floor) correspond to configuration 35 (Table 1) and configurations 64 and 61 (see pages B4 and B5), respectively. Details on flows and submergences are given in Table 2.

2.6 Sensitivity Tests - Effect of Bellmouth Entrance

Tests on configuration 64 (see Appendix B) tested under Phase I tests [1], an 8 ft x 10 ft sump 4.5 ft deep, were repeated with a bellmouth attached at the pipe entrance (Figure 8) for submergence of 5 ft only.

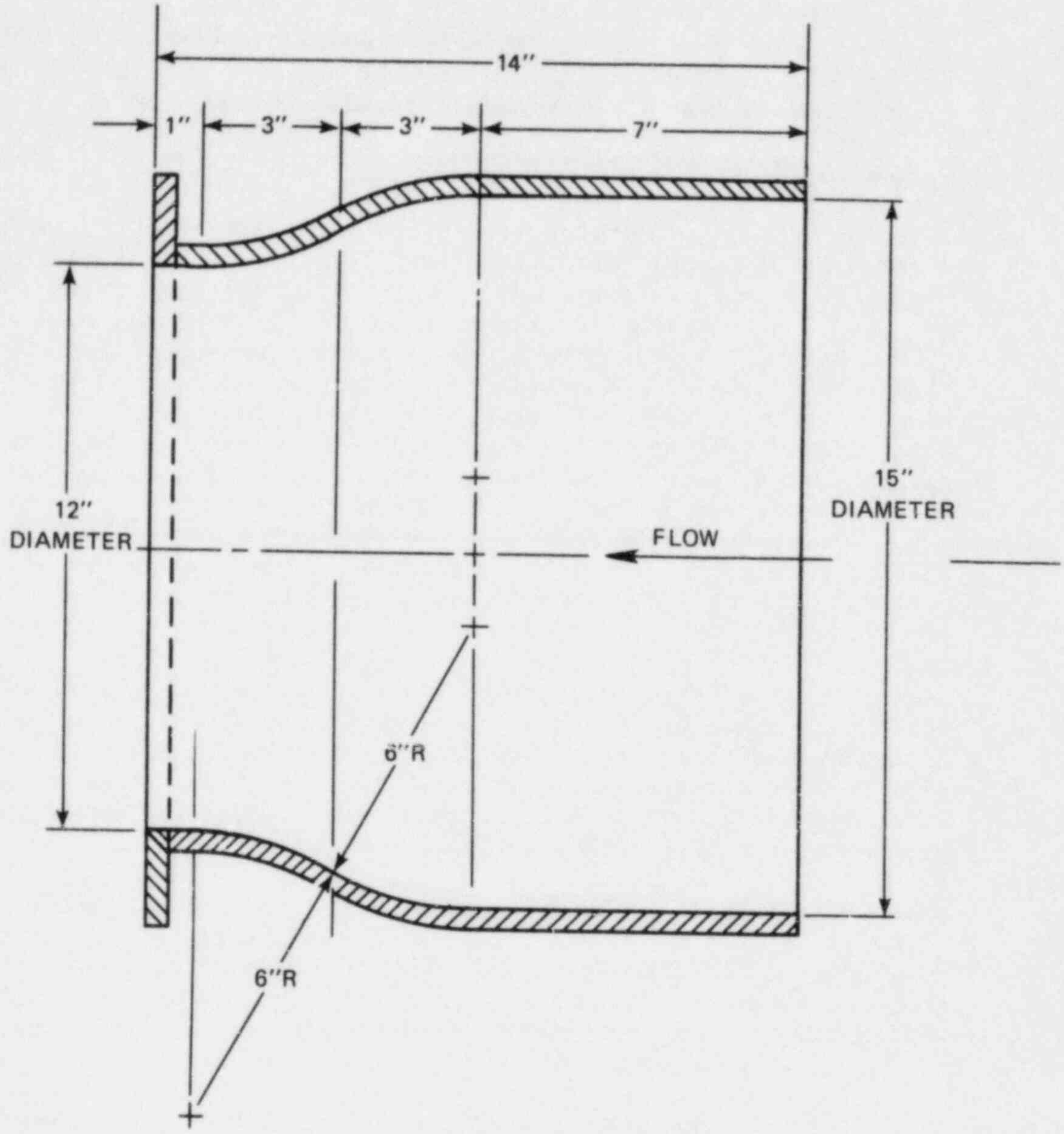


FIGURE 8 BELLMOUTH ENTRANCE USED FOR TESTS

3.0 KEY FINDINGS SUMMARY

From the test results presented and discussed in Chapter 4.0, certain key findings are obtained and summarized in this section. A listing of the most significant findings is also given in Table 3.

3.1 Vortex Suppressors

a. 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. Both the cage shaped grating suppressors as well as the horizontal floor grates were made of standard 1.5 inch floor grates. Adverse sump screen blockages were used in conjunction with sump configurations which produced considerable air-ingestion and strong vortexing without the suppressors; thus, the suppressors effectiveness was tested when hydraulic conditions were most undesirable. The suppressors also reduced pipe swirl and did not cause any significant increase in inlet losses.

b. Tests on a cage shaped suppressor less than 3 ft on a side indicated the existence of air-core vortices on the water surface for certain ranges of flows and submergences, even though air-withdrawals were found reduced to insignificant levels. Visual observations indicated that the air-core on reaching the cage, broke into bubbles which were drawn into the suction pipe.

c. When a single grating is used, it is advantageous to have it about 6 inches below the minimum water level since in this case, any air-core vortices were found to be suppressed to surface dimples. More than one layer of horizontal grating was found to be unnecessary for vortex suppression, but the second layer did produce some additional reduction in pipe flow swirl.

d. Either properly sized cage shaped suppressors made of floor grating, or horizontal 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.

3.2 Single Outlet Sumps

a. 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). With perturbed flows, zero or near zero air-withdrawals were measured in both sumps for Froude numbers less than 0.8, but for Froude numbers above 0.8, a few tests with screen blockages indicated significantly high air-withdrawals (up to 17.4 percent air by volume; 1 minute average), especially for the smaller sized sump (see Figure 32).

b. Swirl of the pipe flows was insignificant for both the tested sumps, being in the range of from 2 to 3 degrees (at 14.5 pipe diameters from the entrance) even with approach flow perturbations.

c. The inlet loss coefficients for both sump configuratons were in the expected ranges for such protruding inlets; namely, 0.8 ±0.2.

d. For Froude numbers above 0.8 and with approach flow perturbations, single outlet sumps were found to generate stronger vortices with greater air-withdrawals compared to double outlet sumps (both outlets operating) of comparable geometry (see Figures 31 and 32). This is presumably due to higher magnitudes of circulation which can be generated by screen blockage in a single outlet sump.

3.3 Double Outlet Sumps With a Solid Partition Wall

a. Four double 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 a solid partition wall in the sumps between the pipe outlets. For these tests to evaluate the effect of a partition wall, only one outlet was operated as the partition wall would have little effect with both outlets running. With or without approach flow perturbations (screen blockage), all measured air-withdrawals were less than 1 percent (1 minute or 30 minute average void fraction), swirl angles were always less than 7 degrees (at about 14.5 pipe diameters from the entrance) and inlet loss coefficients ranged from 0.7 to 1.2.

b. None of the tests indicated any large increases in vortexing, air-withdrawals, swirl, or inlet losses compared to similar dual inlet pipe operation in sumps without partition walls. Thus, providing a partition wall in a sump should not cause any additional problems, and guidelines developed from double suction sumps may be applied to sumps with partition walls.

3.4 Pipe Diameter Effects

In assessing the impact of pipe diameter on the sump performance at the same flow and water level, it should be noted that the Froude number for a 24 inch diameter pipe will be 1/4 of that for 12 inch and 1/16 of that for 6 inch diameter pipes. The major findings are listed below.

a. At the same flow and water level in a given sump, the use of larger pipe diameters lowered the pipe flow velocity and hence the Froude number, and helped reducing average vortex types and air-withdrawals due to vortices. Hence, in this regard, using a larger pipe diameter is advantageous (see Figures 46 and 47 and compare the data at corresponding Froude numbers, eg., F = 0.3 for 24 inch to F = 1.2 for 12 inch).

b. At the varying Froude numbers corresponding to the same flow and submergence, higher flow swirl angles were recorded (up to 9 degrees at 15 pipe diameters from the inlet) for 24 inch diameter outlet configurations compared to 12 and 6 inch diameter outlet configurations (see Figure 50). The reason for higher swirl angles may be due to an increased level of submerged vortices relative to a reduced magnitude of axial momentum for the larger pipe size. For a given flow and submergence, the approach flow velocities and the angular momentum associated with submerged vortices generated by the flow separation at the sump floor depression remain the same irrespective of pipe size. But the axial momentum in the pipe is reduced as the diameter is increased, resulting in higher ratios of angular to axial momentum and hence higher swirl angles. Swirl decays with distance [14, 20], and the swirl angles at the pump location contributed by the sump geometry may be negligible compared to the swirl angles indicated by bends.

c. For the tested sump, the inlet loss coefficients were found to be higher with the 24 inch outlets (generally 1.2 ±0.2) compared to those with 12 inch and 6 inch outlets (generally 0.8 ±0.2 and 0.65 ±0.2, respectively) as shown in Figure 52. The higher loss coefficients may be due to higher swirl angles indicated for the larger pipe diameters. However, it may be noted that for a given flow and submergence, the actual inlet losses (in ft) would be considerably less for 24 inch pipes (even though loss coefficients are higher) because of lower velocity heads.

3.5 Bellmouths at Pipe Entrance

a. Limited tests on a sump configuration were conducted with and without a bellmouth (Figure 8) attached 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. A reduction of up to about 40% in inlet losses was measured with the addition of a bellmouth, which more or less agrees with handbook values, [12].

3.6 Pump Overspeed Test

a. Tests with flows up to 8000 gpm (to $F = 1.6$) were conducted with nearly uniform approach flows for two 8 ft x 10 ft x 4.5 ft sumps, one with 12 inch horizontal outlets and the other with 12 inch vertical outlets. These tests, at increased flows to simulate pump overspeed or runout, showed no air-withdrawals greater than 1% (1 minute or 30 minute averages). The pipe swirl angles were less than 1 degree at the measured location (14.5 pipe diameters from entrance) and the loss coefficients were in the range of 0.8 ±0.2.

b. Based on these results for unperturbed approach flows, no significant increases in air-withdrawals or loss coefficients were observed with flow increases up to 30% (Froude numbers to 1.6) above normal pump flows.

3.7 Envelope Analysis

Using the data of all horizontal single outlet and double outlet tests presented in this report, an envelope analysis was made to obtain maximum bounding lines for the variable of interest (see Figures 54 to 57 in Section 4.0). These envelope lines are compared with those obtained using Phase I data on horizontal 12 inch double outlet sumps [1]. The major findings are as follows.

a. The void fraction envelope line for single outlet sumps was found to be above the envelope line for doublet outlet sumps (Phase I envelope line valid for all doublet outlet sumps), indicating higher maximum values of void fractions for a given Froude number.

   An envelope line of maximum 1 minute average void fraction (α) related to Froude number (F) is given by $\alpha = -4.75 + 18.04F$ for single outlet (horizontal) sumps, and $\alpha = -2.47 + 9.38F$ for double outlet (horizontal) sumps, valid for $0.26 \leq F \leq 1.6$ (see Figure 55). For a given permissible value of air ingestion, the envelope for the single sumps yield a lower maximum Froude number than for the double outlet sumps.

b. Bounding values of swirl angles and inlet loss coefficients were found to be dependent on the outlet pipe diameter. The maximum values of swirl angle were about 2 to 9 degrees at about 15 pipe diameters from the entrance (both single and double outlets) depending on the pipe diameter, while the average inlet loss coefficients were about 0.7 ±0.2 to 1.2 ±0.2 depending on the outlet pipe diameter. The higher values of both these parameters were for sumps with larger outlet pipe diameters (see Figures 56 and 57). Even though the loss coefficients are higher for larger pipe diameters, the actual inlet losses will be substantially lower for larger pipe diameters for a given flow, since pipe flow velocities would be lower for larger pipe diameters.

c. The envelope curves derived herein (Figures 55 to 57) can be used in prescribing guidelines for satisfactory sump performance for single outlet sumps as well as double outlet sumps (also using Phase I test data) with or without partition walls.

TABLE 3

Summary of Significant Findings

Category	Findings	Reference Figures
Vortex Suppressors	Both cubic cage grating and horizontal floor grating vortex suppressors were effective in suppressing air-core vortices and reducing air-ingestion to zero. Cage type suppressors less than 3 ft on a side were found to be somewhat less effective.	9, 10, 13, 14, 20, 21, 24, 25
	Both types of vortex suppressors reduced pipe flow swirl and did not cause any significant increases in inlet losses.	11, 12, 15, 16, 22, 23, 26, 27
Single Outlet Sumps	For Froude numbers less than 0.8, no significant vortexing problems were observed and air-withdrawals were less than 1% void fraction, even with partial screen blockages. For Froude numbers higher than 0.8 and with partial screen blockages, strong vortices, with air-withdrawals up to 17.4% void fraction, were observed for a few tests.	31, 32
	Measured pipe flow swirl angles were 2 to 3 degrees and inlet loss coefficients were mostly in the range of 0.8 ±0.2.	33, 34
Double Outlet Sumps With a Solid Partition Wall	Single pipe operation in double outlet sumps with a solid partition wall between the outlets indicated air-withdrawals of less than 1% void fraction, pipe flow swirl less than 7 degrees, and inlet loss coefficients in the range of from 0.7 to 1.2.	37 to 39
	These results are similar to those obtained with dual pipe operation without a partition wall, such that the guidelines developed for the latter sumps also apply to sumps with partition walls.	

TABLE 3
(continued)

Category	Findings	Reference Figures
Inlet Pipe Diameter	At the same flow and submergences, the larger the pipe diameter, the better the sump performance in terms of air-withdrawals.	46 to 49
	Irrespective of Froude number, larger pipe diameters gave higher pipe flow swirl and inlet loss coefficients for the tested sump. But, the actual inlet losses (head of water) would be considerably smaller for larger pipe diameter sumps.	50 to 52
Higher Flows (due to to Pump Overspeed)	Tests with uniform approach flow showed no significant vortexing, air-withdrawals, swirl or inlet loss coefficients for flows giving Froude numbers up to 1.6. The measured values are comparable to those obtained for normal pump flows at Froude numbers about 1.0 to 1.2.	45
Bellmouth Entrance	No effect on vortexing, air-withdrawals, or swirl; but the inlet loss coefficient was reduced by as much as 40%.	53
Envelope Analysis	An envelope line of maximum 1 minute average void fraction (α) to Froude number (F) is given by $\alpha = -4.75 + 18.04F$ for single outlet (horizontal) sumps while $\alpha = -2.47 + 9.38F$ for double outlet (horizontal) sumps. These equations are valid for $0.26 < F < 1.6$.	55
	A maximum value of swirl angle would be about 2 to 9 degrees at about 15 pipe diameters from the entrance, depending on pipe diameter (both single and double outlets) while the corresponding inlet loss coefficients would be about 0.7 ±0.2 to 1.2 ±0.2, depending on pipe diameter. Higher values were obtained with a 24 inch outlet pipe.	56 and 57

4.0 RESULTS

In the presentation of results, the performance variables of interest (indicative of sump hydraulic performance); namely, test average values of vortex types, 1 minute or test average void fractions indicating air-withdrawals, test average swirl angles, and test average inlet loss coefficients, are plotted against the Froude number, $u/\sqrt{gs}$, where u is the velocity of flow in the suction pipe, g is the acceleration due to gravity and, s is the submergence of the pipe centerline from the water surface. The inlet losses include screen and entrance losses and also bend losses when applicable. For cases where both pipes were operating such as the vortex suppressor tests, the highest value of the performance variable, irrespective of which pipe it occurred, is used in the plots of results. Wherever a direct comparison of two cases (such as sumps with and without partition walls) are desired, the variables for each case are plotted to one another considering test points at the same flows and submergences. In this way, the deviations of plotted points from a 45 degree line through the origin would indicate any noticeable differences in performance. Any maximum values of void fractions, swirl angles, or inlet loss coefficients compared to the corresponding values of tests conducted for horizontal and vertical outlet sumps conducted earlier [1, 2] would be mentioned separately. The notations used for pipe flow velocity, flow per pipe, submergence, void fraction and Froude number are u, Q, s, α, and F, respectively.

4.1 Vortex Suppressor Tests

4.1.1 Cage Type Suppressors

Figures 9 to 12 show the maximum vortex type, average void fraction, average swirl angle, and inlet loss coefficients with and without cage suppressors for the horizontal outlet configuration (configuration 41) under screen blockage (Scheme 5). Similar results for vertical outlet configuration (configuration 42) are shown in Figures 13 to 16. Void fraction data indicated zero air-withdrawals for all the vortex suppressor tests.

Two of the three single cages tested; namely, 4 ft x 4 ft x 4 ft and 3 ft x 3 ft x 3 ft, and the larger double layer cage (cages 1, 2, and 5 in Figure 3), were found effective to suppress completely an air-core vortex to a non-air-core vortex (mostly to a dimple). But the smallest single cage, 1.5 ft x 1.5 ft x 1.5 ft, and the smallest double layer cage (cages 3 and 4 in Figure 3) occasionally gave stronger vortices at higher flows, trash pulling vortex (type 4) to weak air-core (type 6). However, all of the five cages tested reduced the test average vortex types to less than 3.0. None of the tests with vortex suppressors (all of the tested ones) indicated any measurable air-withdrawals since void fraction readings were zero. This again stresses the point that any reasonable size cage of floor gratings was found to work well in suppressing air-core vortices. Figures 17 to 19 are photographs showing typical free-surface vortexing with suppressors of cage type.

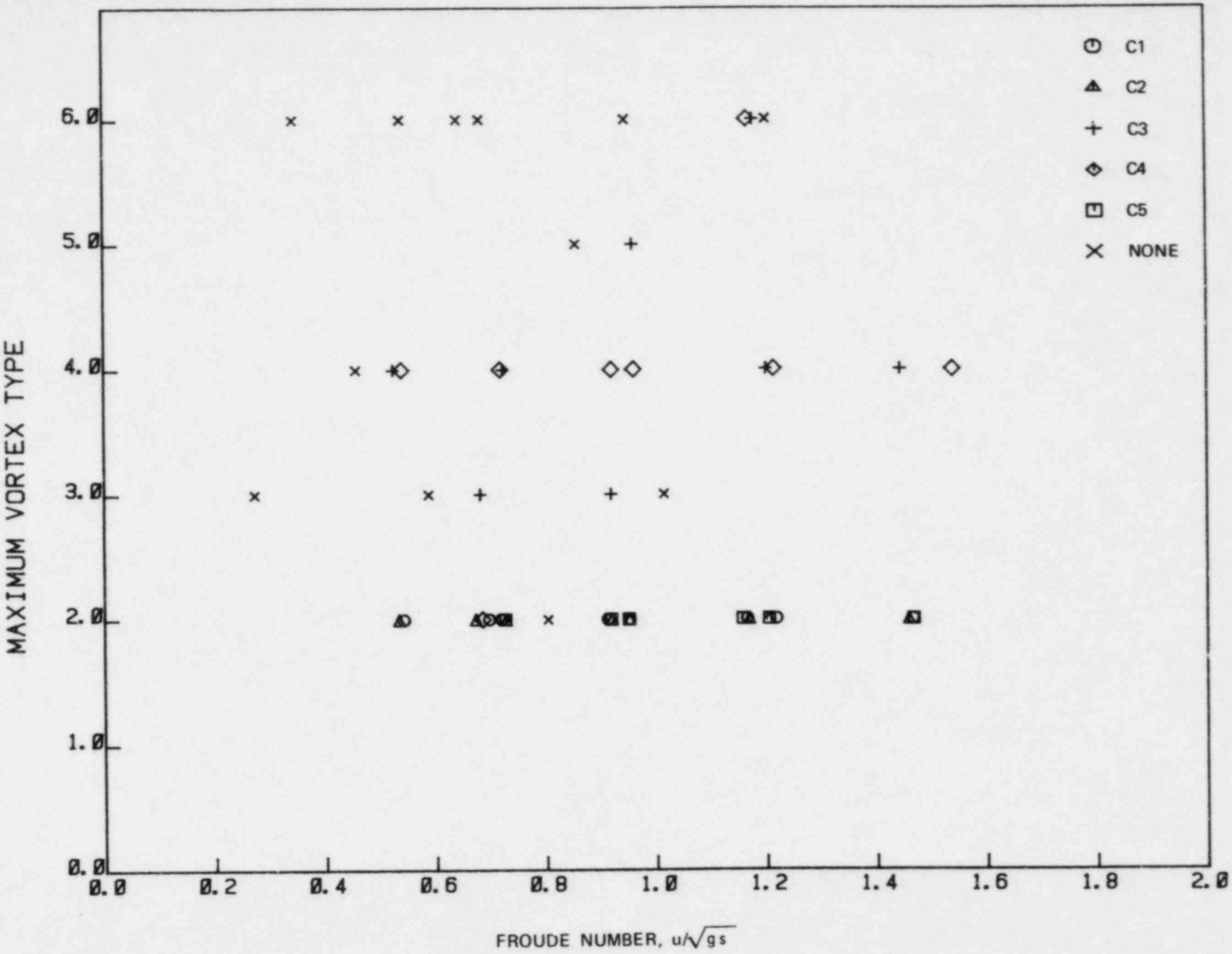


FIGURE 9 MAXIMUM VORTEX TYPES WITH AND WITHOUT CAGE SUPPRESSORS; CONFIGURATION 41

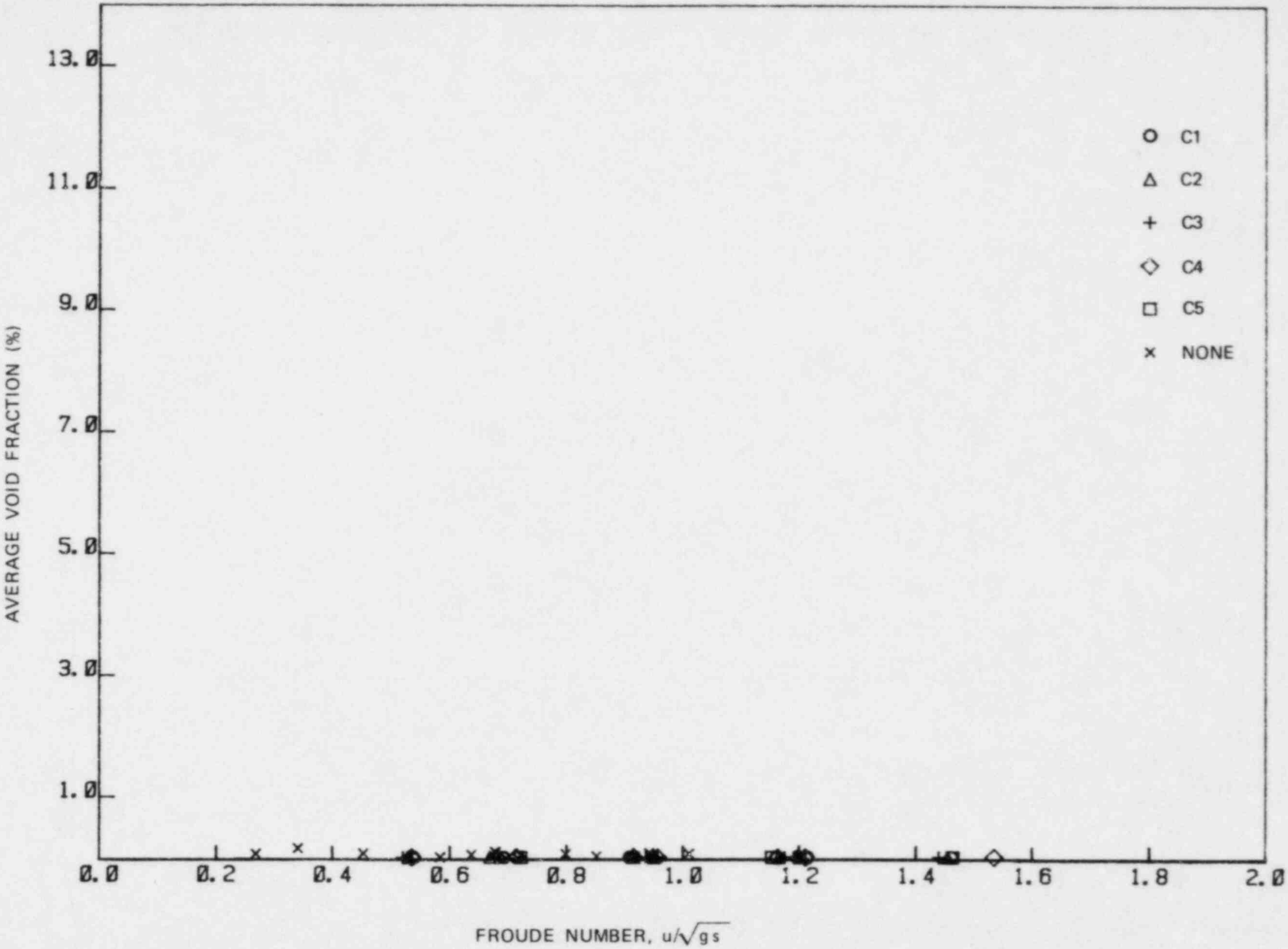


FIGURE 10 TEST AVERAGE VOID FRACTIONS FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT CAGE VORTEX SUPPRESSORS; CONFIGURATION 41

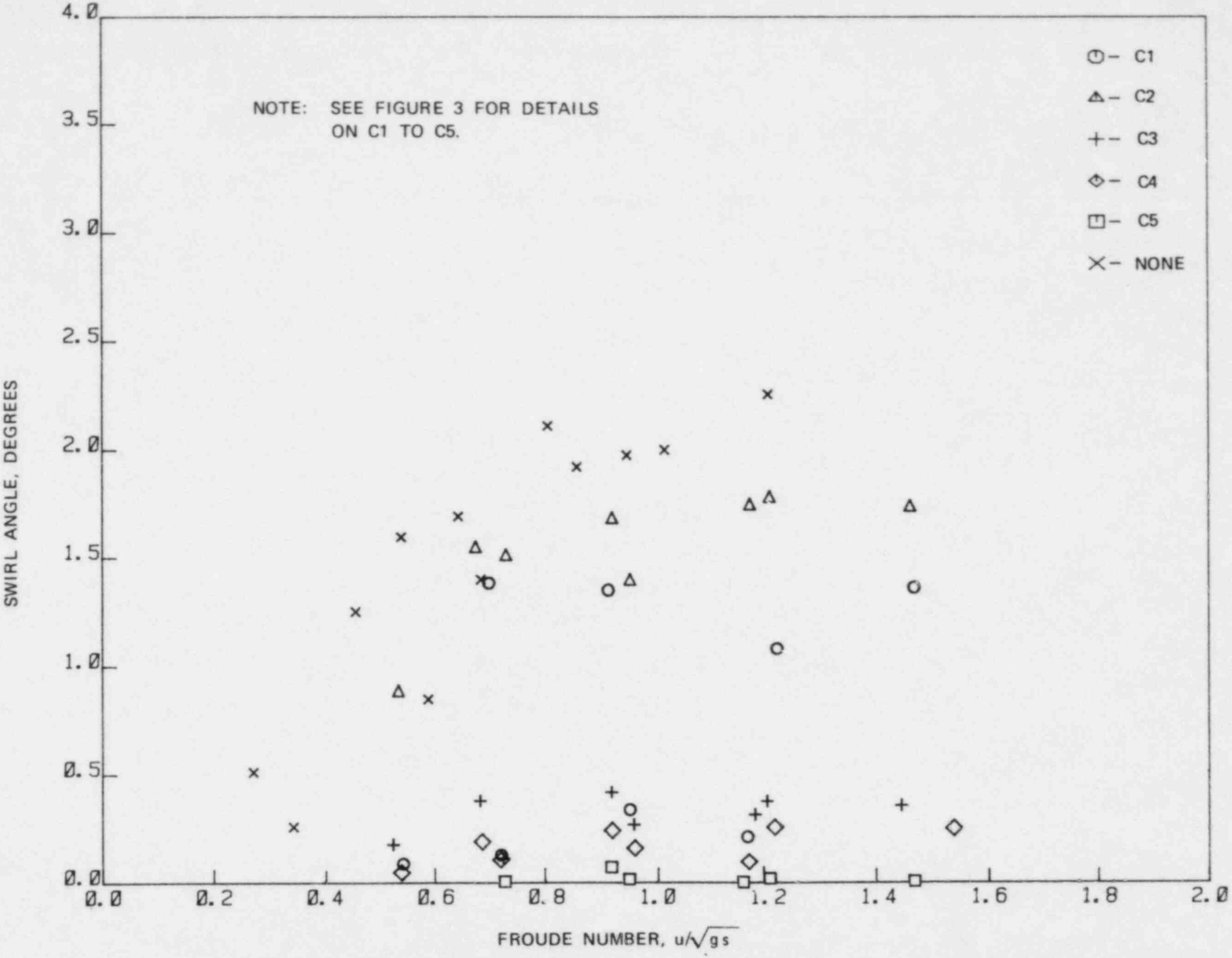
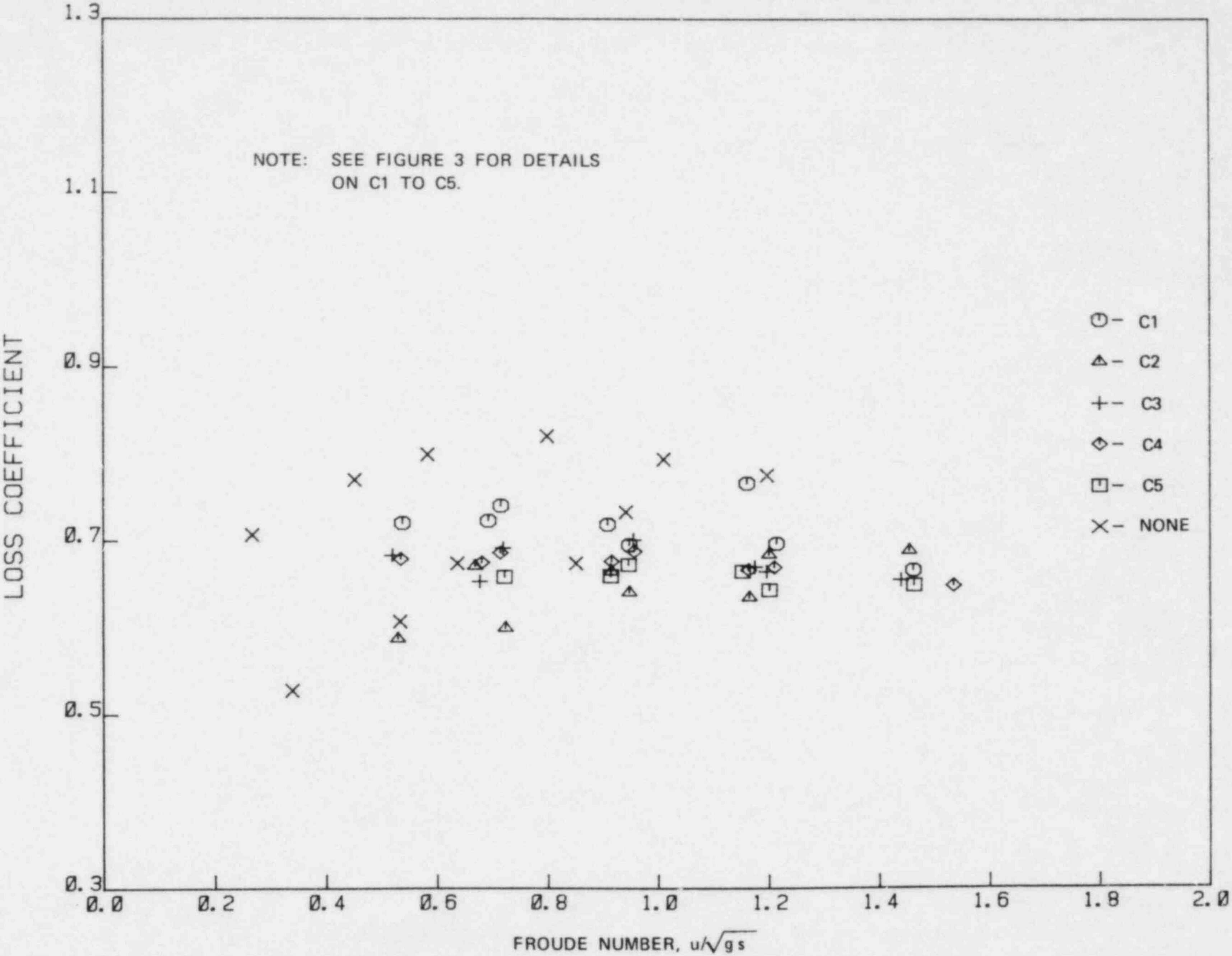


FIGURE 11 AVERAGE SWIRL ANGLES FOR TESTED FROUDE NUMBER RANGE WITH AND WITHOUT CAGE TYPE VORTEX SUPPRESSORS; CONFIGURATION 41



NOTE: SEE FIGURE 3 FOR DETAILS ON C1 TO C5.

FIGURE 12 AVERAGE INLET LOSS COEFFICIENTS FOR TESTED FROUDE NUMBER RANGE WITH AND WITHOUT CAGE TYPE VORTEX SUPPRESSORS; CONFIGURATION 41

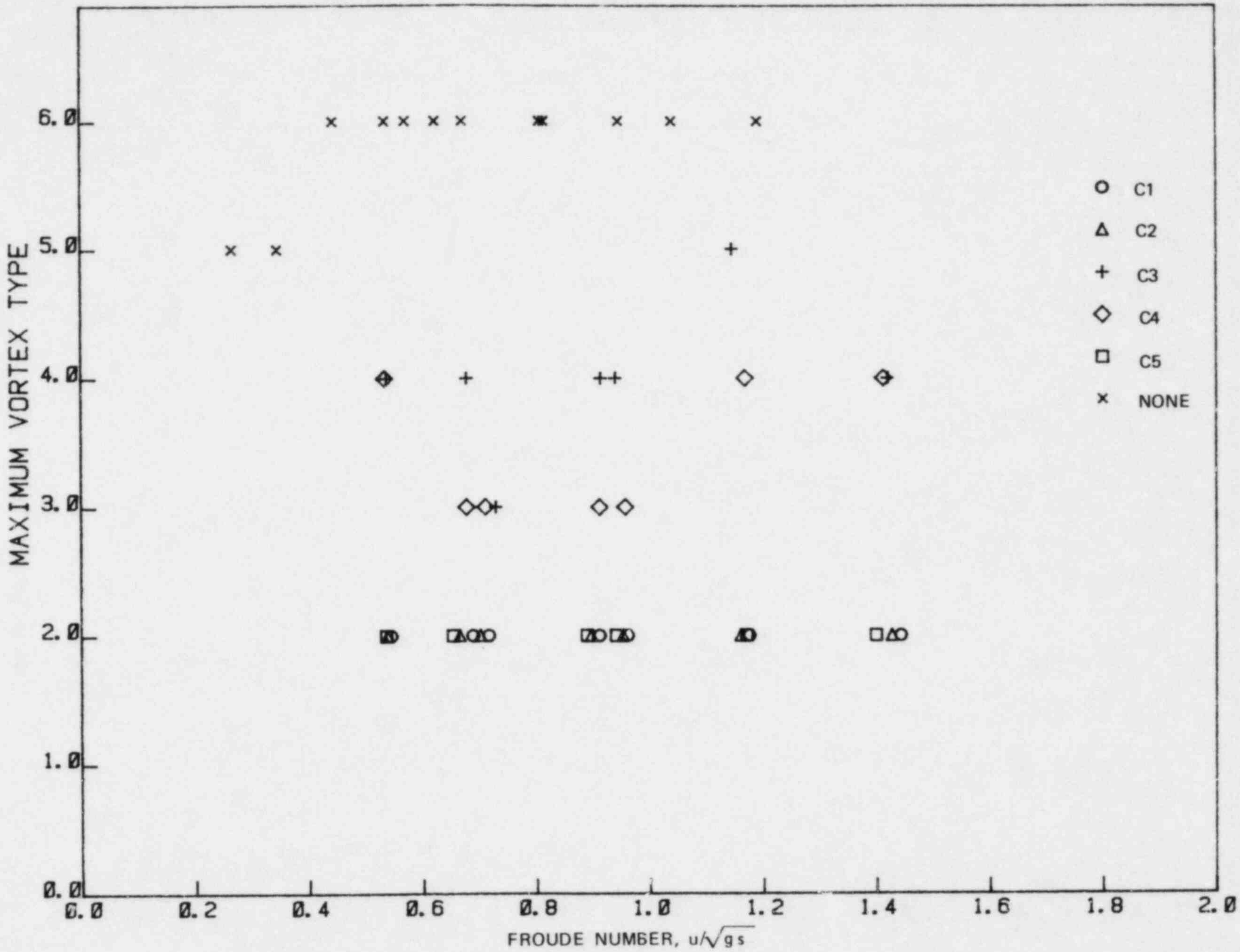


FIGURE 13 MAXIMUM VORTEX TYPES WITH AND WITHOUT CAGE TYPE SUPPRESSORS; CONFIGURATION 42

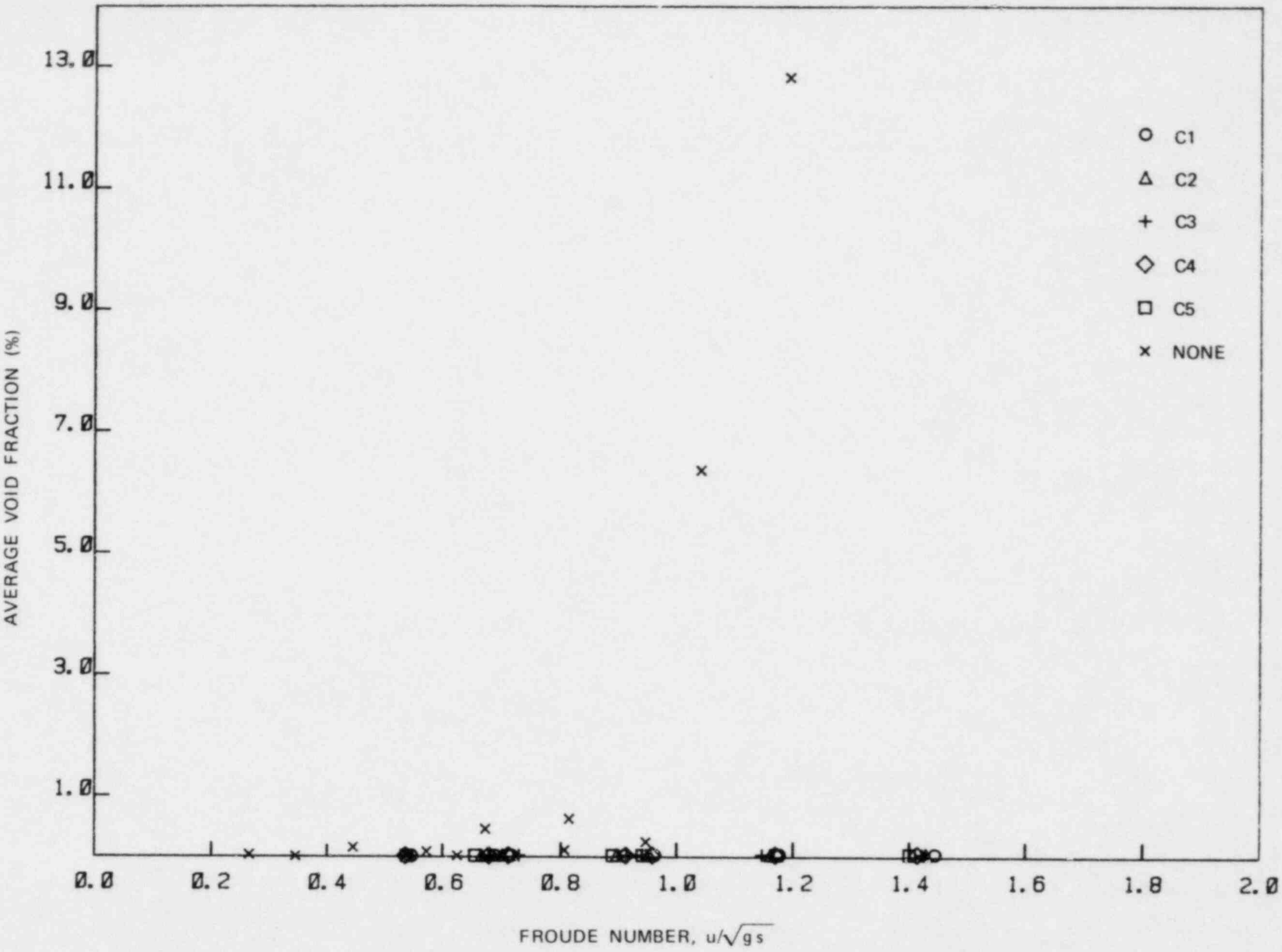


FIGURE 14 TEST AVERAGE VOID FRACTIONS FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT CAGE SUPPRESSORS; CONFIGURATION 42

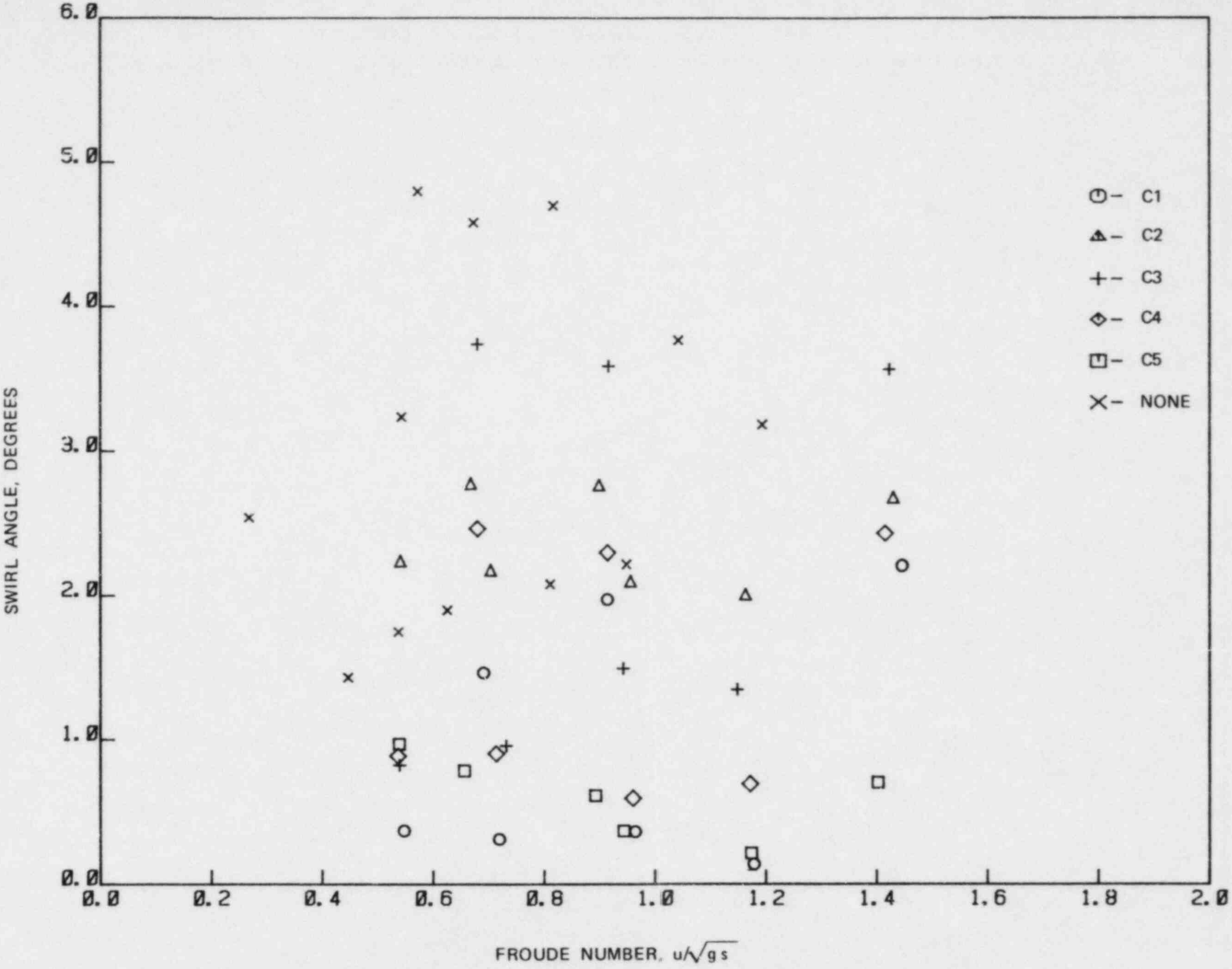


FIGURE 15 AVERAGE SWIRL ANGLES FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT CAGE TYPE SUPPRESSORS; CONFIGURATION 42

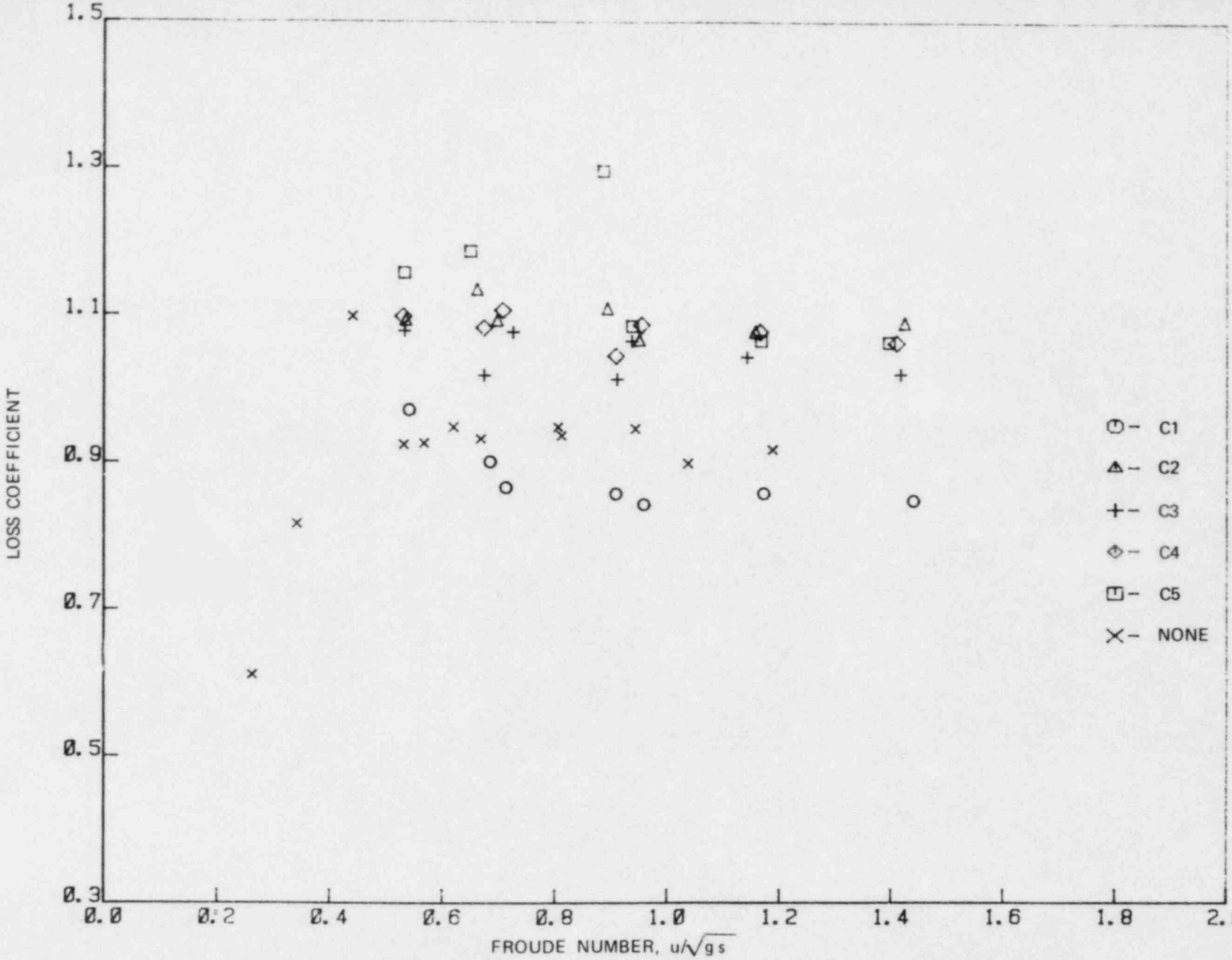


FIGURE 16 INLET LOSS COEFFICIENTS FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT CAGE TYPE SUPPRESSORS; CONFIGURATION 42 (INCLUDES BEND LOSSES)

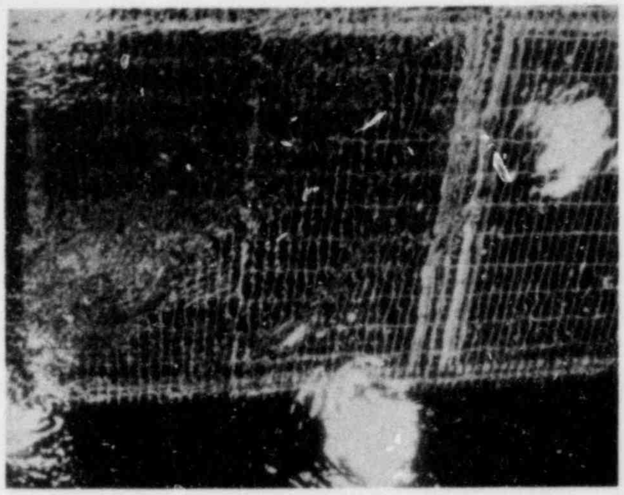


FIGURE 17 AIR-CORE VORTICES SUPPRESSED BY CAGE SUPPRESSORS C1; CONFIGURATION 42; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.0

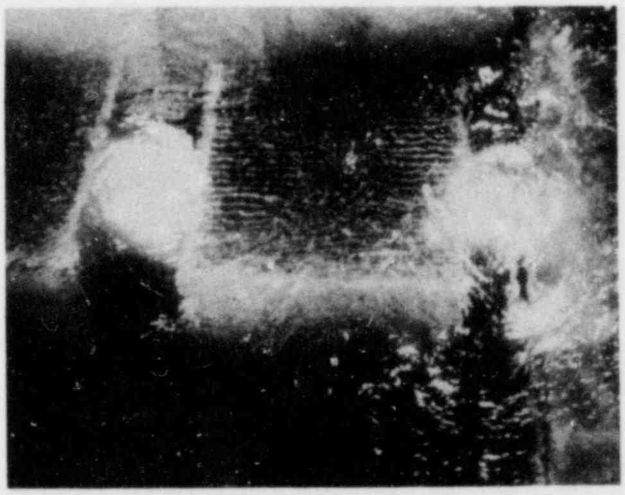


FIGURE 18 AIR-CORE VORTICES SUPPRESSED BY CAGE SUPPRESSORS C2; CONFIGURATION 41; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.0

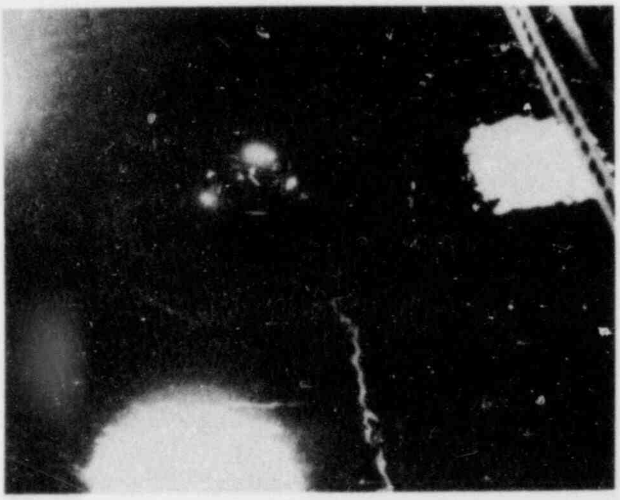


FIGURE 19 WEAK AIR-CORE VORTEX IN SPITE OF A CAGE SUPPRESSOR C3; CONFIGURATION 41; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.01

As regards to swirl, all of the cage type suppressors reduced, but did not eliminate, pipe swirl. The double cage (3 ft cube over 1.5 ft cube) arrangement #5 performed the best in significantly reducing the pipe swirl. The double cage arrangement presumably reduced the strength of any submerged vortices, which might have had a major contribution to swirl as indicated in earlier test results [1, 2]. It may be noted, however, that the swirl angles, even without suppressors, were small and were not of any major concern (less than 10 degrees over a 30 minute period).

The inlet loss coefficients were mostly in the range of 0.7 to 0.9 for all tests in horizontal outlet configuration and 0.9 to 1.1 for vertical outlet configurations including bend losses, which show that the addition of any of the cages tested did not cause any significant head loss increases.

4.1.2 Horizontal Type Suppressors

Figures 20 to 23 show the maximum vortex type, average void fractions, average swirl angles, and inlet loss coefficients with and without cage suppressors for horizontal outlet configuration (configuration 41) under screen blockage (Scheme 5). Similar results for vertical outlet configuration (configuration 42) are shown in Figures 24 to 27. All of the five horizontal grating setups tested (Figure 4); namely, three single layer arrangements and two double layer arrangements, were found effective in suppressing an air-core vortex completely to a non-air-drawing one. In comparison to cage type suppressors, the horizontal grates covering the entire sump were performing better in that not even occasional stronger vortices (Type 4 and greater) were observed with horizontal gratings. When a single grating is used, it is advantageous to have the grating closer to the minimum water level since the average vortex types were 2 or less for this case (arrangement H3 in Figure 4). With no air-withdrawing vortices present, all the tests with suppressors showed zero air-withdrawal. Photographs of typical cases of vortex suppression with horizontal suppressors are given in Figures 28 to 30. All of the horizontal suppressors reduced but did not eliminate swirl in the suction pipes. The two-layer arrangements (H5) with each layer at different levels, performed the best in swirl reduction. The inlet loss coefficients for all of the suppressors fell mostly in the range of 0.7 to 0.9 for horizontal outlet sump and 0.9 to 1.1 for vertical outlet sump including bend losses indicating no appreciable increases in head losses due to suppressors themselves.

4.2 Single Outlet Sumps

Figures 31 to 34 show plots of average vortex types, void fractions (1 minute average), swirl angles, and inlet loss coefficients for cases of approximately uniform approach flow and for cases of screen blockages (up to 75% blocked) for both the sumps tested, plotted against Froude number. Without any screen

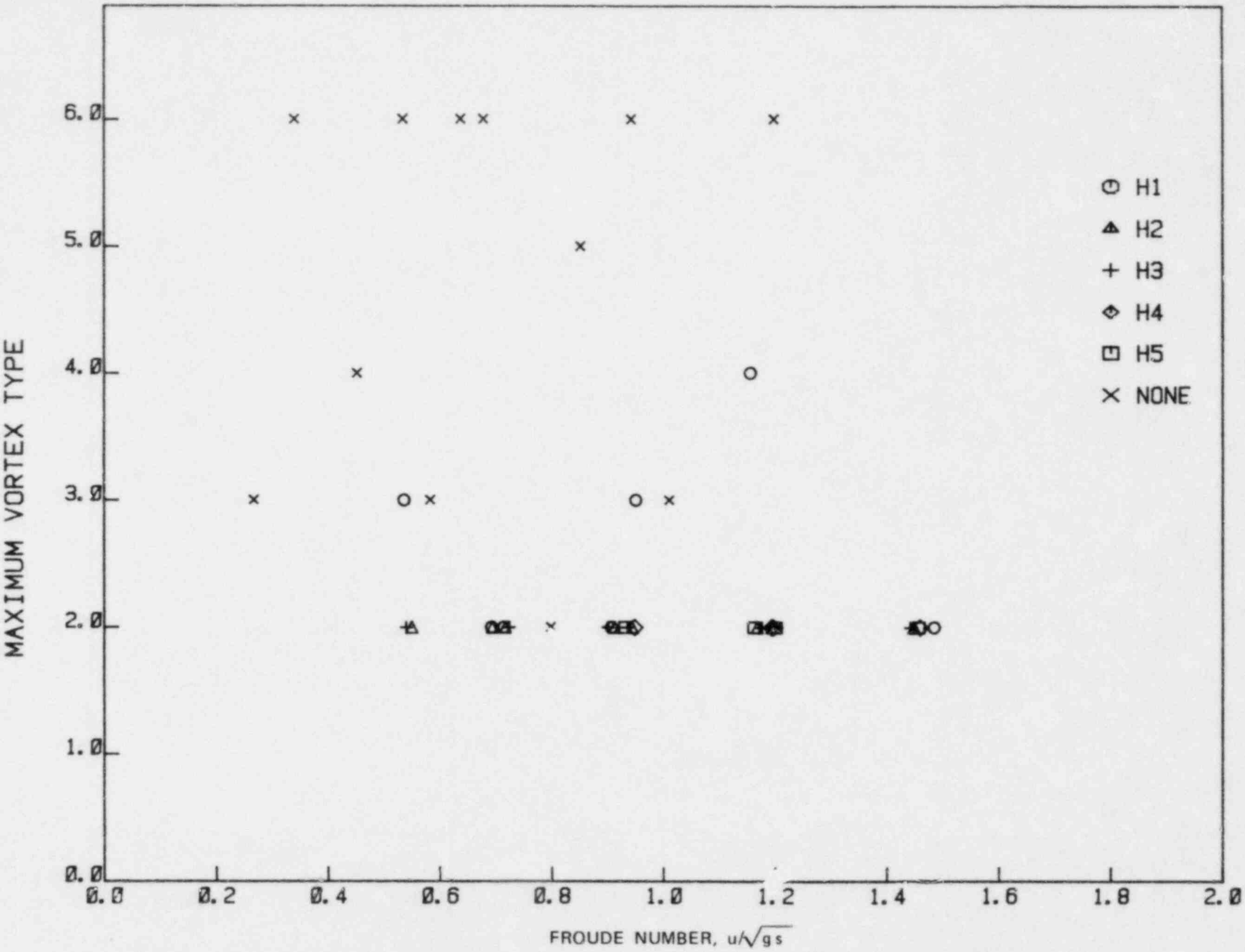


FIGURE 20 MAXIMUM VORTEX TYPES WITH AND WITHOUT HORIZONTAL GRATING SUPPRESSORS; CONFIGURATION 41

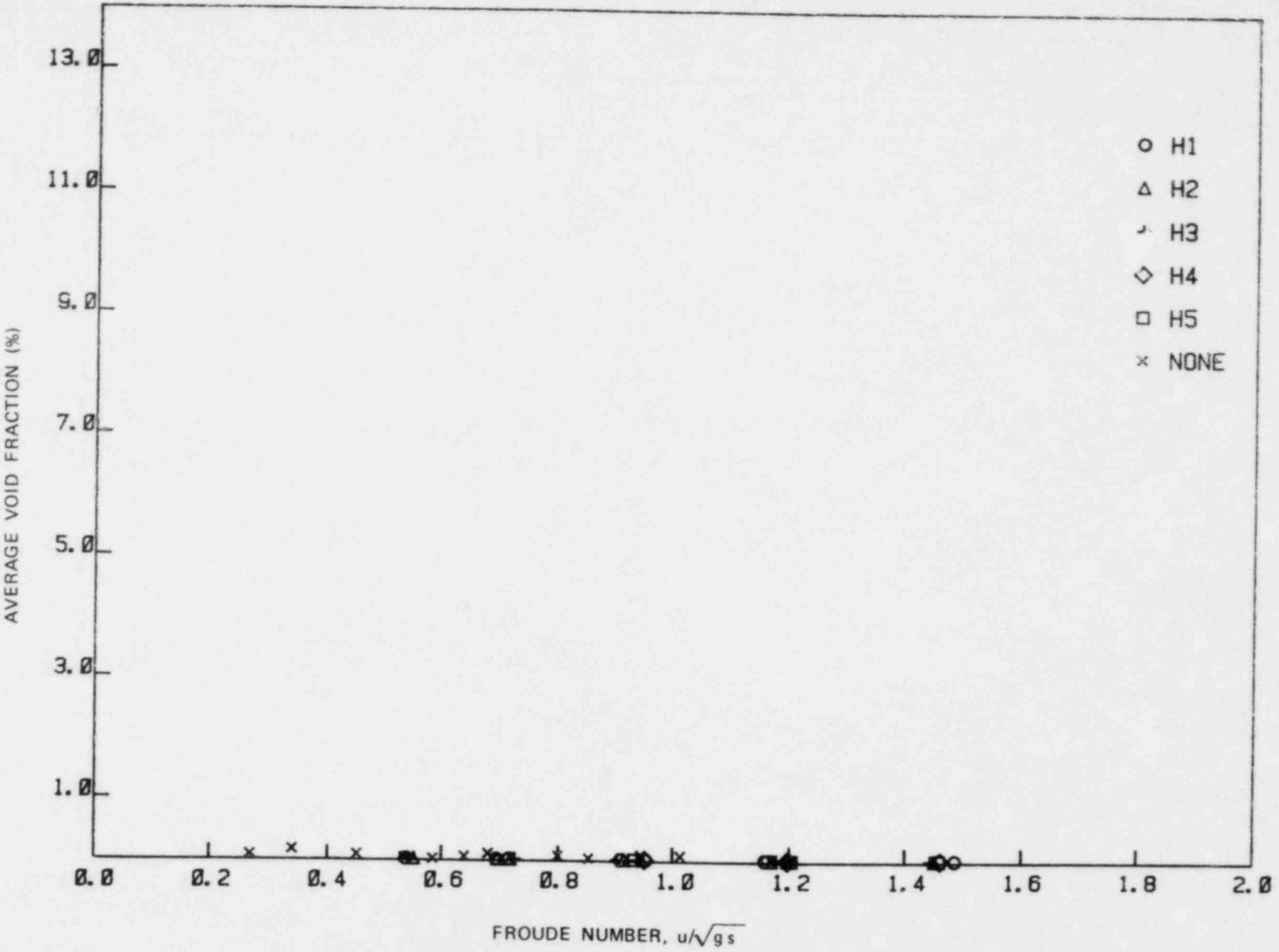


FIGURE 21 TEST AVERAGE VOID FRACTIONS FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT HORIZONTAL GRATING VORTEX SUPPRESSORS; CONFIGURATION 41

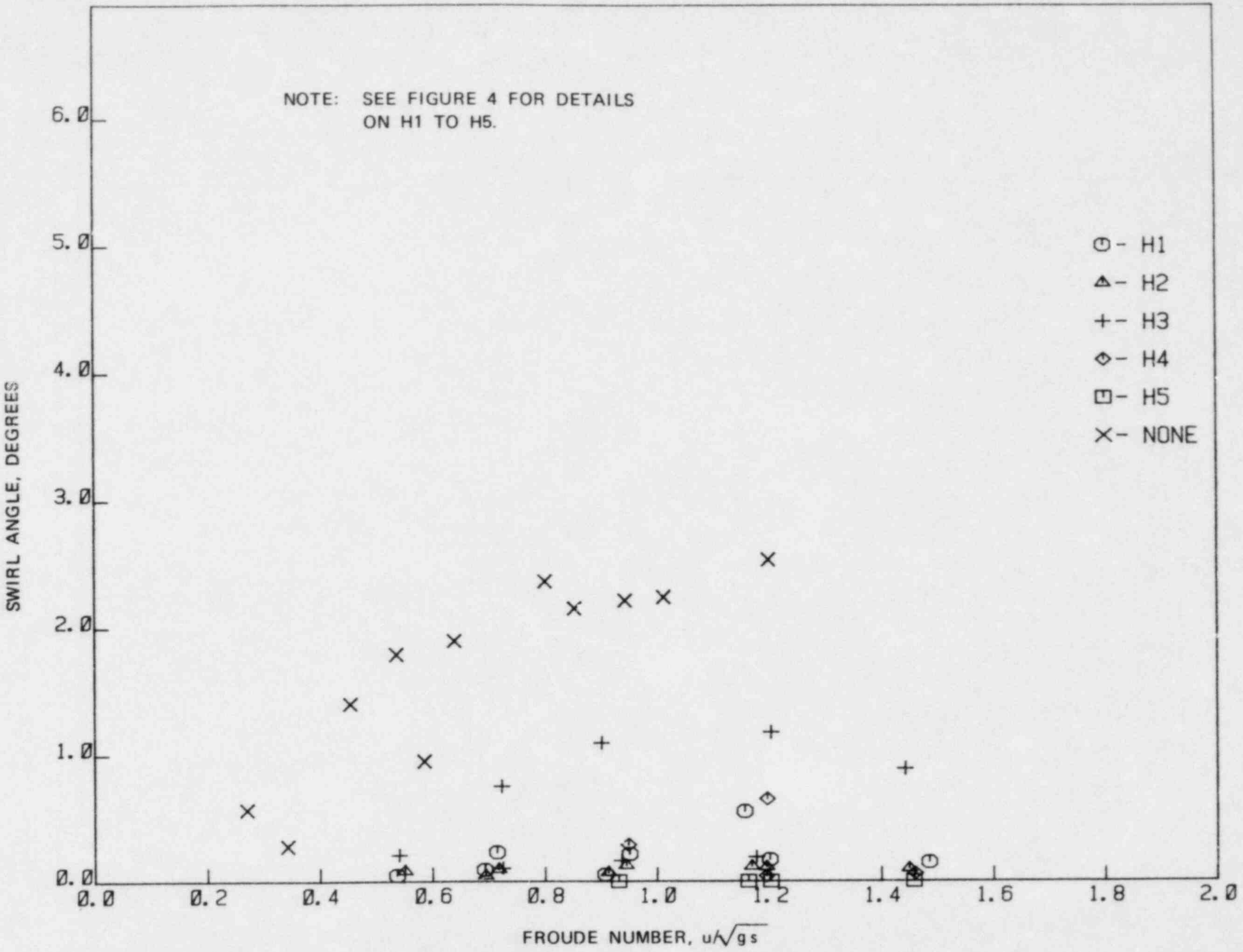


FIGURE 22 AVERAGE SWIRL ANGLES FOR TESTED FROUDE NUMBER RANGE WITH AND WITHOUT HORIZONTAL FLOOR GRATING TYPE VORTEX SUPPRESSORS; CONFIGURATION 41

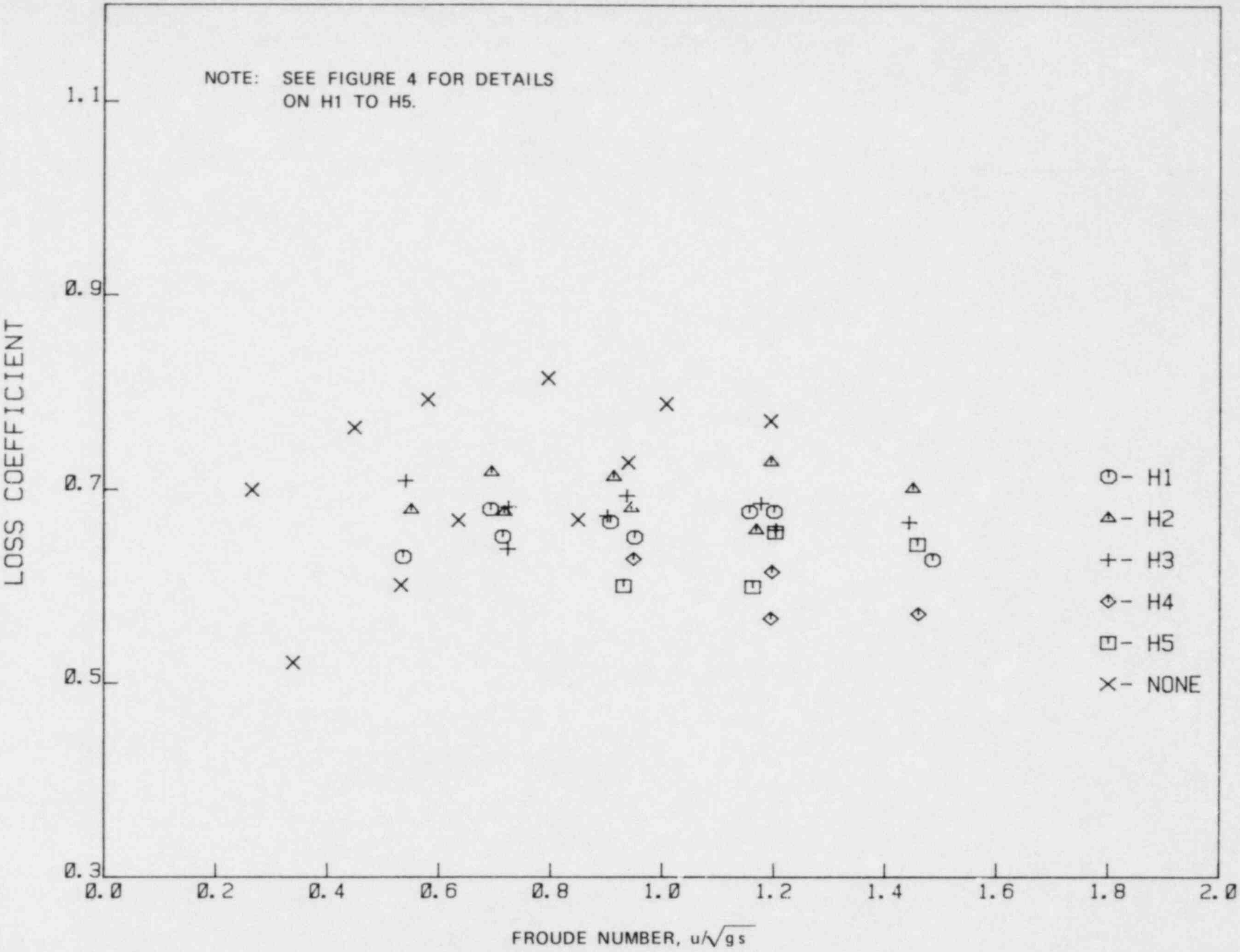


FIGURE 23 AVERAGE INLET LOSS COEFFICIENT FOR TESTED FROUDE NUMBER RANGE WITH AND WITHOUT HORIZONTAL FLOOR GRATING TYPE VORTEX SUPPRESSORS; CONFIGURATION 41

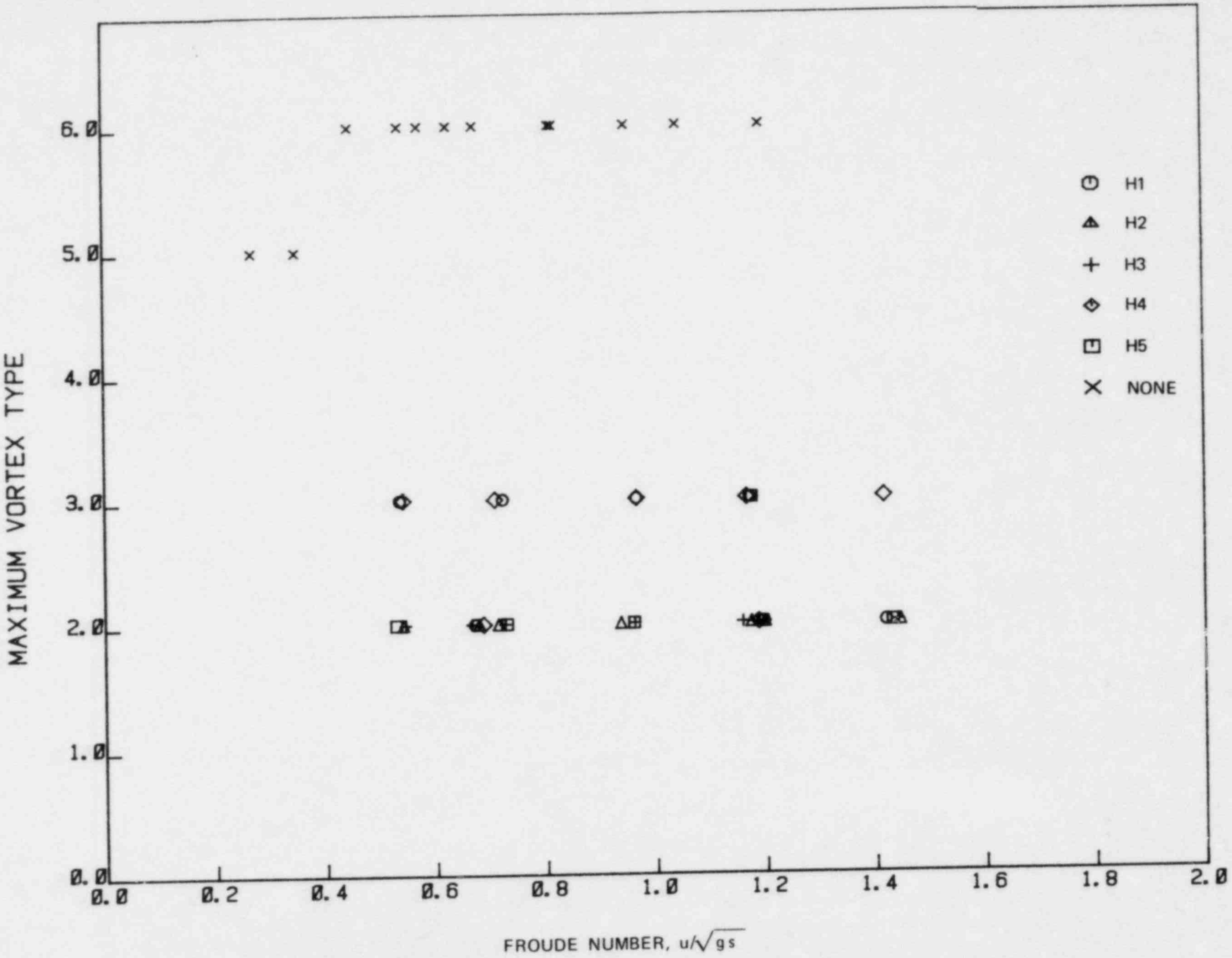


FIGURE 24 MAXIMUM VORTEX TYPES WITH AND WITHOUT HORIZONTAL GRATING SUPPRESSORS; CONFIGURATION 42

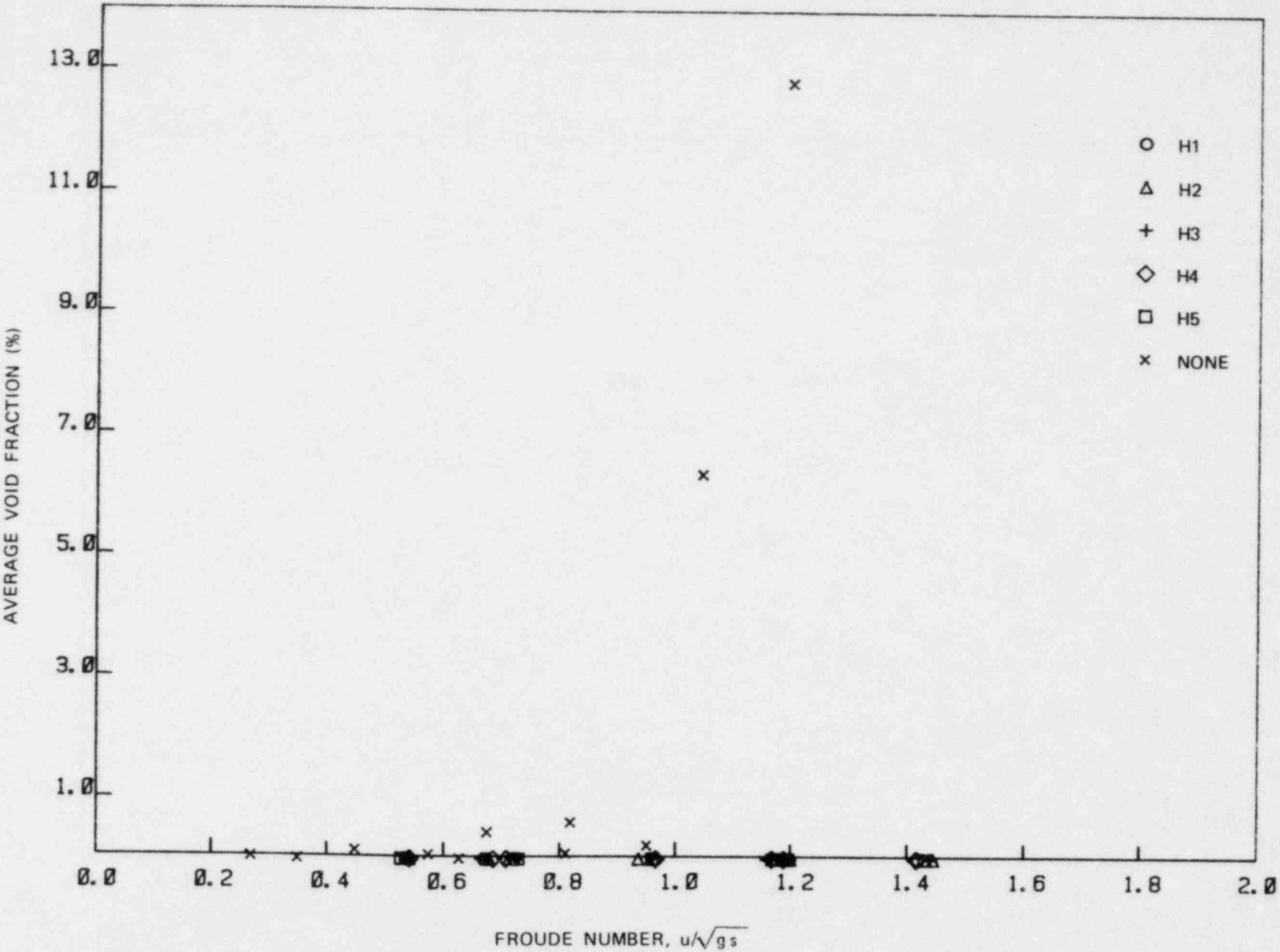


FIGURE 25 TEST AVERAGE VOID FRACTIONS FOR THE FROUDE NUMBER RANGE TESTED; WITH AND WITHOUT HORIZONTAL SUPPRESSORS; CONFIGURATION 42

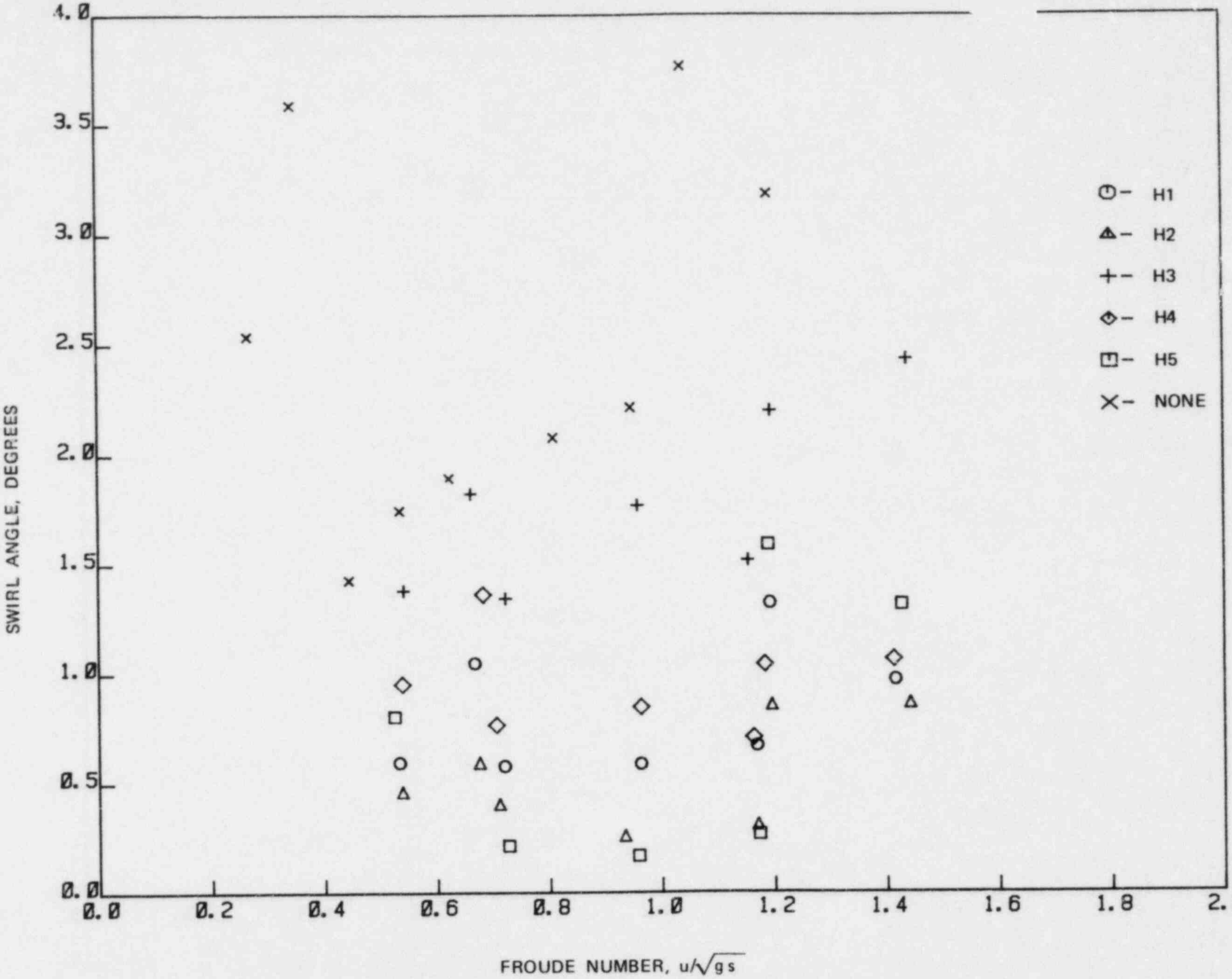


FIGURE 26 AVERAGE SWIRL ANGLES FOR THE TESTED FROUDE NUMBER RANGE; WITH AND WITHOUT HORIZONTAL GRATING TYPE SUPPRESSORS; CONFIGURATION 42

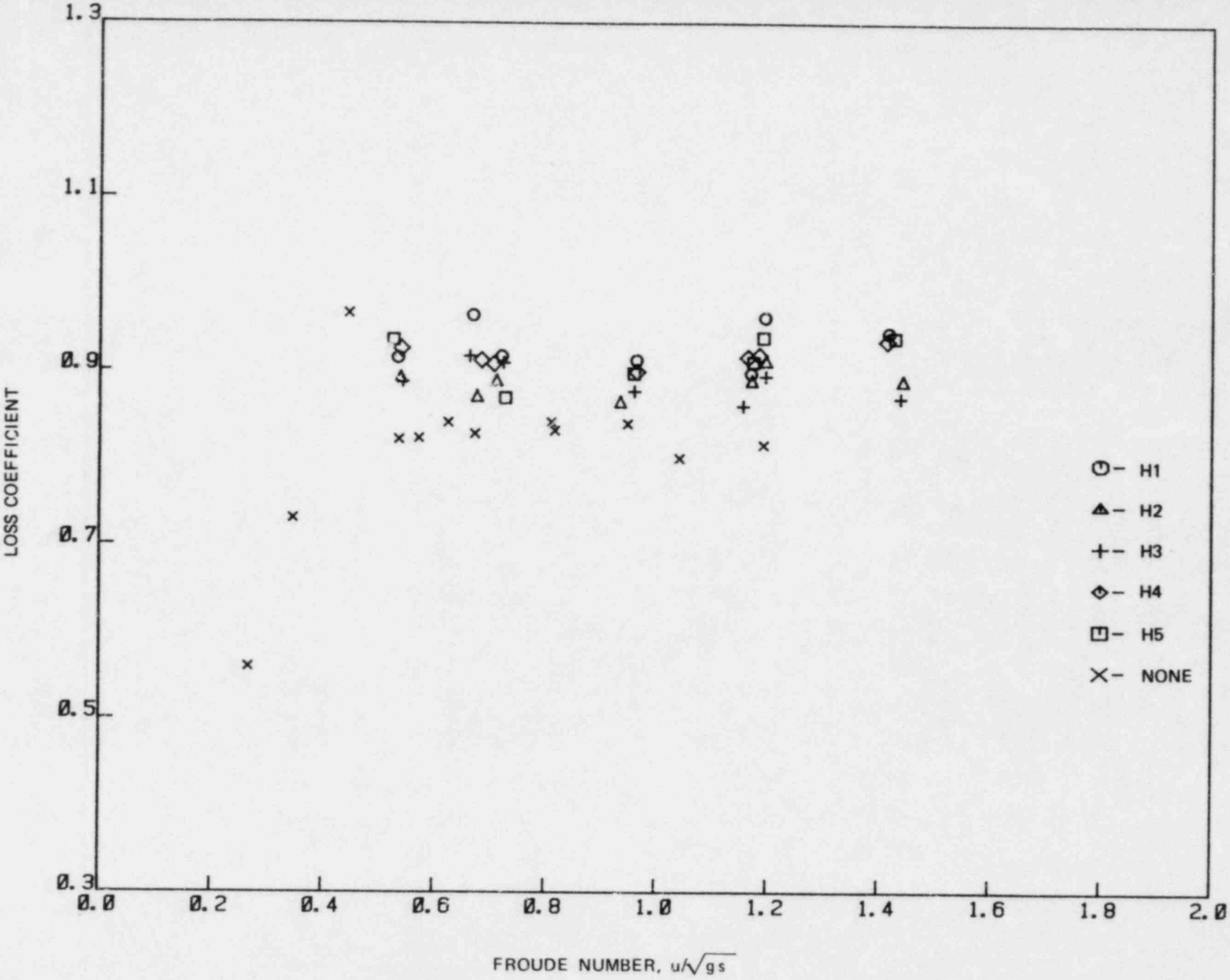


FIGURE 27 INLET LOSS COEFFICIENTS FOR THE TESTED FROUDE NUMBER RANGE; WITH AND WITHOUT HORIZONTAL GRATING TYPE SUPPRESSORS; CONFIGURATION 42 (INCLUDING BEND LOSSES)

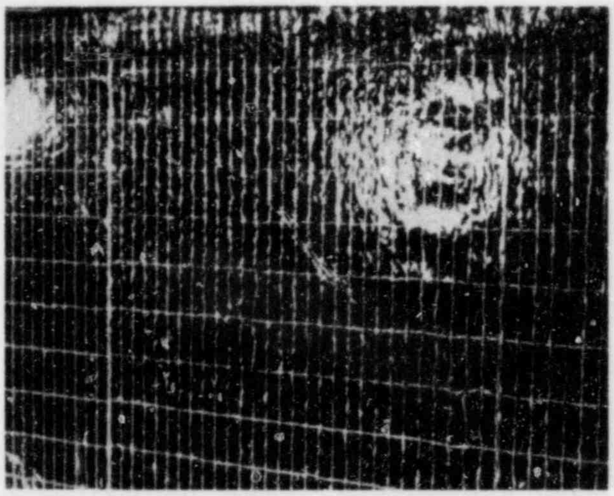


FIGURE 28 AN AIR-CORE VORTEX SUPPRESSED TO SURFACE DIMPLE; CONFIGURATION 41; HORIZONTAL GRATING SUPPRESSOR H3; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.0

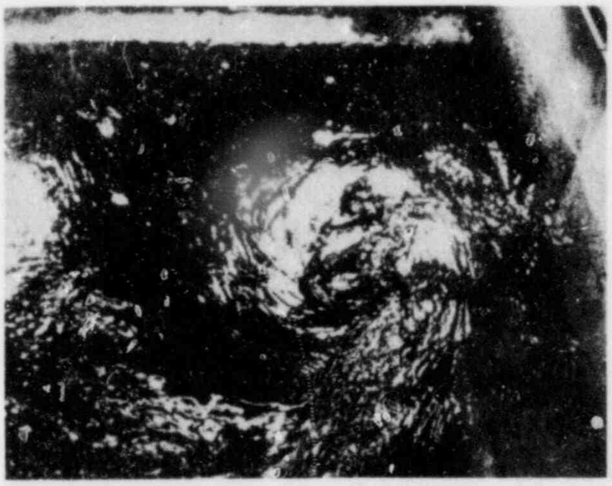


FIGURE 29 AN AIR-CORE VORTEX SUPPRESSED TO A SURFACE DIMPLE; CONFIGURATION 41; HORIZONTAL GRATING SUPPRESSOR H4; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.0

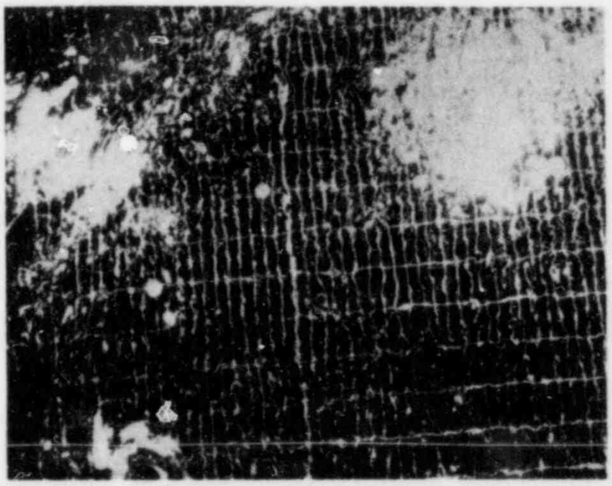


FIGURE 30 AN AIR-CORE VORTEX SUPPRESSED BY HORIZONTAL CONFIGURATION 41; GRATING SUPPRESSOR H5; Q = 6600 gpm; s = 5′; F = 1.5; a = 0.0

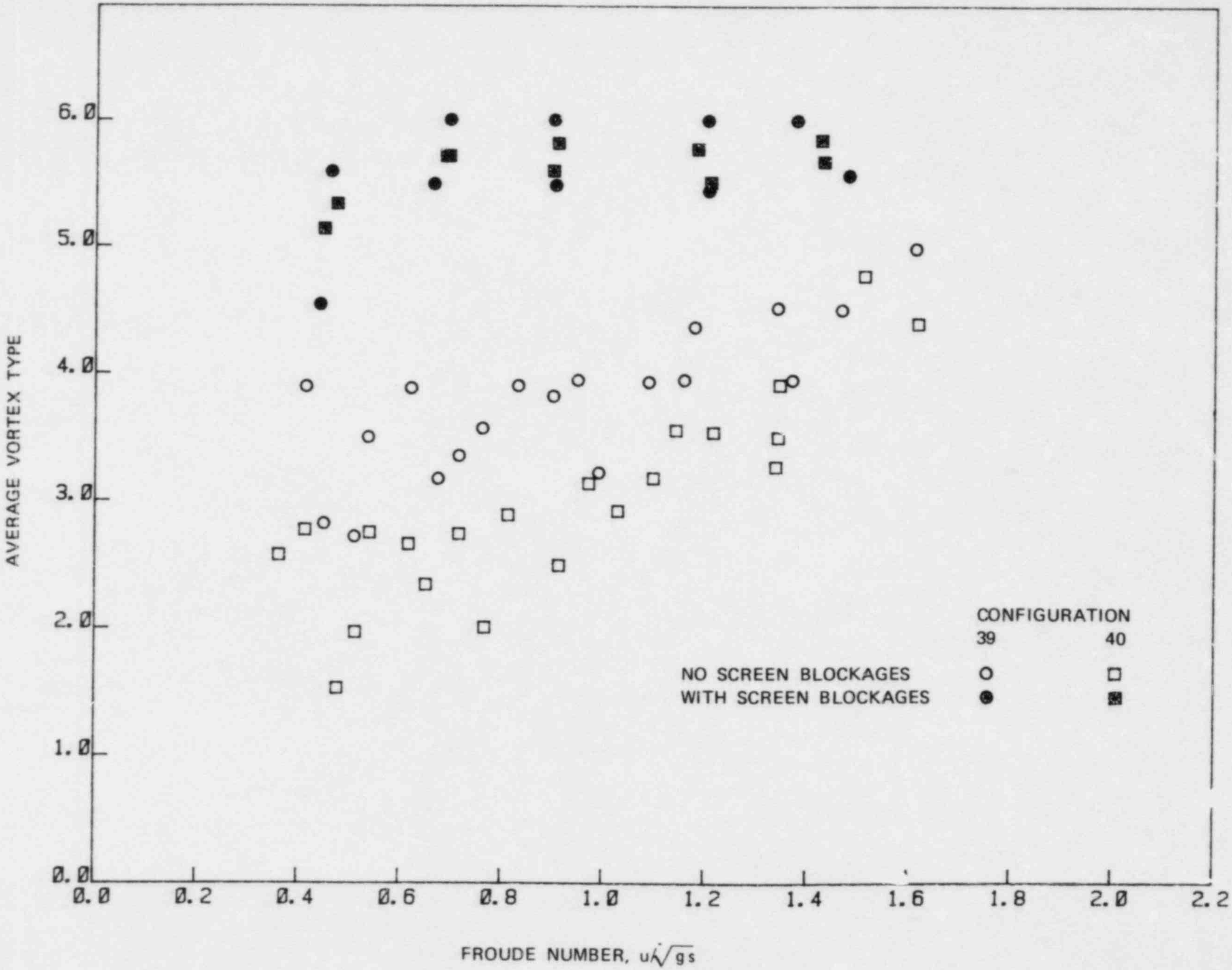


FIGURE 31 TEST AVERAGE VORTEX TYPES; SINGLE OUTLET SUMPS

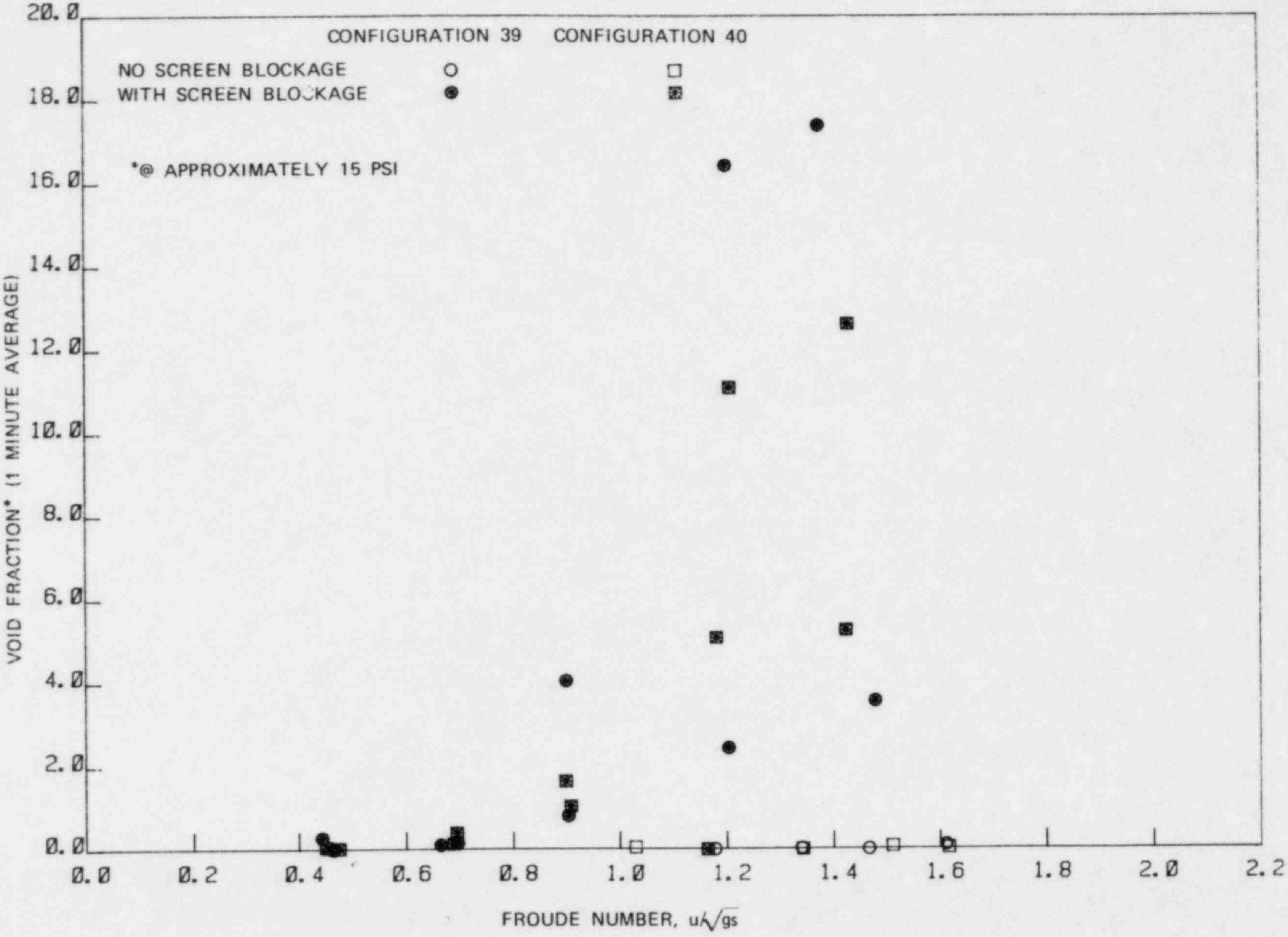


FIGURE 32 AVERAGE AIR-WITHDRAWALS FOR VARIOUS FROUDE NUMBERS; SINGLE OUTLET SUMPS

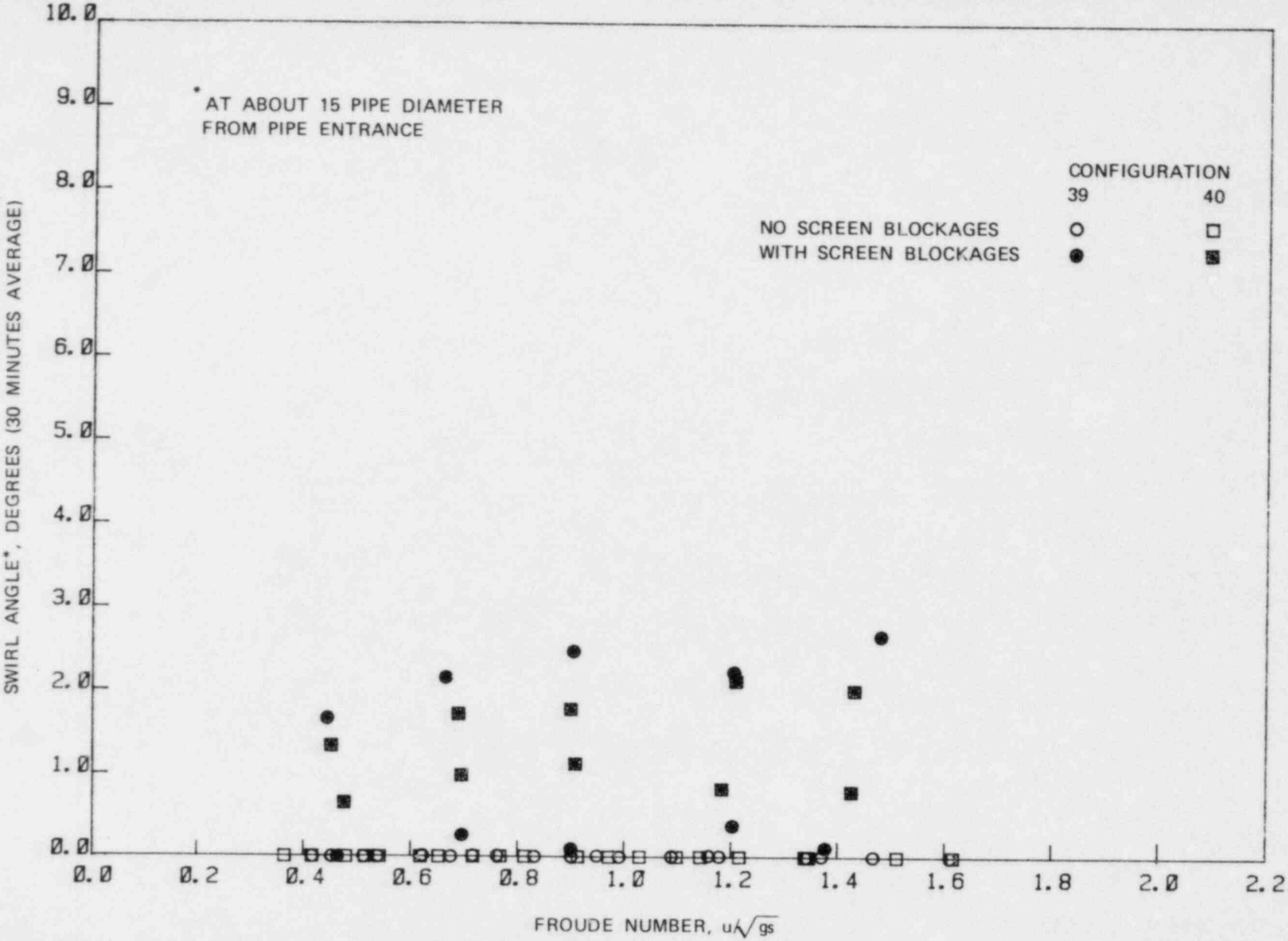


FIGURE 33 AVERAGE SWIRL ANGLES FOR VARIOUS FROUDE NUMBERS; SINGLE OUTLET SUMPS

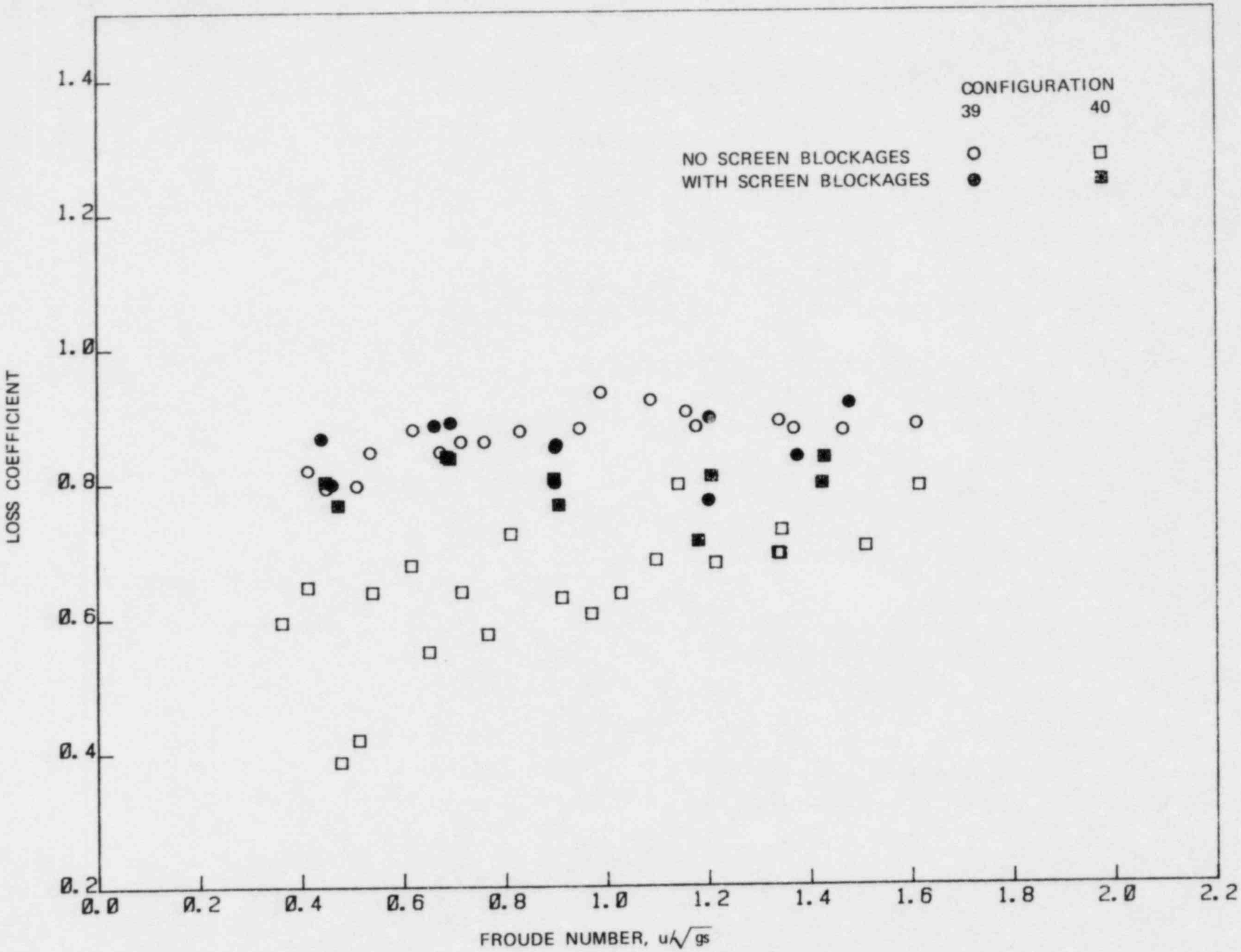


FIGURE 34 INLET LOSS COEFFICIENTS FOR VARIOUS FROUDE NUMBERS; SINGLE OUTLET SUMPS; WITH AND WITHOUT SCREEN BLOCKAGES

blockages weak air-core vortices were observed only for submergences less than 6 ft at flows above 4000 gpm (F greater than 0.8). With screen blockages, both the sumps had air-core vortices at the tested submergences of 5 ft for all of the tested flows (F = 0.4 to 1.4). However, the measured void fractions (indicating air-withdrawals) were less than 1% (both 1 minute and 30 minute average) for F greater than 0.8. The highest air-withdrawals measured (for F = 1.4) were 17.4% void fraction for 4 ft x 4 ft sump and 12.6% void fraction for 7 ft x 5 ft sump over a 1 minute period (see Figure 32). The corresponding 30 minute averages were 13.7% and 7.6%, respectively. It may be pointed out that these values are higher than the maximums observed for two-outlet horizontal sumps, with both pipes operating [1]. Figure 35 shows photographs of air-core vortices for both the tested sump configurations.

The pipe swirl angles (average over 30 minutes) measured at about 14.5 pipe diameters from the entrance were less than 1 degree (30 minute average) for tests with no screen blockages, but were as high as 2.7 degrees for 4 ft x 4 ft sump and 2.1 degrees for 7 ft x 5 ft sump (the corresponding 1 minute values are 4.8 and 4.3 degrees, respectively) for tests with screen blockages.

The inlet loss coefficients for both sumps were mostly in the range of 0.6 to 0.8, giving an average of about 0.7, agreeing with published values [12].

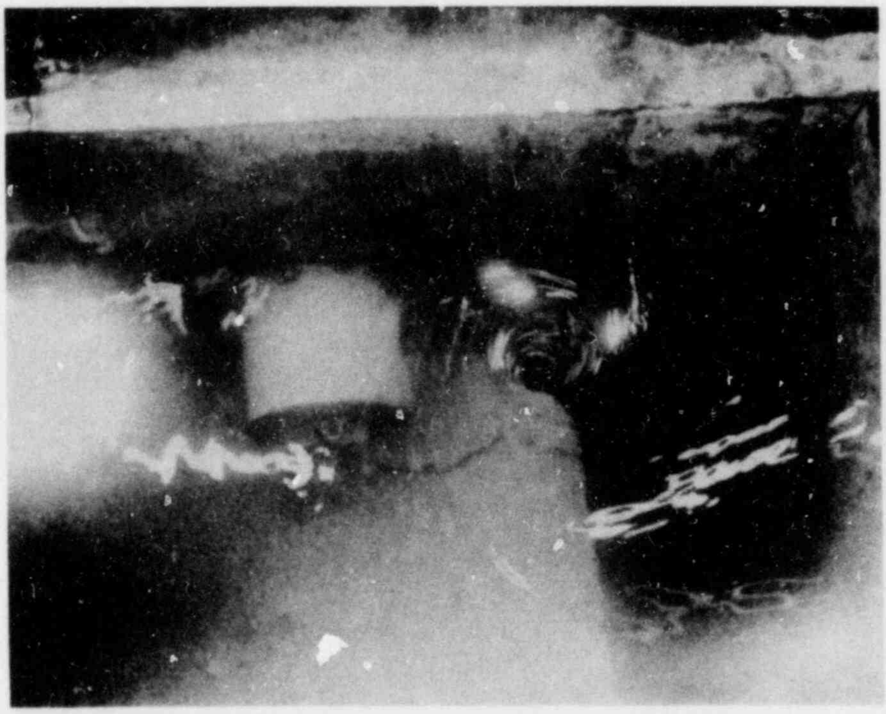
4.3 Tests on Double Outlet Sumps with Solid Partition Walls

For all of the tested sumps; namely, configurations 34 and 36 (24 inch diameter sumps) and configurations 37 and 38 (12 inch and 6 inch diameter outlet pipes), the average vortex types, swirl angles, void fractions, and inlet loss coefficients are all shown in Figures 36 to 39, for the tested ranges of Froude numbers and for cases with and without screen blockages.

For configurations 34 and 36, only weak air-core vortices were observed even with screen blockages and the air-withdrawals were less than 0.2% (1 minute or 30 minute average void fractions) for all the tests. These two configurations, being 24 inch outlet pipe sumps, were tested for Froude numbers up to about 0.6 only due to facility flow limitation. Also, for configurations 37 and 38 even with screen blockages, only weak air-core vortices were observed with air-withdrawals less than 1% (30 minute average void fraction) and less than 3% (1 minute average void fraction).

As regards to swirl, configurations 34 and 36 showed test average swirl angles as high as 6.7 degrees and 9.9 degrees, respectively, (under screen blockages for the latter). The swirl angles were measured for these two configurations at about 8 pipe diameters from inlet. For comparison purposes, the above swirl angles were converted to values at 14.5 pipe diameters from entrance using an exponential swirl decay with decay parameter

A. AN AIR-CORE VORTEX IN CONFIGURATION 39 WITH SCREEN BLOCKAGE; F = 1.4; Q = 6200 gpm; s = 5′; α (1 MINUTE AVERAGE) = 17.4%



B. AN AIR-CORE VORTEX IN CONFIGURATION 40 WITH SCREEN BLOCKAGE; F = 1.4; Q = 6370 gpm; s = 5′; α (1 MINUTE AVERAGE) = 5.3%

FIGURE 35 AIR-CORE VORTICES IN SINGLE OUTLET SUMPS

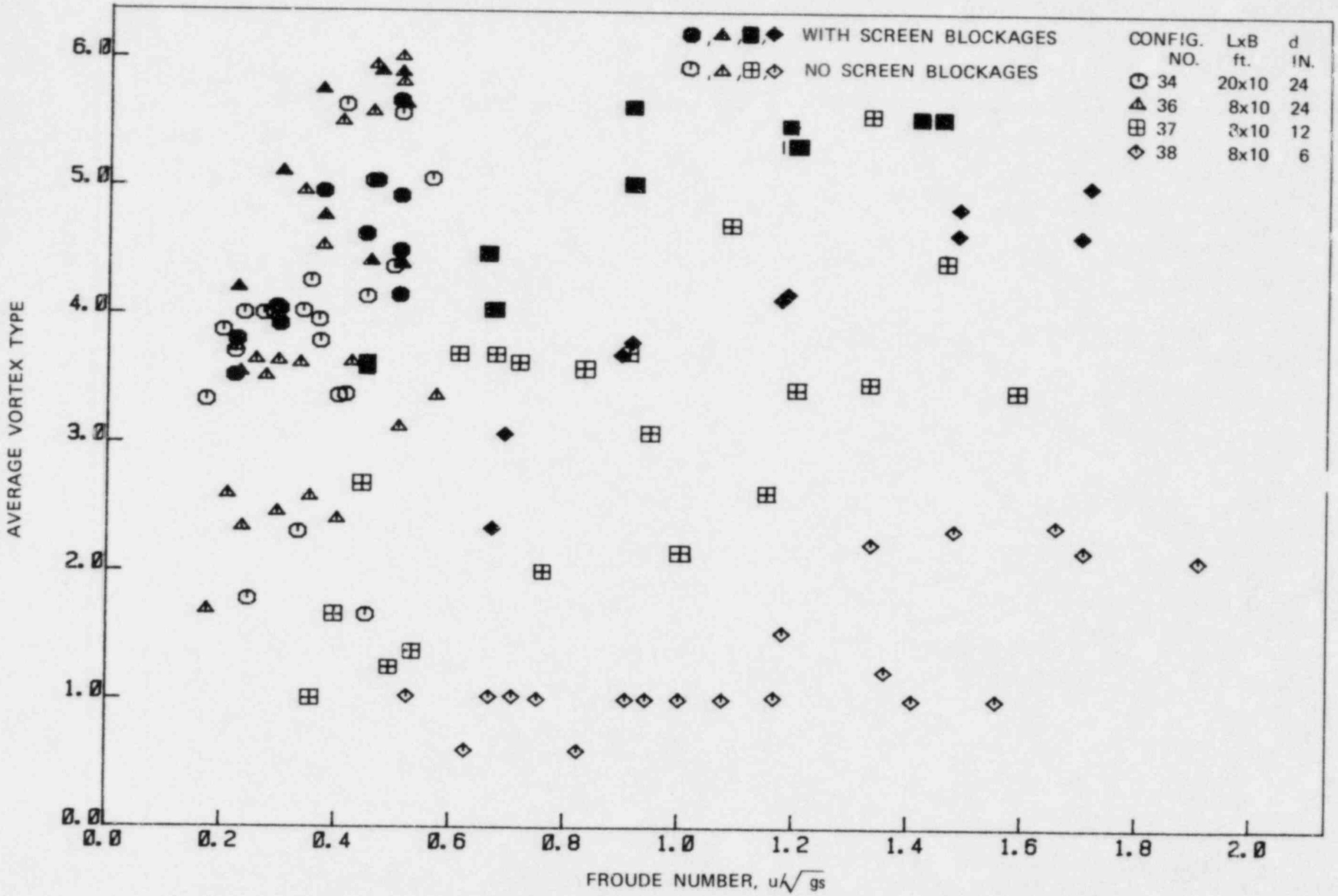


FIGURE 36 AVERAGE VORTEX TYPE VARIATION WITH FROUDE NUMBER; SUMPS WITH SOLID PARTITION WALLS

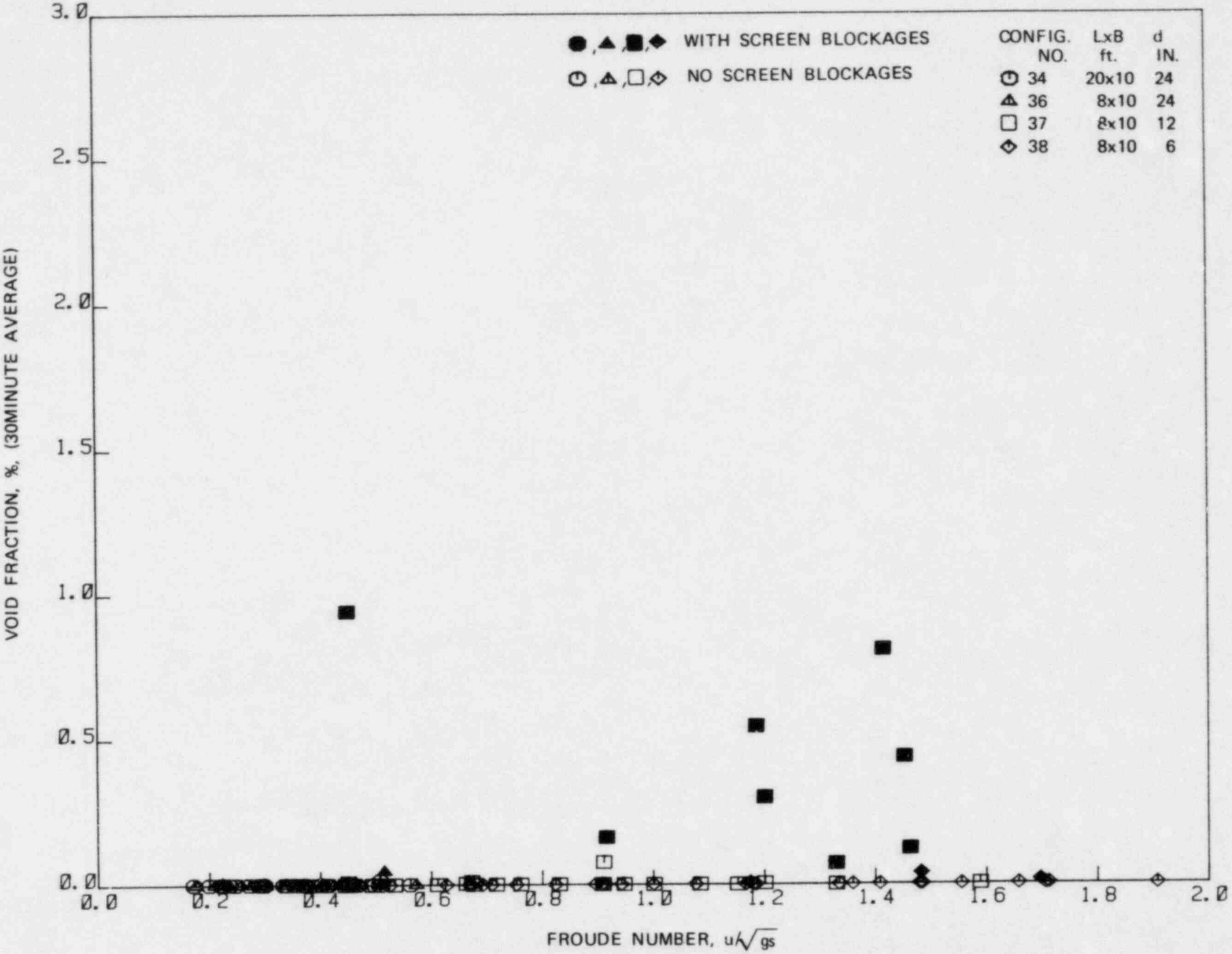


FIGURE 37 AVERAGE AIR-WITHDRAWALS FOR TESTED FROUDE NUMBER RANGE; SOLID PARTITION WALL SUMPS

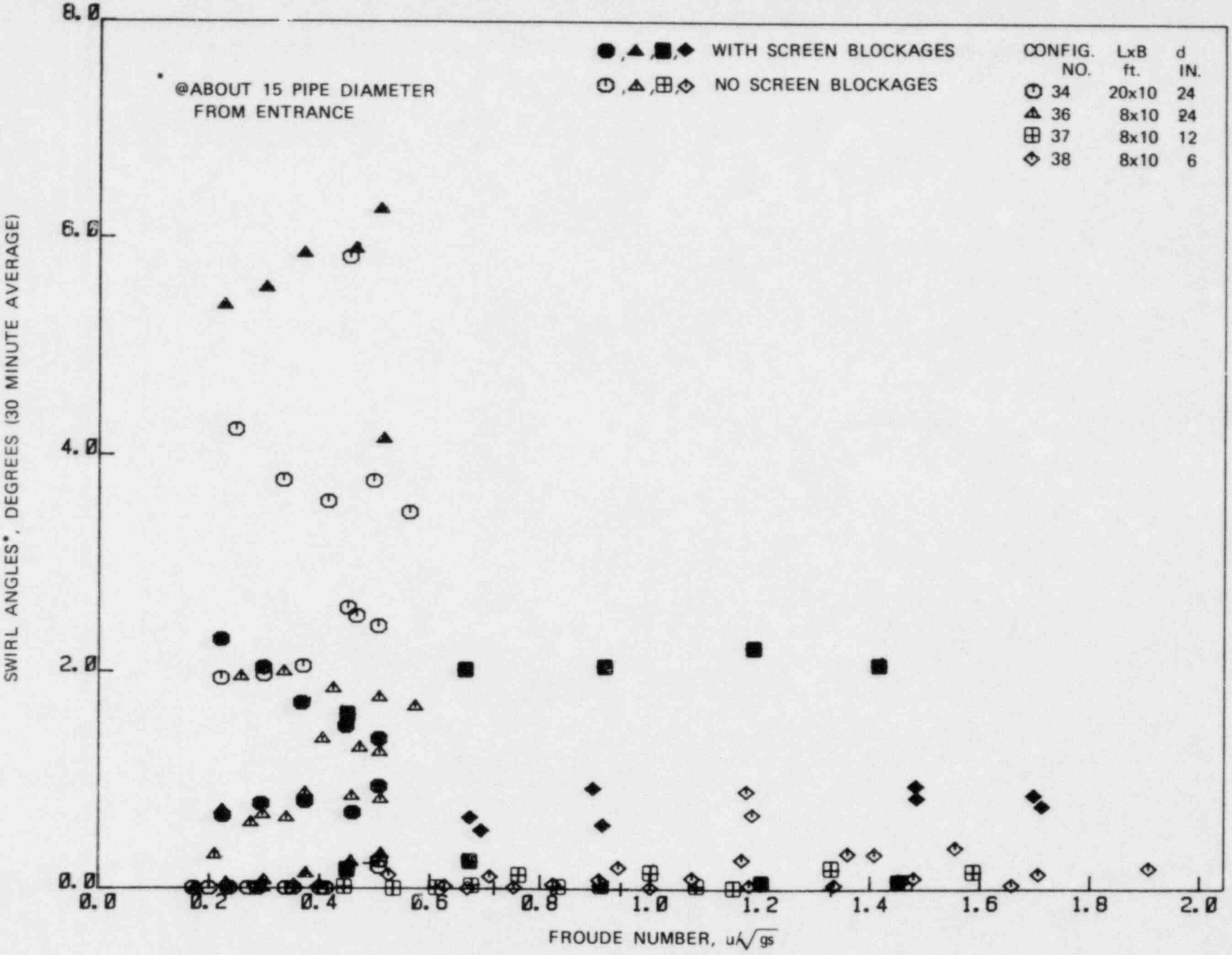


FIGURE 38 AVERAGE SWIRL ANGLE VARIATION WITH FROUDE NUMBER; SUMPS WITH SOLID PARTITION WALLS

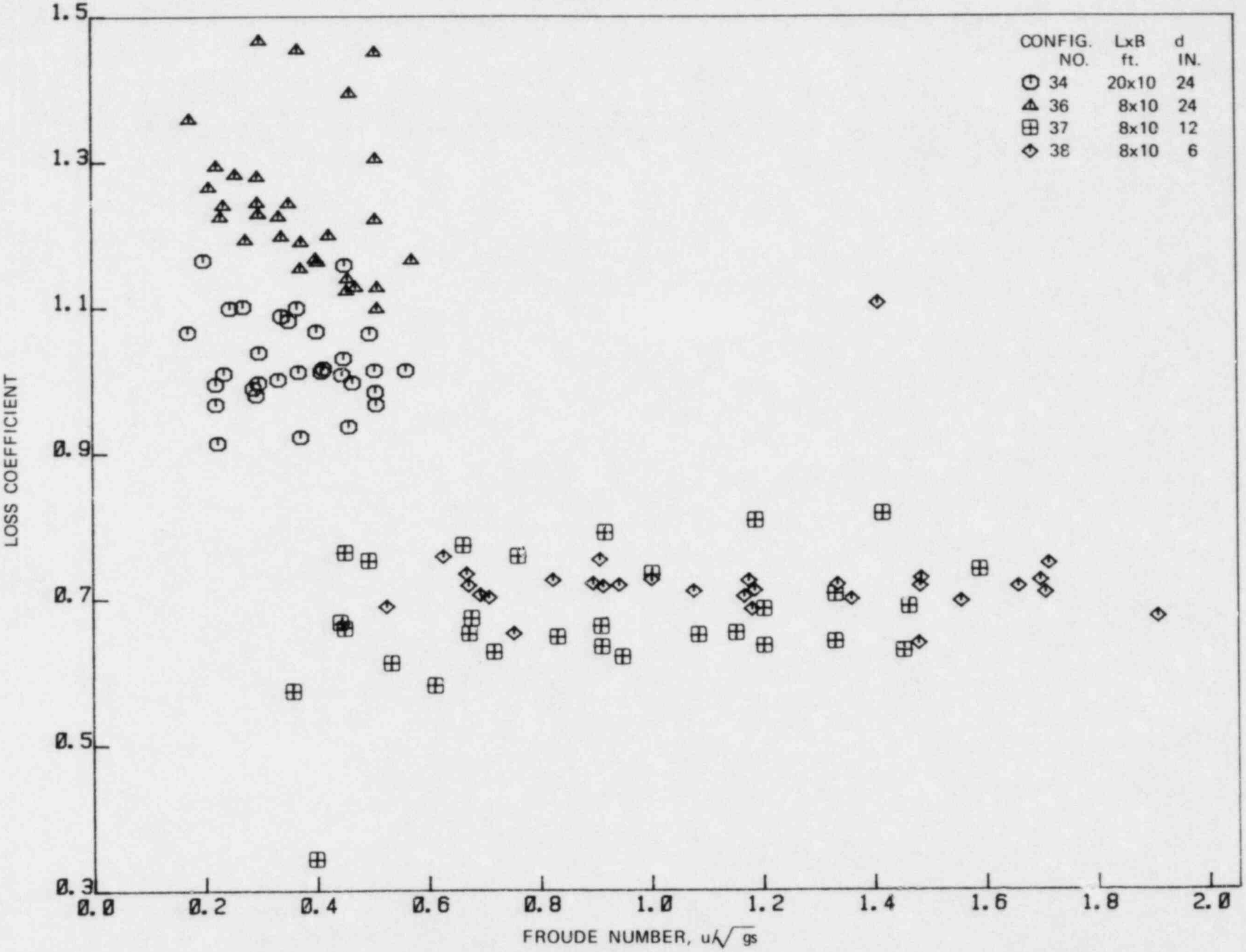


FIGURE 39 INLET LOSS COEFFICIENT VARIATION WITH FROUDE NUMBERS; SUMPS WITH SOLID PARTITION WALLS; WITH AND WITHOUT SCREEN BLOCKAGES

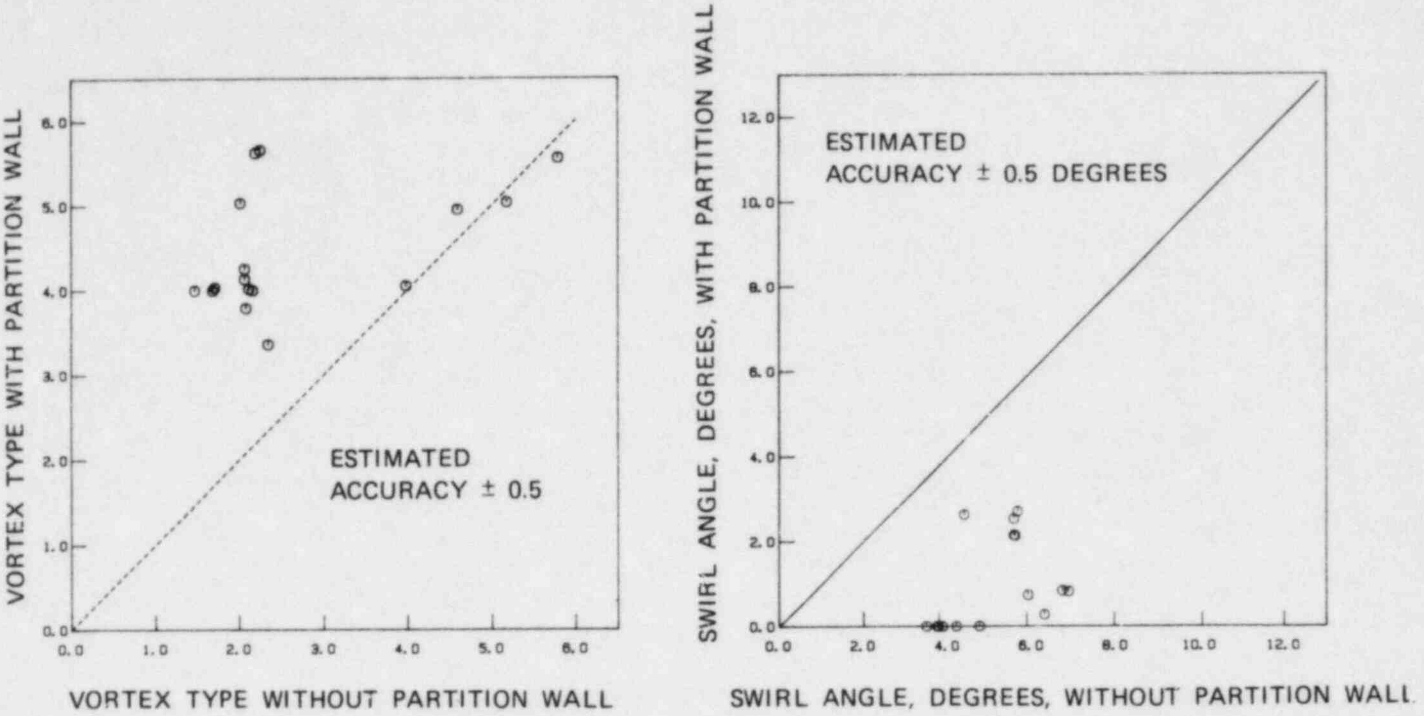
of 0.07 [13]. The values are 4.3 degrees for configuration 34 and 6.4 degrees for configuration 36. For configurations 37 and 38, the swirl angles were measured at about 14.5 pipe diameters and were as high as 2.2 degrees for configuration 37 and 0.4 degree for configuration 38.

Configurations 34 and 36 with pipes projecting to 3 ft into the sump (which also showed higher swirl in the pipes) showed a higher average inlet loss coefficient, C_L, averaging to about 1.2 for configuration 34 and to about 1.0 for configuration 36. The inlet loss coefficients for configurations 37 and 38 averaged to about 0.7. The pipe projection, e_y, was kept at one pipe diameter for all the configurations, but e_y/B, the ratio to sump width, varied from 0.2 for configurations 34 and 36 to 0.1 and 0.05, respectively, for configurations 37 and 38. The increased value of C_L for configurations 34 and 36 could be partly due to higher e_y/B and partly due to higher inlet swirl. Figures 40 to 43 illustrate performance comparisons between sumps with and without solid partition wall under uniform approach flows. Void fractions are not plotted for the sumps with 24 inch diameter outlet pipes since they indicated no significant air-withdrawals. For sumps with partition walls, the tests were conducted with single outlet operations. But, limited tests with both pipes operational in configuration 36 showed very little difference in sump performance when partition walls are provided whether one or two pipes operate. In general, as regards to vortexing, sumps with solid partition walls were found to perform more or less similar compared to those without, under approximately uniform flow conditions. Even under screen blockages, the tested sumps with solid partition walls did not show any significant air-withdrawals which was also the case with the corresponding sumps without partition walls. Overall, sumps with partition walls showed lower swirl angles compared to those without. No consistent or significant differences in inlet loss coefficients were noticeable for the two cases. The effectiveness of a 4 ft x 4 ft x 4 ft cage of floor gratings (1.5 inch standard) vortex suppressor at 3 ft above the pipe centerline was tested for cases with air-core vortices under screen blockages for the 8 ft x 10 ft sump with 12 inch horizontal outlets and later repeated for the same sump with vertical outlets (configuration 45 and 46 in Table 2). It was found that both the cage type and horizontal floor grate type suppressors were effective in suppressing the air-core vortices observed for solid partition wall sumps to surface dimples (zero air-ingestion).

Figure 44 shows a few typical vortexing photographs for each of the tested sumps with partition walls.

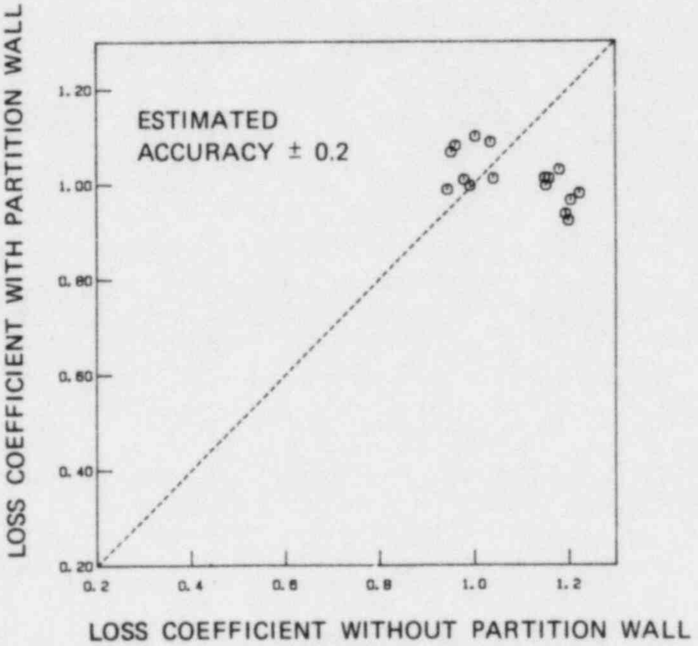
4.4 Pump Overspeed Tests (Tests at Higher Than Normal Flows)

For the two configurations tested; namely, configuration 43 with horizontal outlet and configuration 44 with vertical outlet, the results of average vortex types, swirl angles, air-withdrawal (void fraction), and inlet loss coefficients are all shown in Figure 45 for the tested Froude numbers up to about 1.7. All tests were conducted with approximately uniform approach flows. The highest values of void fraction and swirl angles for the pump overspeed tests



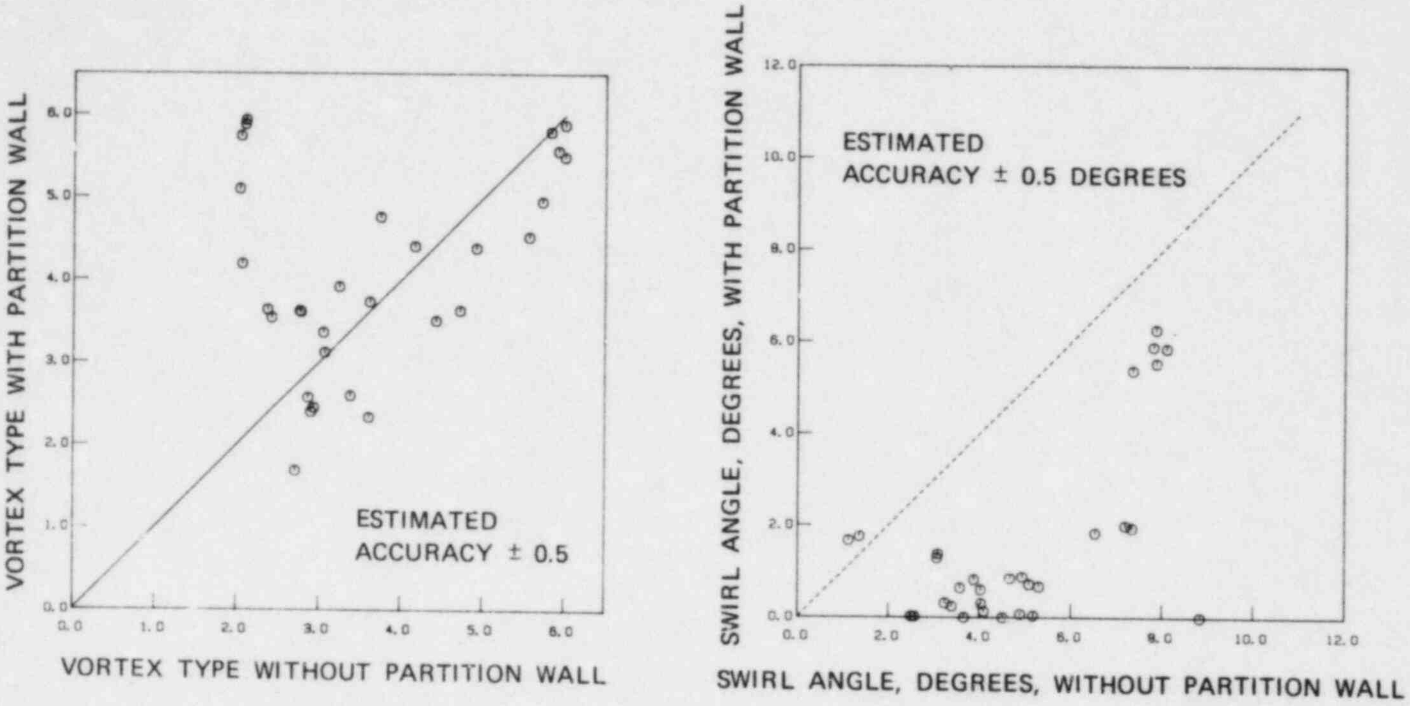
A. AVERAGE VORTEX TYPES

B. AVERAGE SWIRL ANGLES AT 14.5 PIPE DIAMETERS FROM ENTRANCE



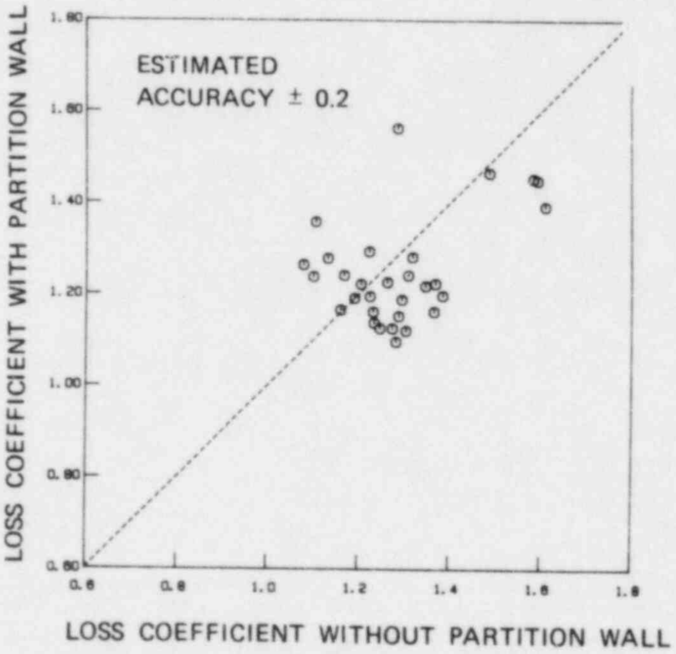
C. INLET LOSS COEFFICIENT

FIGURE 40 COMPARISON OF PERFORMANCE; WITH AND WITHOUT PARTITION WALLS; CONFIGURATIONS 33 AND 34 (20′ x 10′ SUMP, 24″ OUTLET)



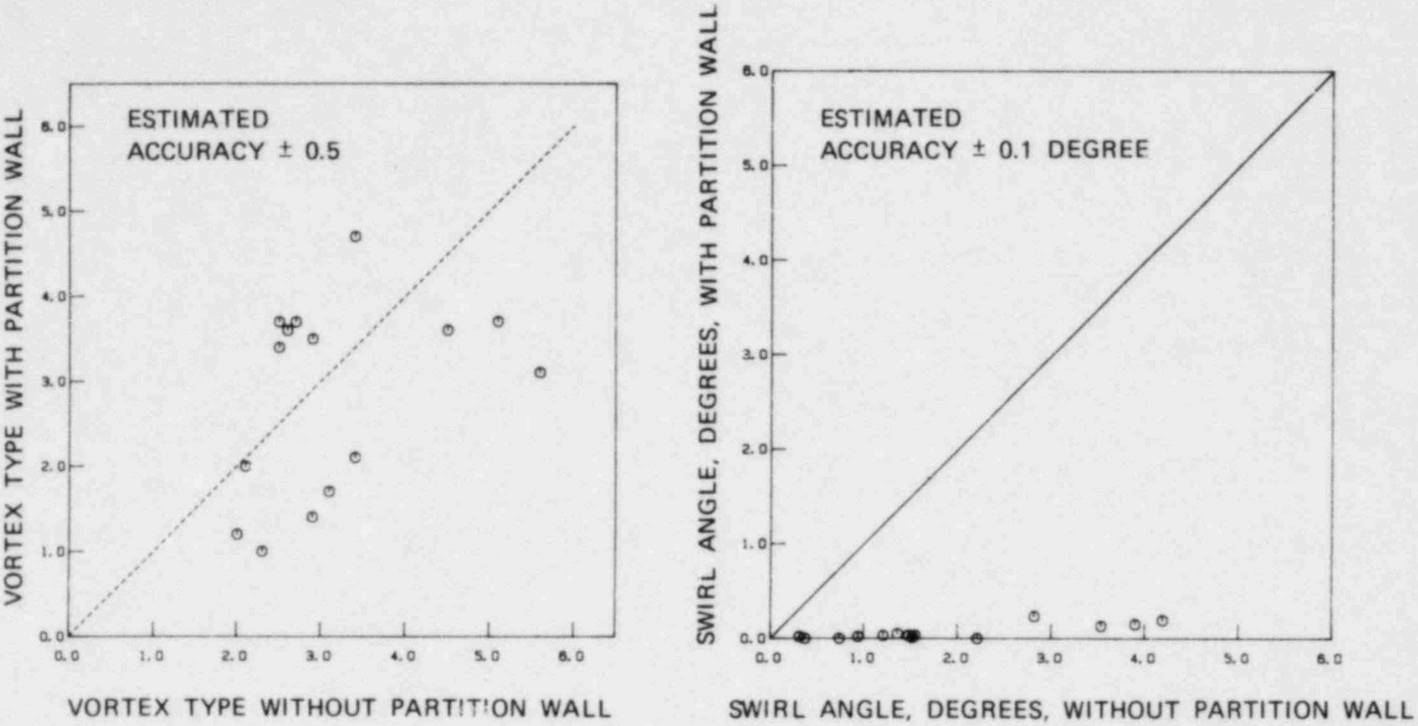
A. AVERAGE VORTEX TYPES

B. AVERAGE SWIRL ANGLES AT
14.5 PIPE D AMETERS FROM ENTRANCE



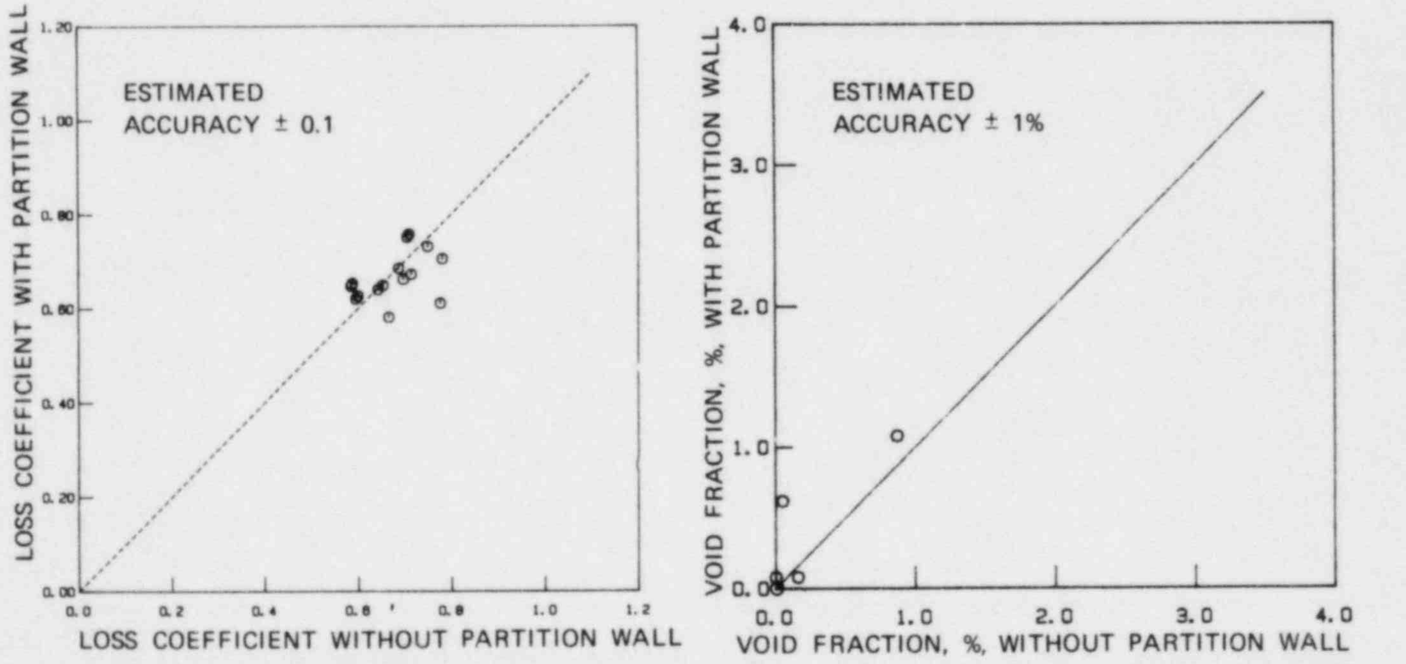
C. INLET LOSS COEFFICIENT

FIGURE 41 COMPARISON OF PERFORMANCE; WITH AND WITHOUT PARTITION WALL; CONFIGURATIONS 35 AND 36 (8′ x 10′ SUMP; 24″ OUTLETS)



A. AVERAGE VORTEX TYPES

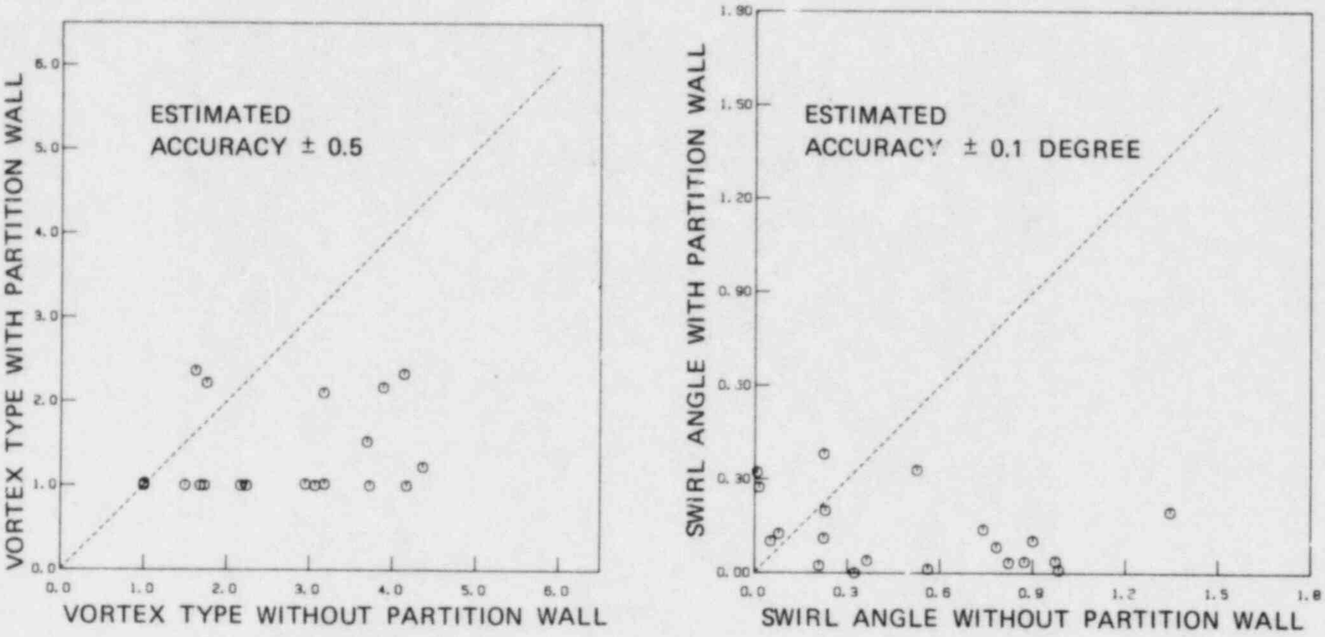
B. AVERAGE SWIRL ANGLES AT 14.5 PIPE DIAMETERS FROM ENTRANCE



C. INLET LOSS COEFFICIENT

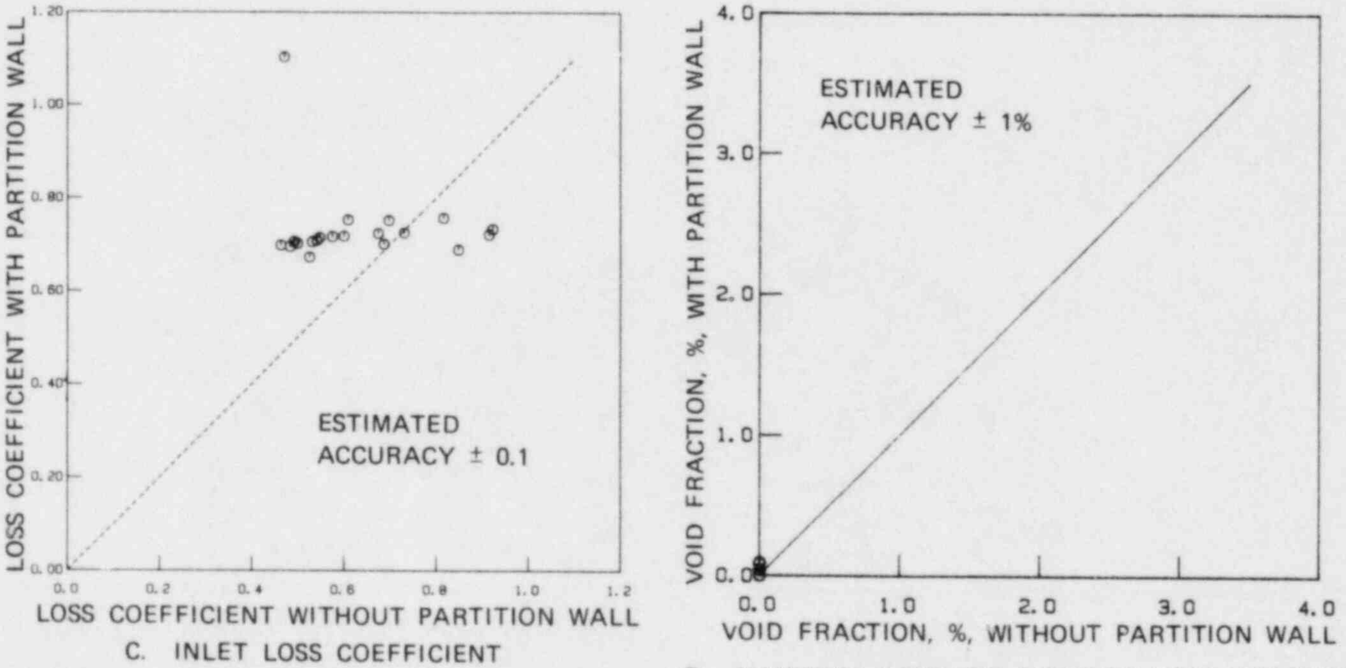
D. MAXIMUM 1 MINUTE AVERAGE VOID FRACTION

FIGURE 42 COMPARISON OF PERFORMANCE; WITH AND WITHOUT PARTITION WALL; CONFIGURATIONS 2 AND 37 (8′ x 10′ SUMP; 12″ OUTLET)



A. AVERAGE VORTEX TYPES

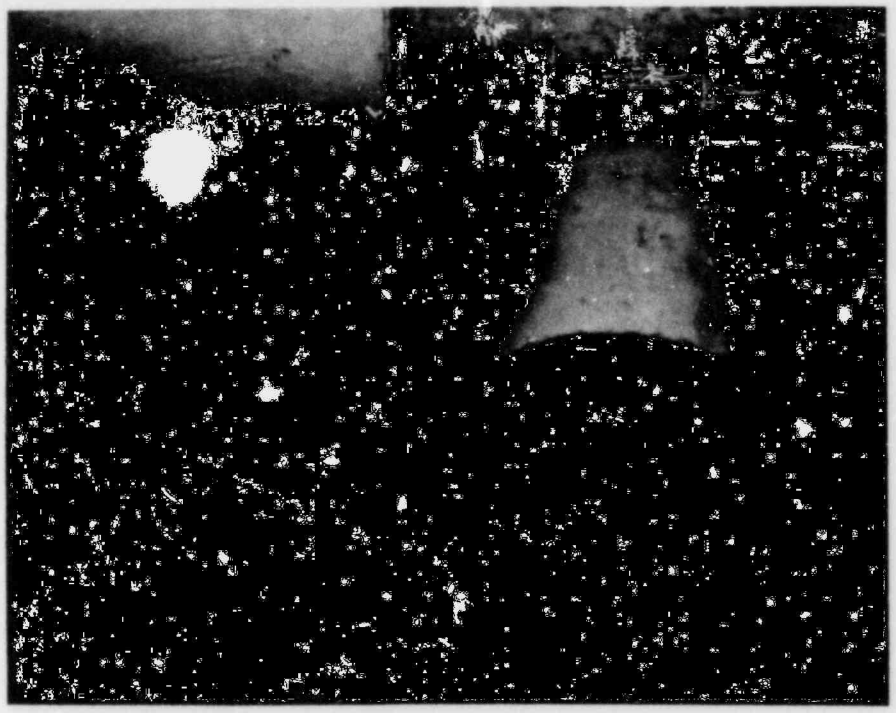
B. AVERAGE SWIRL ANGLES



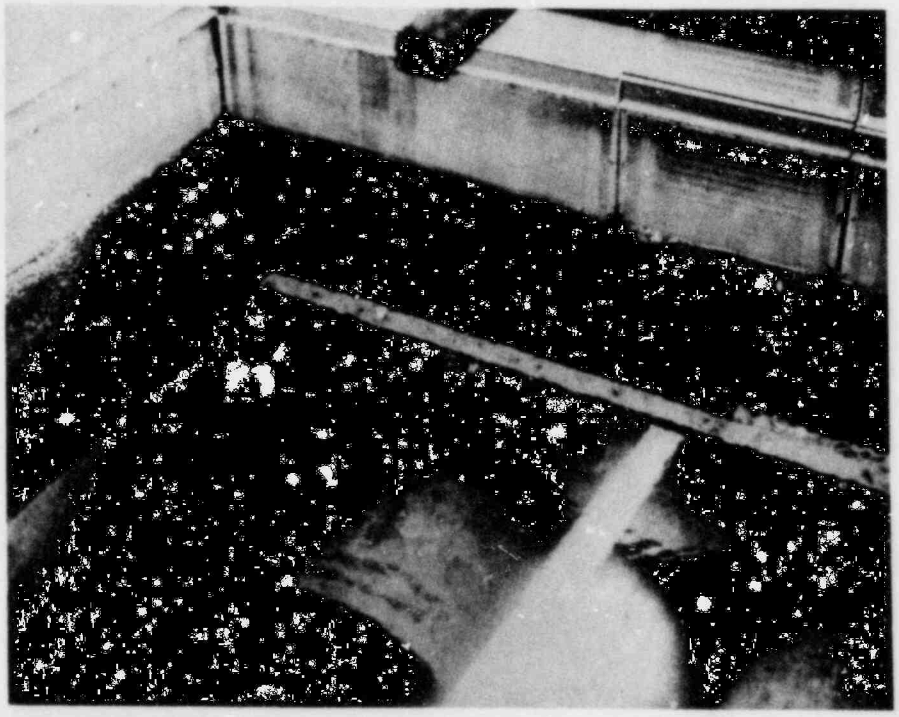
C. INLET LOSS COEFFICIENT

D. MAXIMUM 1 MINUTE AVERAGE VOID FRACTION

FIGURE 43 COMPARISON OF PERFORMANCE WITH AND WITHOUT PARTITION WALLS; CONFIGURATIONS 38 AND 61 (8′ x 10′ SUMP WITH 6″ OUTLET PIPES)

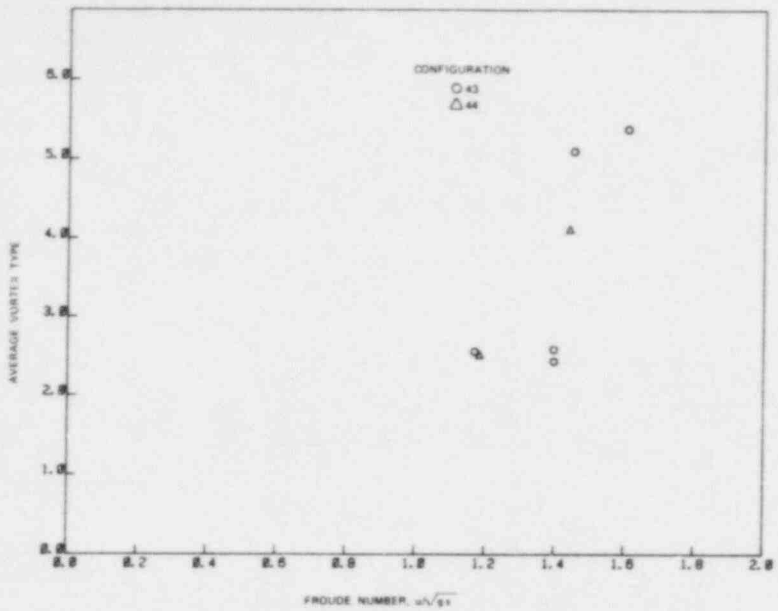


A. AN AIR-CORE VORTEX IN CONFIGURATION 34
UNDER SCREEN BLOCKAGE 8; Q=9000 gpm; s=5'; F=0.5
MAX. VOID FRACTION, α = 0.09% (1 MIN. AVERAGE)

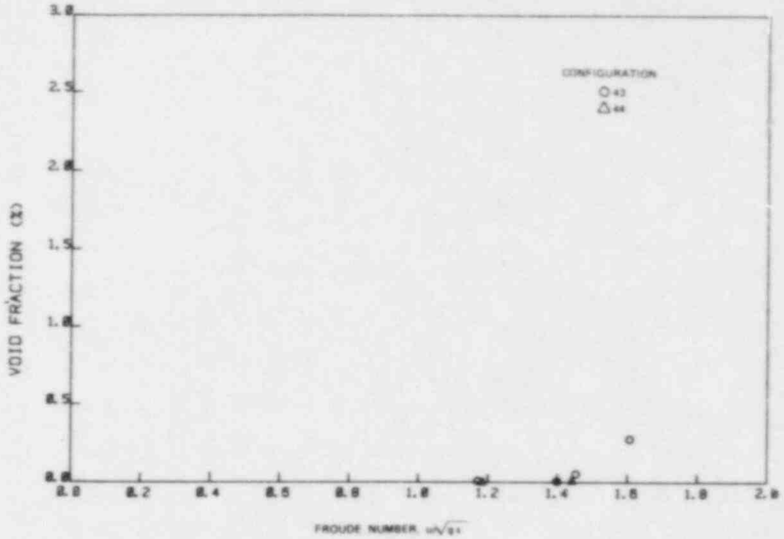


B. AN AIR-CORE VORTEX IN CONFIGURATION 36
WITH SCREEN BLOCKAGE 4; Q=9100 gpm; s=5'; F=0.5
MAX. VOID FRACTION, α = 0.15% (1 MIN. AVERAGE)

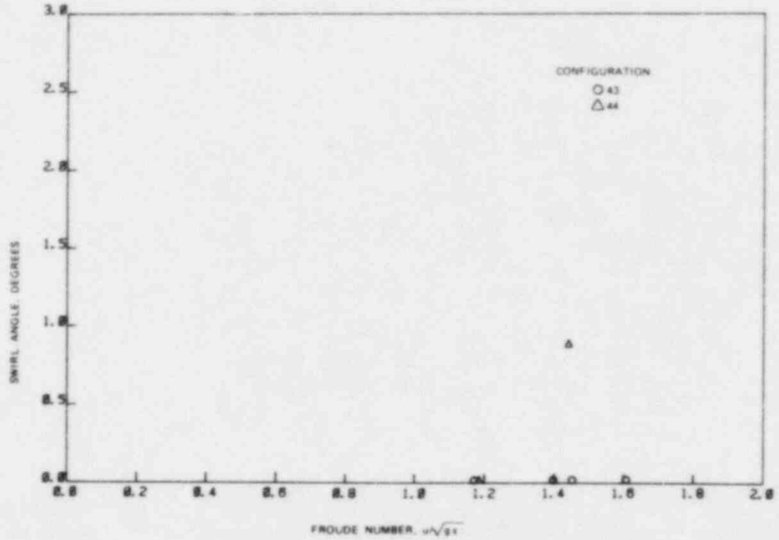
FIGURE 44 AIR-CORE VORTICES OBSERVED IN SOLID PARTITION WALL SUMPS



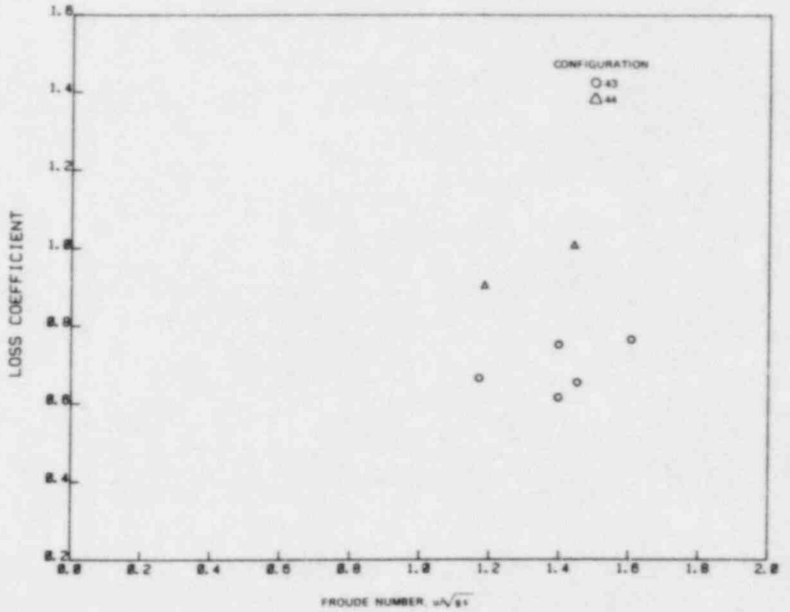
A. TEST AVERAGE VORTEX TYPE



B. TEST AVERAGE VOID FRACTION (30 MINUTE AVERAGE)



C. TEST AVERAGE SWIRL ANGLES



D. TEST AVERAGE LOSS COEFFICIENT

FIGURE 45 RESULTS OF PUMP OVERSPEED TESTS; HORIZONTAL OUTLET AND VERTICAL OUTLET CONFIGURATIONS (43 AND 44) were 0.6% (1 minute average) and 0.9 degrees, respectively, which are not significantly higher than those for identical sumps at lower Froude numbers (0.3 to 1.3) reported in [1]. Hence, any higher flows due to pump overspeed under normal uniform approach flow conditions may not cause any higher vortex severities than that would exist with flow perturbations at normal flows.

4.5 Sensitivity Tests - Effect of Pipe Diameter

The effect of pipe diameter was investigated in an 8 ft by 10 ft sump with the pipe centers located 3 ft below the containment floor. Figures 46 and 47 show the average vortex type and void fraction against Froude number for the 24 inch, 12 inch, and 6 inch outlets, corresponding to sump configurations 35, 64, and 61, respectively. These data are for tests with unperturbed flows. The tested Froude number ranges for the 24 inch, 12 inch, and 6 inch outlets were approximately 0.2 to 0.6, 0.3 to 1.4, and 0.5 to 2.0, respectively. In using Figures 46 and 47, it should be remembered that for a given flow and submergence, the Froude number for a 24 inch diameter pipe configuration would be 1/4 of that for a 12 inch diameter pipe configuration and 1/16 of that for a 6 inch diameter pipe configuration. Hence, for comparing the pipe diameter effects at a given flow and submergence, the corresponding Froude numbers for the flows and pipe diameters under consideration should be used rather than the same Froude number.

In general, a larger pipe diameter (which gives a lower Froude number at a given submergence and flow) was found to give lesser vortex types and lower air-withdrawals at the corresponding reduced Froude numbers. For example, in Figures 46 and 47, the data for F = 1.2 for 12 inch outlet may be compared to the corresponding reduced Froude number of F = 0.3 for 24 inch outlet. As seen from Figure 47, none of these configurations showed any significant air-withdrawals.

In some tests, higher average vortex types are indicated (see Figure 46) for the 24 inch pipes compared to 12 inch and 6 inch pipes for the same Froude numbers (higher flows and/or lower submergences). To explore this result, the data of Figures 46 and 47 have been replotted and given in Figures 48 and 49, indicating the submergence to pipe diameter (s/d) values. Allowing for some data scatter, it appears that, at the same Froude number, there may be some effect of the parameter s/d on vortex types, but little or no effect on air ingestion. For the same Froude number, a lower s/d gave stronger vortexing, which is in agreement with available literature [15]. Any influence of s/d on vortexing is not relevant to maximize envelope values for sump designs since for the same flow and submergence, the Froude number would be reduced considerably as the pipe diameter is increased. This means the Froude number effect on vortexing would predominate, and the s/d influence would be minor. Further, the sump design guidelines are based on air-withdrawals, which were not influenced (with experimental accuracy) by changes in s/d.

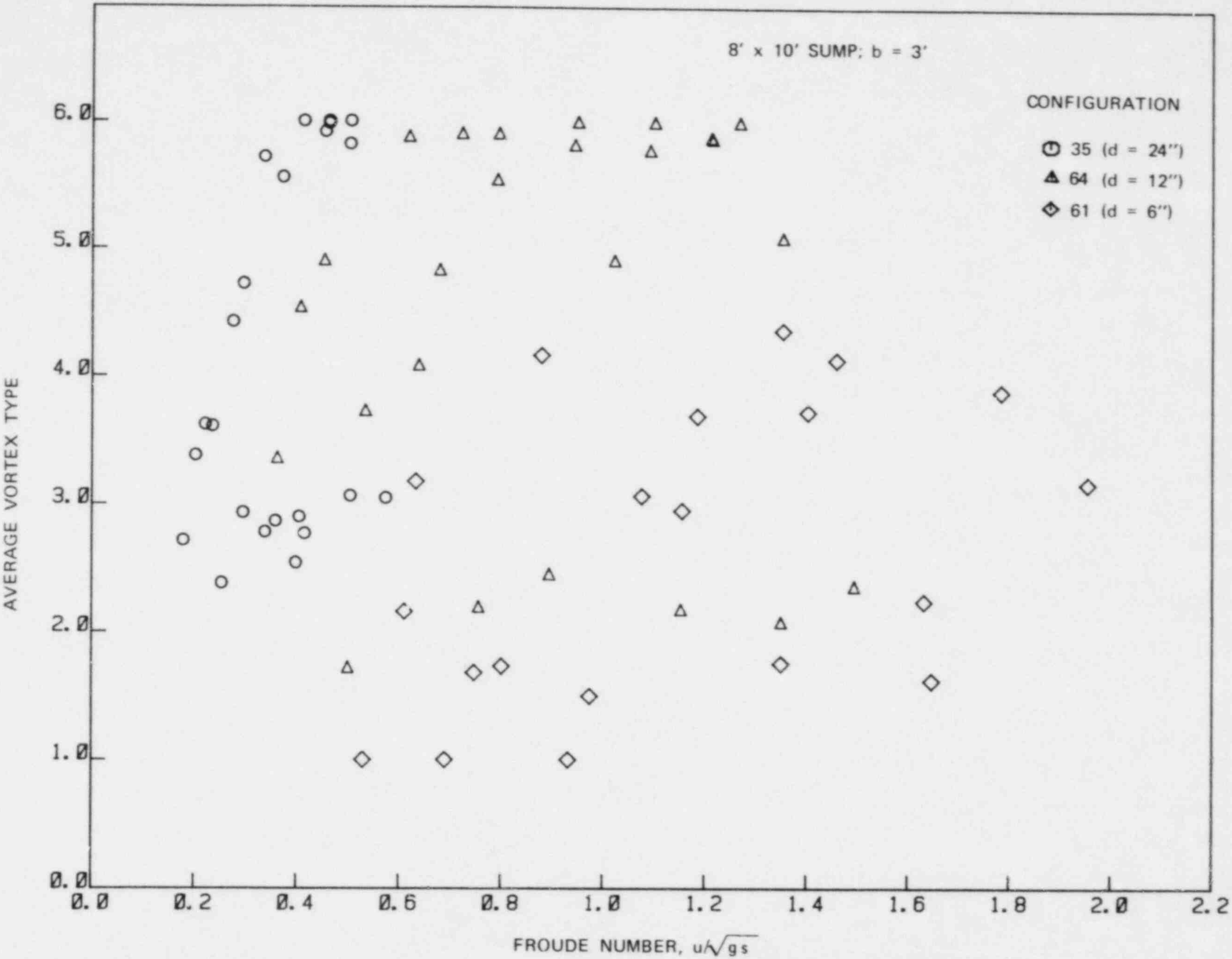


FIGURE 46 AVERAGE VORTEX TYPES FOR THE TESTED FROUDE NUMBER RANGES; PIPE DIAMETERS VARIED

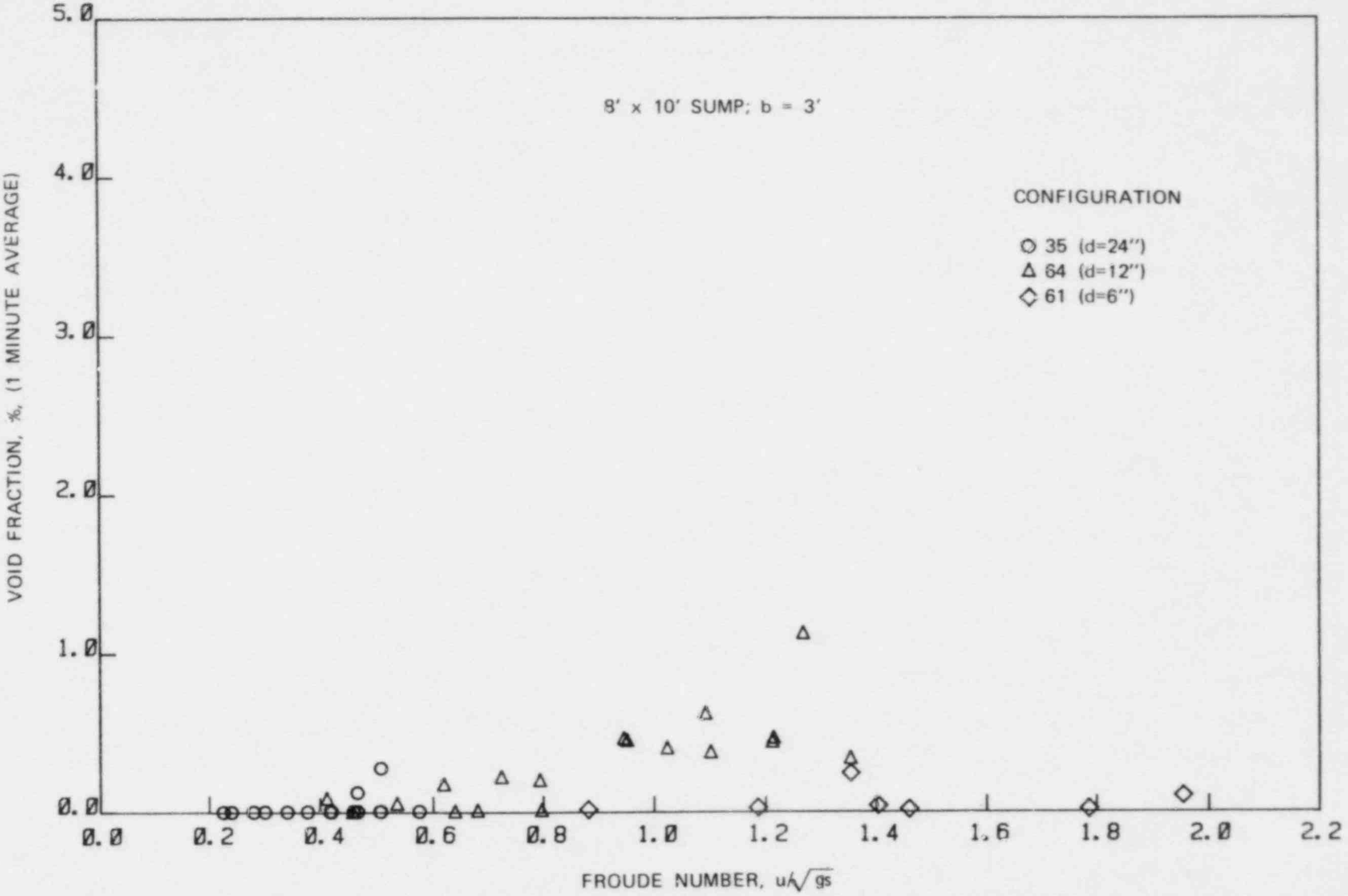


FIGURE 47 AVERAGE VOID FRACTIONS FOR THE TESTED FROUDE NUMBER RANGE; PIPE DIAMETERS VARIED

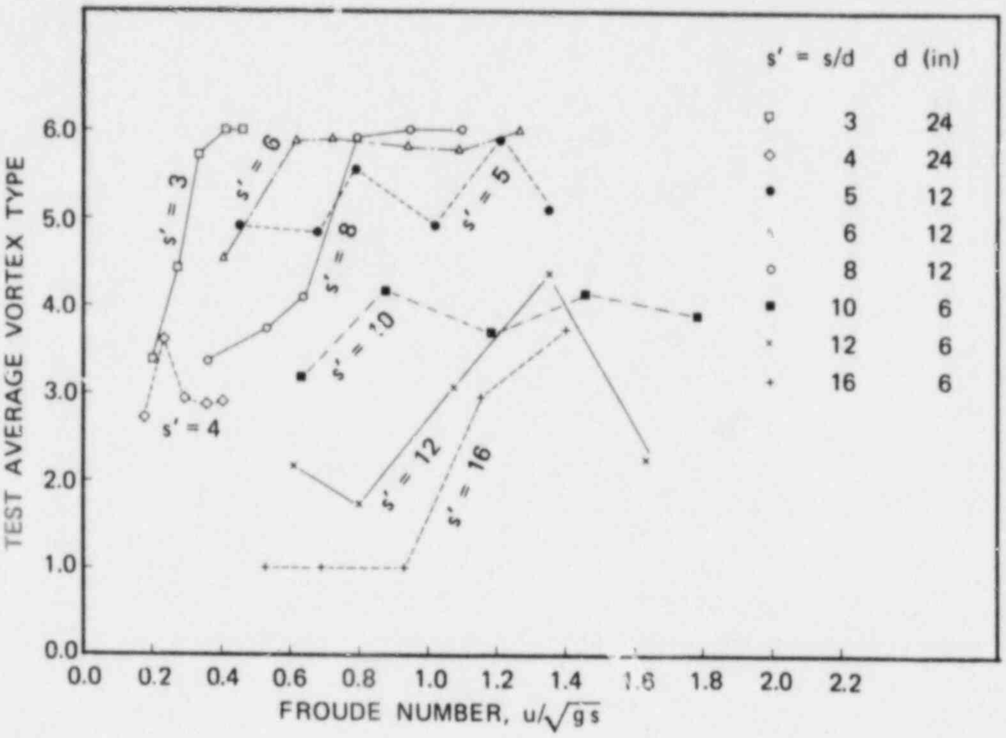


FIGURE 48 EFFECT OF PARAMETER s/d ON VORTEXING;
8' x 10' SUMP, 4½' DEEP

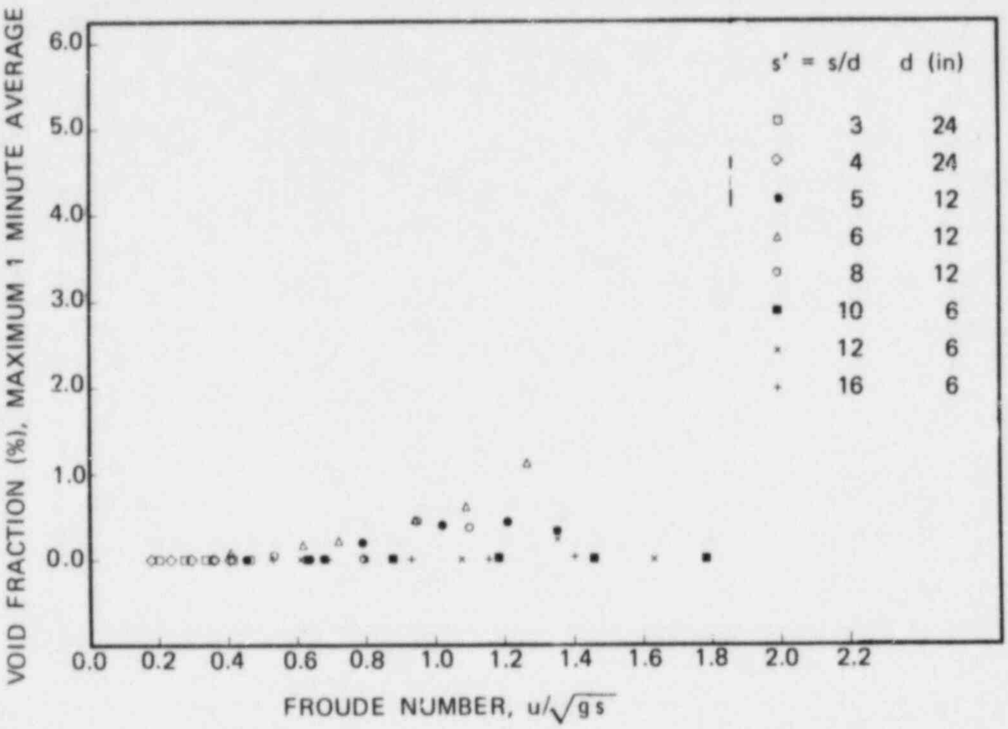


FIGURE 49 EFFECT OF PARAMETER s/d ON AIR INGESTION; 8' x 10' SUMP, 4½' DEEP

In general, irrespective of Froude number (for any given flow and submergence), the 24 inch outlet sump indicated higher swirl angles, up to 9 degrees (Figure 50) than did the smaller outlet pipes. The reason for the higher swirl angles may be attributed to submerged vortices due to eddies at the shear layer formed as the flow entered the depressed portion at the sump from the containment floor (Figure 51). For a given flow, the angular momentum associated with these submerged vortices is dependent on the approach flow velocity, which is independent of pipe diameter. But, the axial momentum in the pipe is dependent on pipe diameter (for a given flow), being lesser for larger pipe diameters. Hence, higher swirl levels (angular momentum to axial momentum ratio) may be expected at the same flows and submergences for larger pipe diameters for sumps of a given size.

Figure 52 shows inlet loss coefficients plotted against Froude number. The measurement uncertainty bands are marked on the plotted points. Because of lower velocities and flatter friction gradients, the data for 24 inch pipes had higher uncertainties. As shown in Figure 52, the 24 inch outlet sump indicated higher average inlet loss coefficients 1.2 ±0.2), compared to 12 inch and 6 inch outlet sumps (average of 0.8 ±0.2 and 0.65 ±0.2, respectively), presumably due to the higher swirl shown in Figure 50. No pipe Reynolds number effects are associated with the higher loss coefficients since the pipe Reynolds number was above 1×10^5 for all tests and in these ranges, no Reynolds number effect on loss coefficients were indicated by the scale tests previously conducted [3]. It should be noted that the actual inlet losses would be much lower at a given flow and submergence for the 24 inch outlets (even though the loss coefficients are higher) compared to 12 inch or 6 inch outlets because of much lower pipe velocity heads in the 24 inch outlets. For example, for a flow of 6000 gpm, the velocity head in 24 and 12 inch diameter pipes would be 0.28 and 4.5 ft, respectively, giving a head loss of 0.34 ft in a 24 inch pipe outlet configuration compared to 3.6 ft in a 12 inch pipe outlet configuration. Hence, the higher loss coefficient should not prevent the use of larger diameter pipes.

4.6 Tests with Bellmouth Entrance

Configuration 64 (see Appendix A), an 8 ft x 10 ft x 4.5 ft sump with 12 inch horizontal outlets, was tested with a bellmouth entrance (Figure 8) for a submergence of 5 ft over a flow range of 1500 to 6000 gpm per pipe. Comparison of vortex types, void fractions, swirl angles, and inlet loss coefficients are shown in Figure 53. The bellmouth did not help in reducing vortexing, air-withdrawals due to vortices or pipe swirl to any significant extent but helped to reduce inlet loss coefficients from an average value of about 0.7 to about 0.4. This reduction is more or less in agreement with handbook values [12]. With a bellmouth, the average air-withdrawals were lower in a few tests mainly due to higher unsteadiness of air-core vortices compared to the case without a bellmouth.

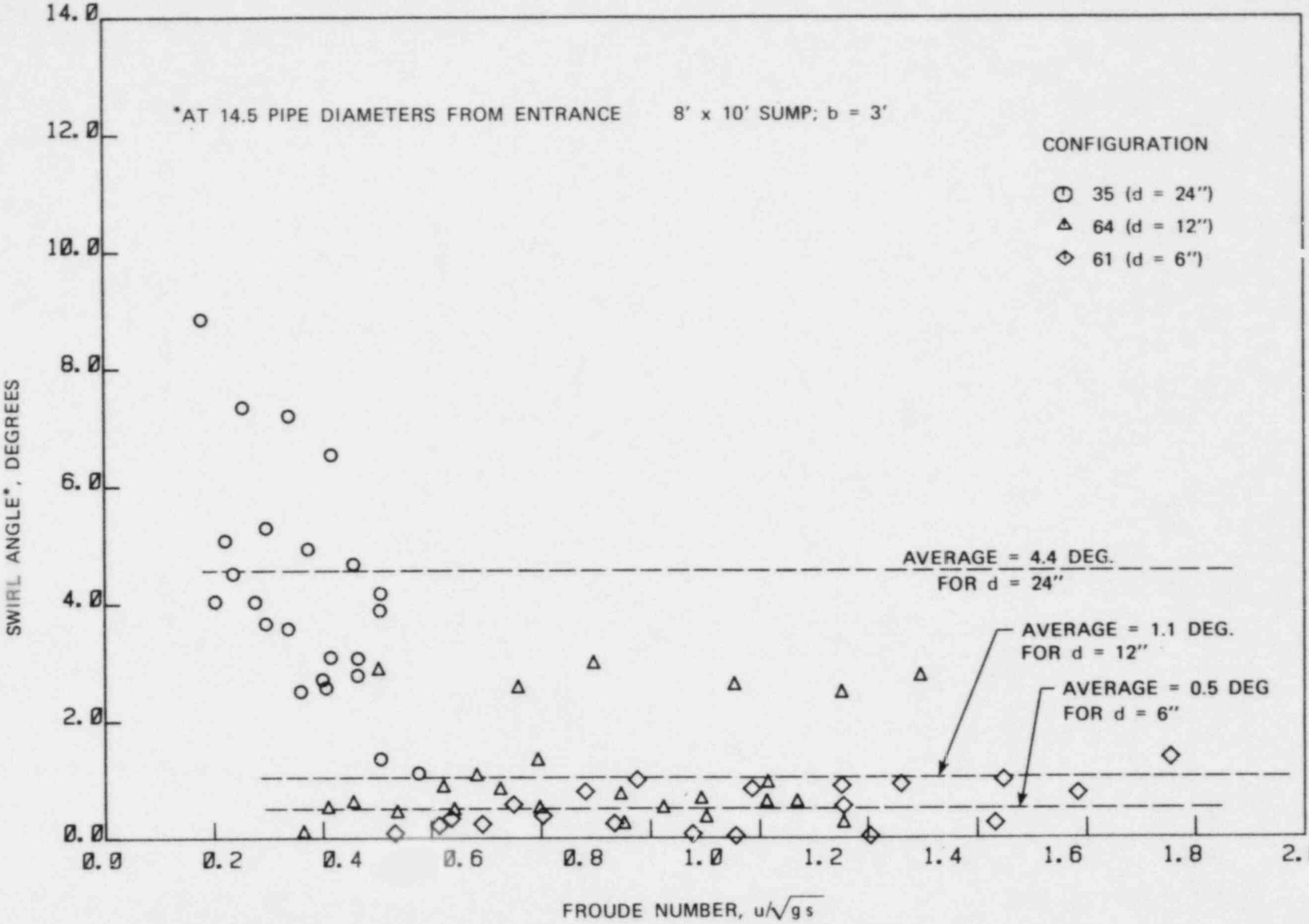


FIGURE 50 AVERAGE SWIRL ANGLES FOR THE TESTED FROUDE NUMBER RANGES; PIPE DIAMETERS VARIED

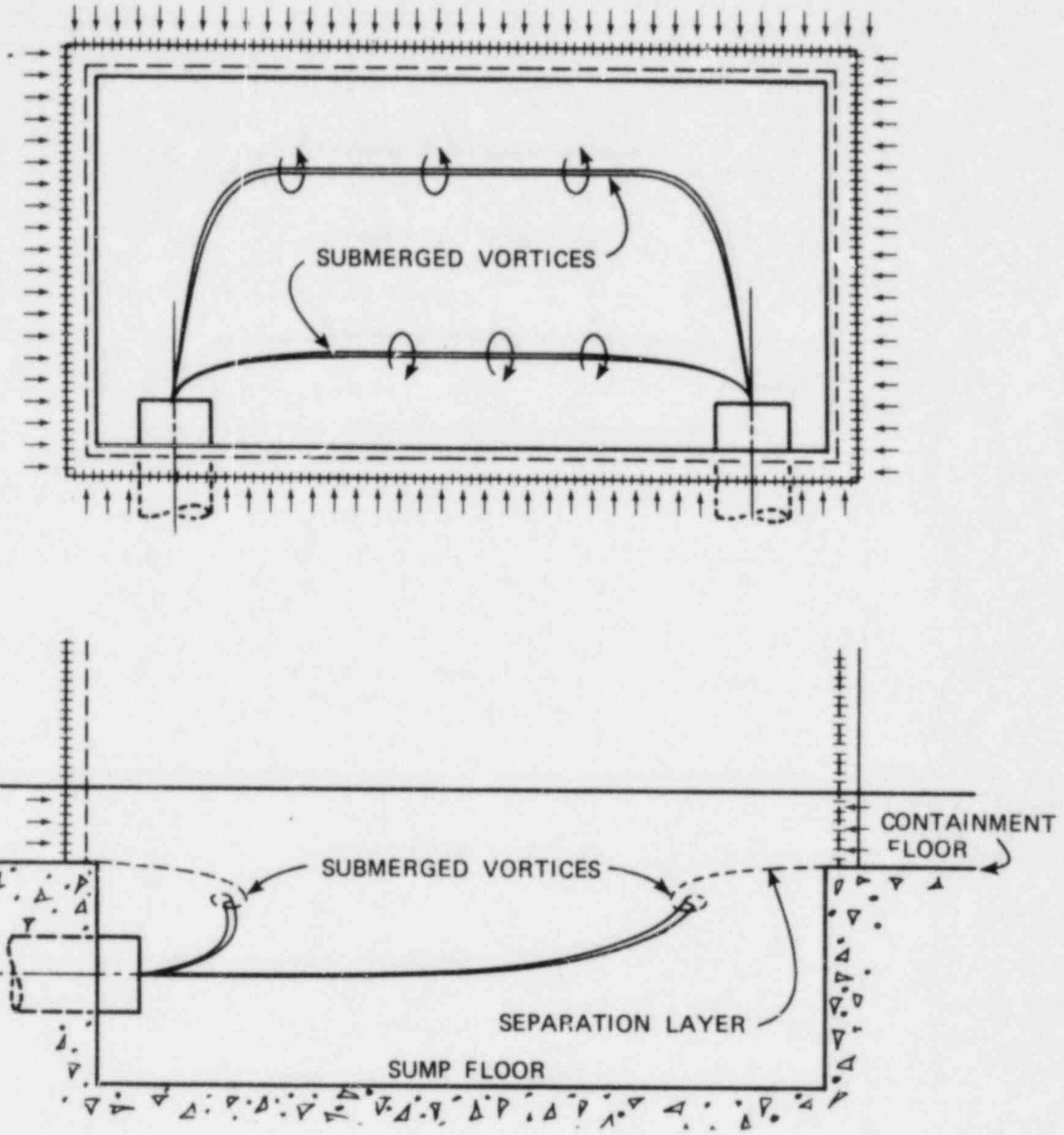


FIGURE 51 SUBMERGED VORTICES (NON-AIR-CORE) GENERATED AT FLOW SEPARATION

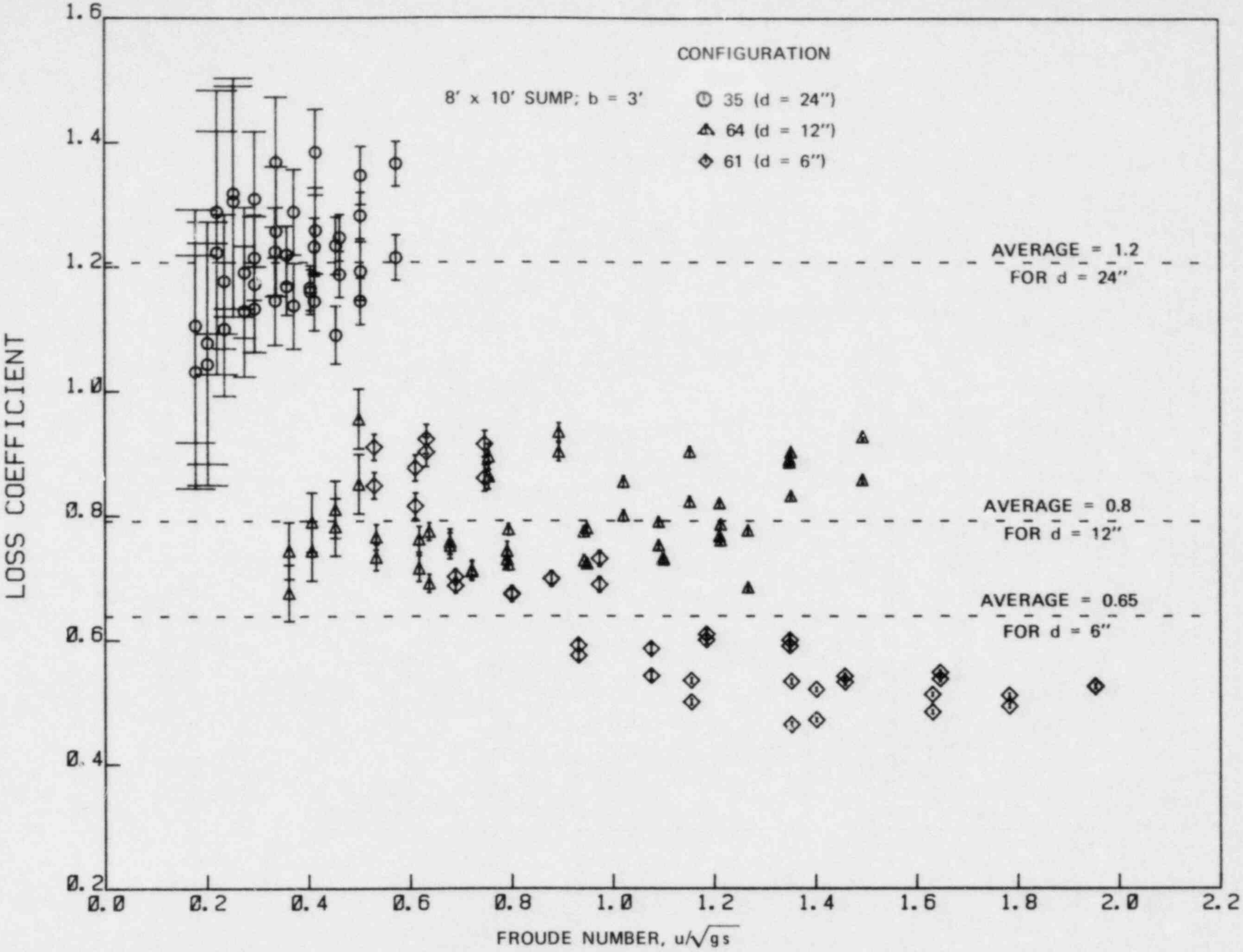
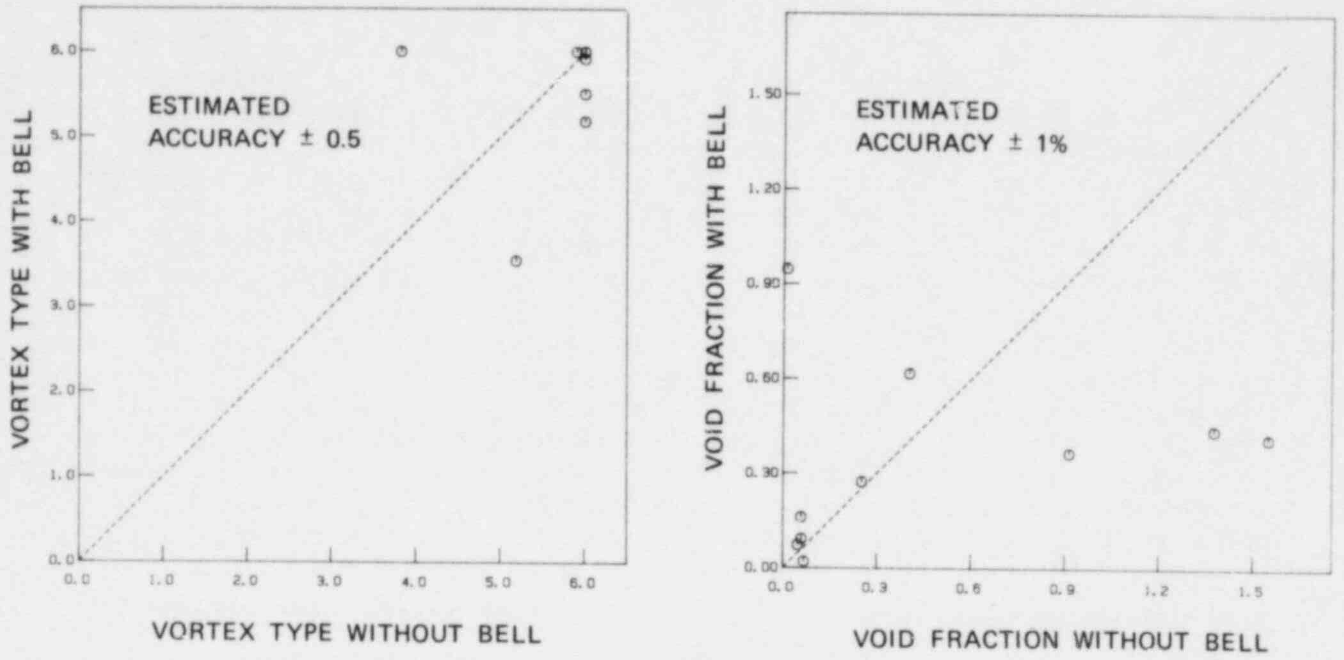
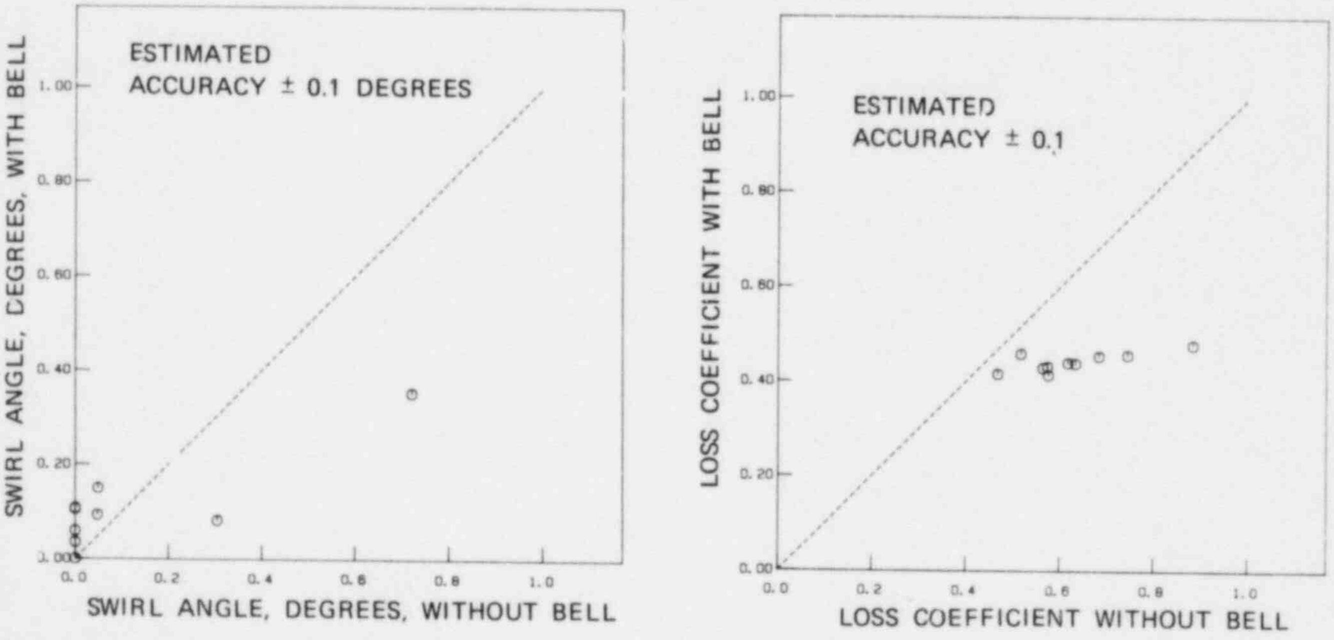


FIGURE 52 AVERAGE INLET LOSS COEFFICIENTS FOR THE TESTED FROUDE NUMBER RANGES; PIPE DIAMETERS VARIED



A. AVERAGE VORTEX TYPES

B. AVERAGE VOID FRACTION



C. AVERAGE SWIRL ANGLES

D. INLET LOSS COEFFICIENT

FIGURE 53 EFFECT OF BELLMOUTH ENTRANCE ON VORTEXING, SWIRL, AND INLET LOSSES

4.7 Envelope Analysis

The test data presented in this report include information on vortexing, air-withdrawal, pipe swirl, and inlet losses for two single outlet and four double outlet sumps with solid partition walls (single pipe operation) over flows ranging up to 9000 gpm per pipe and submergences ranging from 1 to 5 ft of water above the containment floor. These data also contain information on the sump behavior under perturbed flow conditions produced by screen blockages. Together with the previous data on horizontal outlet sumps [1], an envelope analysis is made to predict an upperbound of any hydraulic performance indicator of interest (void fraction, vortex type, swirl angle, and inlet loss coefficient). This analysis is applicable for sumps with or without partition walls as long as the essential features of the sump, both geometric and flow related, fall within the corresponding ranges tested. Conversely, if the upperbound of the hydraulic performance indicators are known, it is possible to prescribe permissible ranges of flow and geometric variables for a given sump, based on corresponding data points and the associated envelope curve.

In the following paragraphs, various envelope curves are discussed and developed using all the available data (both unperturbed flow and perturbed approach flow tests) for all tested sump configurations, including those from earlier tests under Phase I [1].

Figure 54 shows the envelope of vortex data (in terms of a test average vortex type) for the entire Froude number range tested for all configurations with and without perturbations. Average vortex types do not indicate the magnitude of air-withdrawal, which is of prime concern as regards to pump performance. Hence, the effect of single outlet sumps on air withdrawal envelopes is examined in detail.

Inasmuch as the tested single outlet sumps showed higher air-withdrawals at Froude numbers above 0.8 with screen blockages, prescribing separate envelope lines for void fractions for single outlet and double outlet sumps was considered appropriate. The origin for the envelope line for single outlet sumps was set to be the same as that for double outlets based on the similar measured void fractions between single and double sumps at comparable operating conditions (low Froude numbers).

The one minute average void fraction data and associted maximum envelope lines for single and double outlets are shown in Figure 55. The envelope line relative to maximum 1 minute average void fraction $(\alpha)\%$ to Froude number (F) is given by $\alpha = -4.75 + 18.04F$ for single outlet (horizontal) sumps, while $\alpha = -2.47 + 9.38F$ for double outlet (horizontal) sumps for the tested range of $0.26 \leq F \leq 1.6$. Based on available literature, the performance of centrifugal pumps would not be significantly degraded for two-phase flow with volumetric concentrations at pump inlet of approximately 3% or less [16, 17, 18].

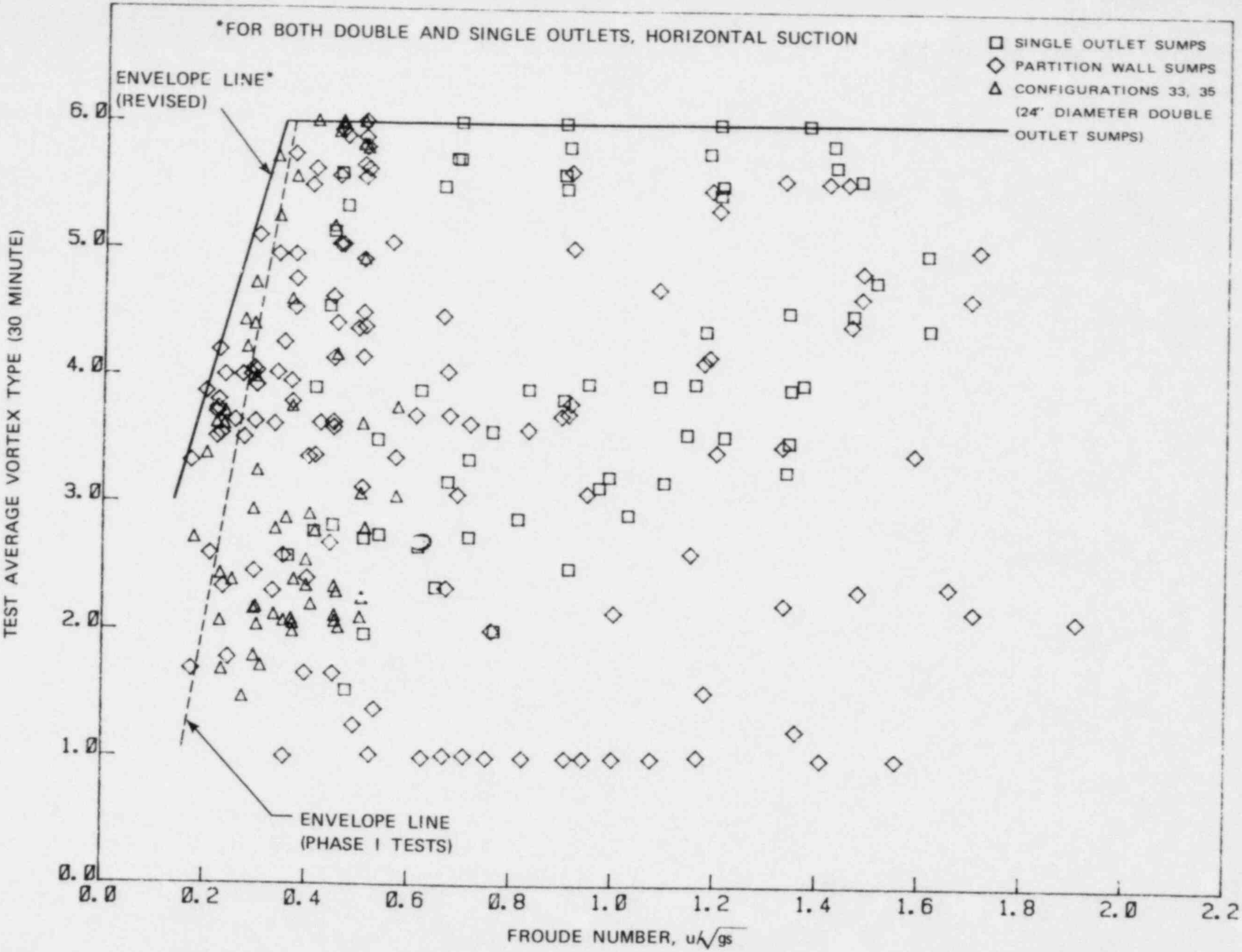


FIGURE 54 ENVELOPE LINE FOR VORTEX DATA; HORIZONTAL OUTLET CONFIGURATIONS

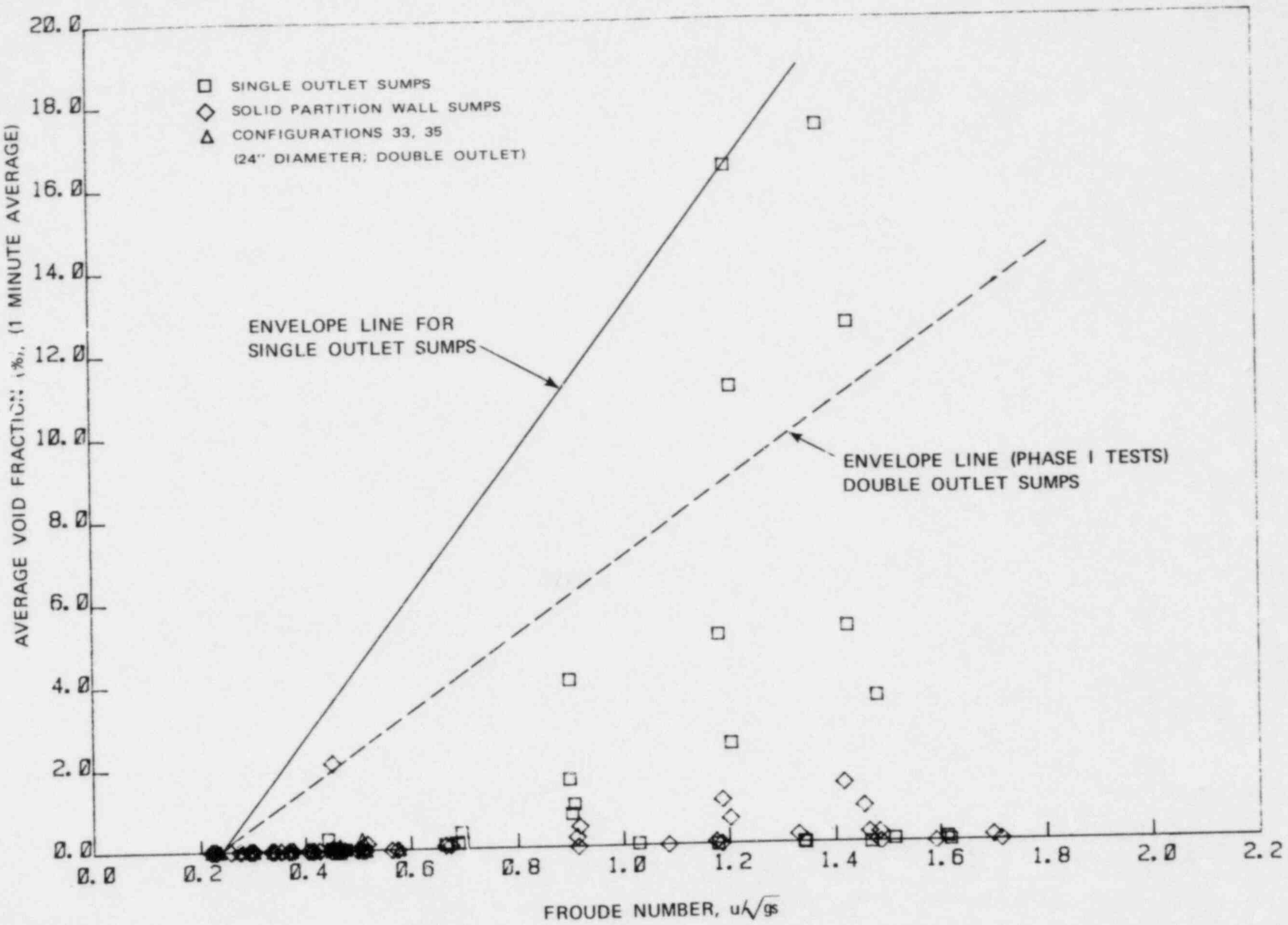
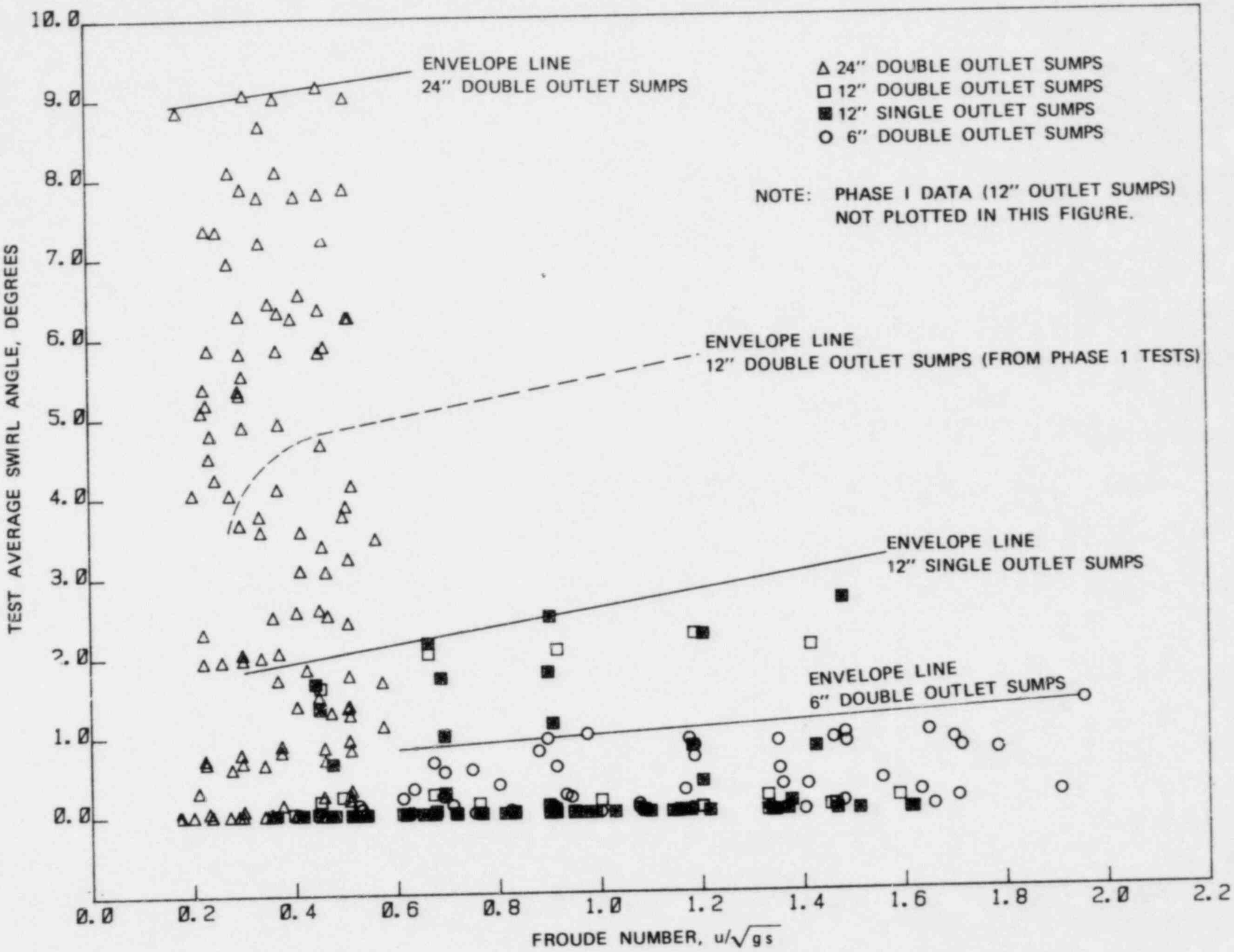


FIGURE 55 ENVELOPE LINE FOR VOID FRACTION DATA; HORIZONTAL OUTLET CONFIGURATIONS

The test average swirl angle data and associated maximum envelope curves are shown in Figure 56 for the various outlet pipe sizes tested. A limiting value of swirl angle of about 9 degrees (at about 15 pipe diameters from inlet) is indicated for 24 inch pipe configurations irrespective of the value of Froude number and irrespective of whether the sump is single or double outlet (with or without partition wall). The corresponding values for 12 and 6 inch pipe outlets are 6 and 2 degrees, respectively. The values for any other intermediate pipe diameter may be obtained by interpolation. For the tested 12 inch diameter single outlet sumps, the highest swirl angle recorded was about 2.7 degrees and hence no increase in bounding values of pipe swirl was evident for single outlet sumps compared to double outlet sumps.

The loss coefficient data are included in Figure 57, and it may be seen that a loss coefficient of about 1.2 ±0.2 for 24 inch outlet sumps, 0.8 ±0.2 for 12 inch outlet sumps, including the tested single outlet sumps, and 0.7 ±0.2 for 6 inch outlet sumps are indicated for both sumps, irrespective of the Froude number. The loss coefficient includes screen and grating losses in addition to entrance losses. For any other intermediate pipe diameters, the loss coefficients could be estimated by interpolation from the above values or by using Figure 58, which is a plot of the range of loss coefficient to pipe diameter. The higher values of loss coefficients should not discourage the use of larger pipes, since for a given flow, the actual inlet losses (in feet) would be substantially reduced as the pipe diameter is increased due to much lower pipe flow velocities.



NOTE: PHASE I DATA (12" OUTLET SUMPS) NOT PLOTTED IN THIS FIGURE.

FIGURE 56 ENVELOPE LINE FOR PIPE SWIRL WITH ALL HORIZONTAL OUTLET DATA

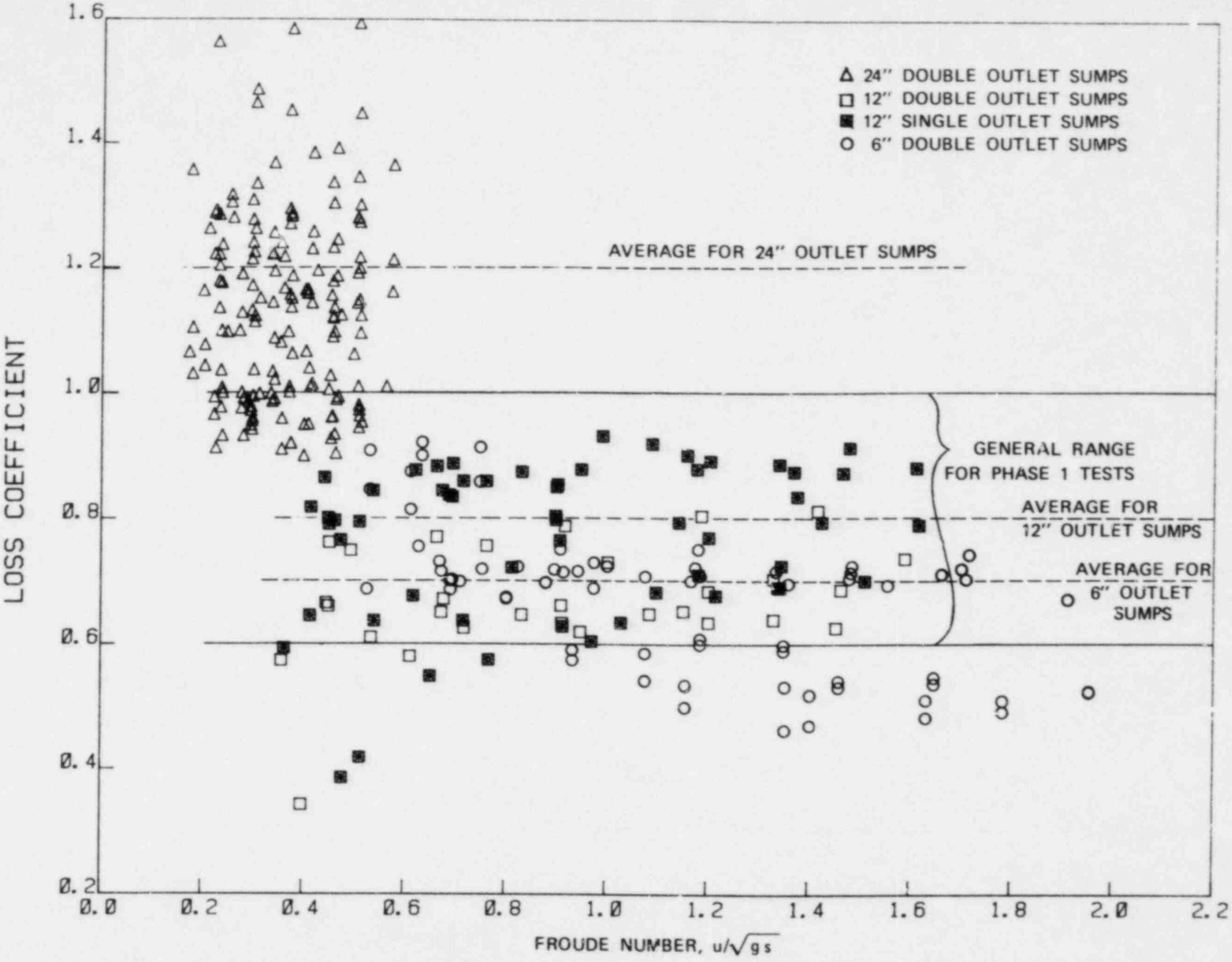


FIGURE 57 INLET LOSS COEFFICIENT DATA FOR HORIZONTAL OUTLET SUMPS

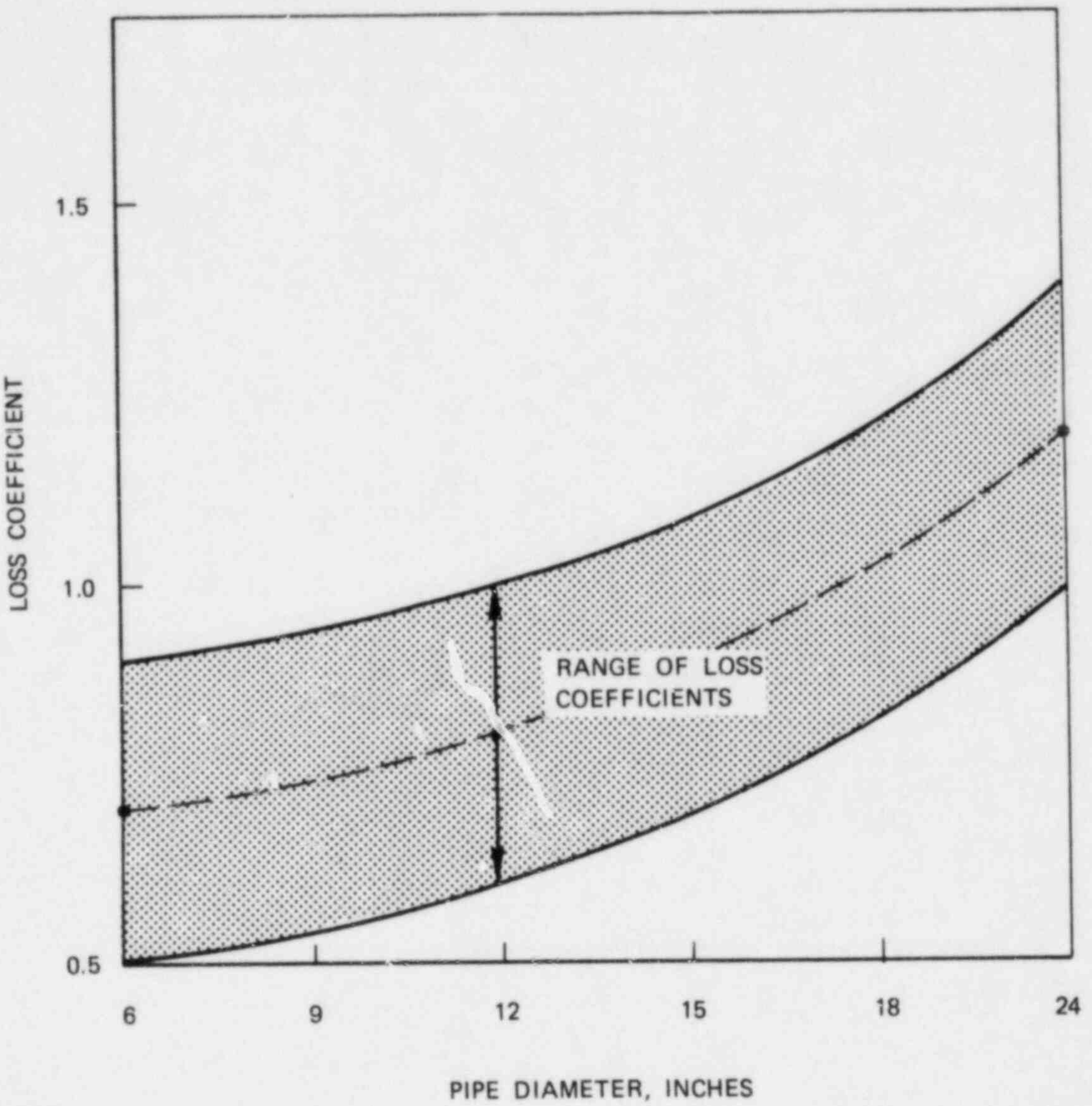


FIGURE 58 INLET LOSS COEFFICIENT RANGES FOR VARIOUS OUTLET PIPE DIAMETERS FOR SUMPS

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APPENDIX A

FACILITY, MEASUREMENT TECHNIQUES, AND DATA ACQUISITION

APPENDIX A
FACILITY, MEASUREMENT TECHNIQUES, AND DATA ACQUISITION

A.1 The Facility

An isometric sketch, plan, and sections of the facility are shown in Figures A1 and A2. The test facility was designed so that any of the flow or geometric parameters of the sump could be varied over typical ranges with least time and effort by simple alterations of floors, walls, and pipe fittings. The facility consists of a concrete main tank, 70 ft x 35 ft x 12.5 ft, and a concrete sump tank, 20 ft x 15 ft x 10 ft, situated within the main tank. Inflow was distributed along three sides of the main tank, and provision was made to produce non-uniform approach flows using blockage. False walls and tank floors were provided such that sump geometries could be varied. Four rows of outlet holes in the front wall were provided with each row having five holes of 24 inch diameter at 4 ft centers. Sets of two holes in a row were used to attach the suction pipes which could be of any diameter in the range of 8 inches to 24 inches.

The suction pipes extend from the sump tank to a suction chamber 50 ft away and are long enough to facilitate swirl, pressure gradient, and discharge measurements. Each of the suction pipes accommodates a vortimeter for swirl measurement and ten pressure taps, one pipe diameter apart for pressure gradient measurements. Flow in the suction pipes can be remotely regulated and measured. The flow capacity was 20,000 gpm and up to 60% of the total flow could be delivered as breakflow and/or drain flow simulations.

Details of the test facility including the design and construction aspects were included in a separate ARL report [10] submitted to Sandia.

The test facility was verified for its functional capability and thorough checks on the operation of its components were conducted. Calibration of instruments and check-out of the data acquisition system was also a part of the check-out phase. Details of the verification program are contained in a separate ARL report [19] submitted to Sandia.

A.2 Measurement Techniques

The observed free surface vortices are an indication of sump performance and a numerical scale is used which is indicative of the types which form. The graduations run from "0" for no visible activity to "6" for a vortex with defined air core entering the inlet. Intermediate numerical values were assigned to discernible stages of development (see Figure A3). An observer entered the vortex type on a keypad at preselected intervals of 30 seconds. These data were then available for time series analysis in the acquisition system. Further documentation of the observations was achieved using photographs, movies, and video recordings.

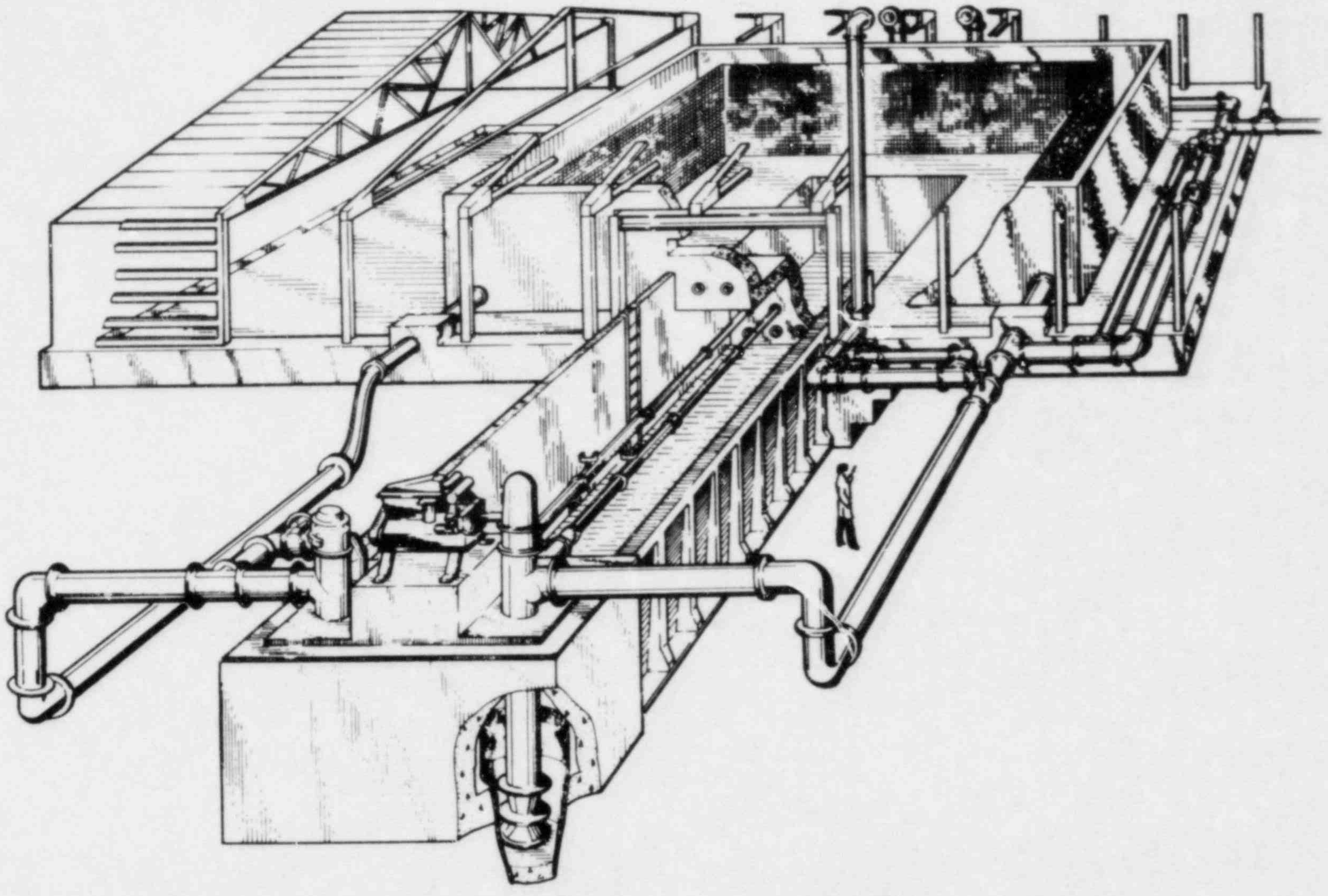
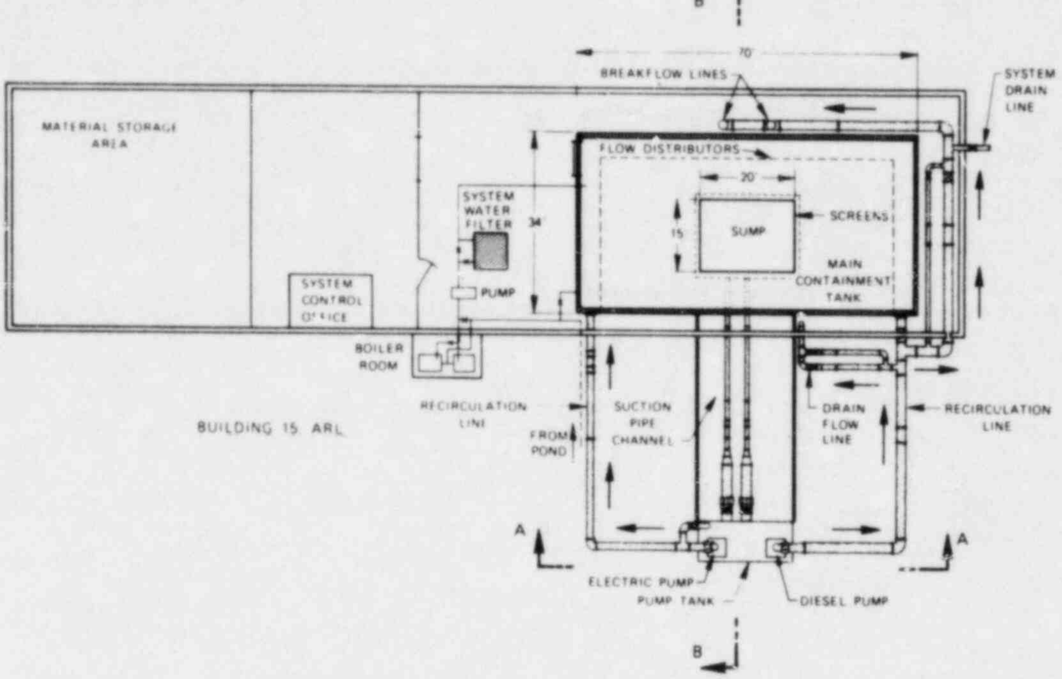
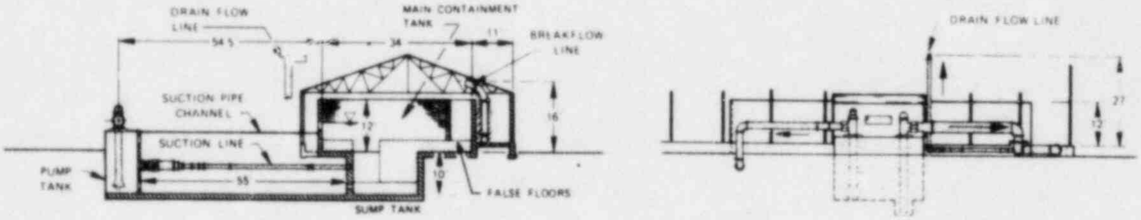


FIGURE A1 PERSPECTIVE VIEW OF THE FACILITY



a PLAN OF FACILITY

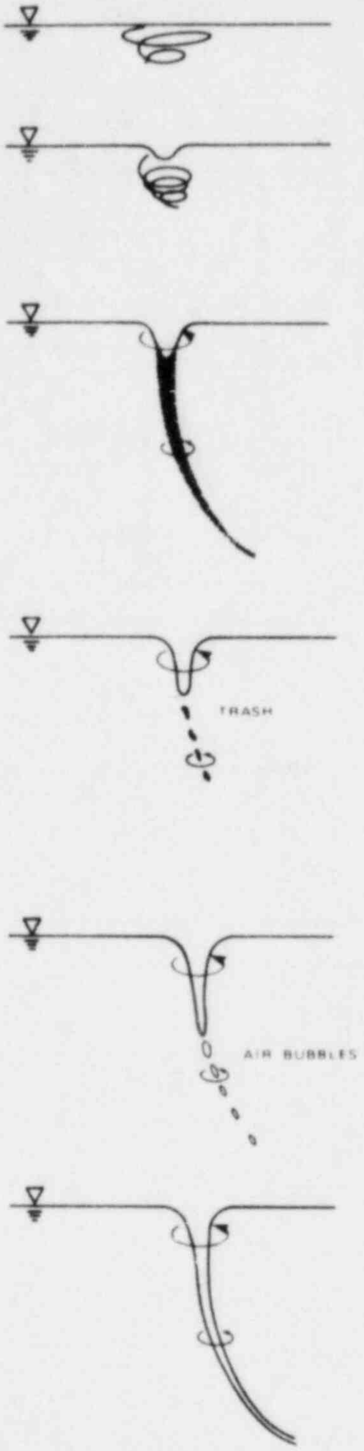


SECTION B-B

SECTION A-A

b SECTIONAL VIEWS OF FACILITY

FIGURE A2 DETAILS OF THE FACILITY



VORTEX TYPE	
1	INCOHERENT SURFACE SWIRL
2	SURFACE DIMPLE; COHERENT SWIRL AT SURFACE
3	DYE CORE TO INTAKE; COHERENT SWIRL THROUGHOUT WATER COLUMN
4	VORTEX PULLING FLOATING TRASH, BUT NOT AIR
5	VORTEX PULLING AIR BUBBLES TO INTAKE
6	FULL AIR CORE TO INTAKE

FIGURE A3 VORTEX TYPE CLASSIFICATION

Pipeline swirl was indicated by crossed-vane swirl meters commonly called vortimeters. These devices rotate about the pipe central axis and the vanes span about 75% of the cross-section. Under most circumstances, the angular rotation speed is indicative of the average swirl angle of the rotational core region of flow [20].

The inlet loss coefficients (including screen and grating losses) were established by measuring the hydraulic gradeline at 1 minute intervals in the discharge lines and extrapolating the average hydraulic gradeline over a test back to the entrance [21]. Ten piezometers were provided in each line and individual locations were selected via a multiport scanning valve under control of the data acquisition system. The water depth outside the sump screens and gratings was also measured with the scanning valve. Figure A4 explains the method of inlet loss coefficient determination.

The void fraction due to air transported in each discharge line was determined using a conductivity meter of the rotating electric field type [27, 23]. The cross-sectional average conductivity was measured and was proportional to the volume of conductive component of the two-phase flow. The calibration data reported in references [22, 23] for a range of void fractions of 0 to 20 percent indicated a standard deviation of about 1 percent void fraction.

A.3 Data Acquisition

A mini-computer based data acquisition system was used to record measurements and observations for each test, as shown in Figure A5. At intervals of 30 seconds, an observer entered the vortex type and location using a small terminal. For the same interval, the system counted the number and direction of vortimeter revolutions in each test line. The pressure gradient in each pipe was measured using duplicate systems consisting of ten gradeline taps, a scanning valve, and differential pressure cells. The taps were monitored for five seconds each including some allowance for settling and averaging of the signal. Since there were two auxiliary pressure measurements for each system, the gradeline for each pipe was established every 60 seconds. A similar pressure scanning system was used to monitor seven differential flowmeters on a 30 second cycle. The analog output from the void fraction meters was sampled every 5 seconds and the water temperature sampled every 30 seconds.

The data were displayed on a video terminal in suitable formats to aid the operators in setting up test runs. During a test, various data summaries were presented to monitor the test progress. At the end of each test run, all data were transferred to disc files for storage and further processing and display.

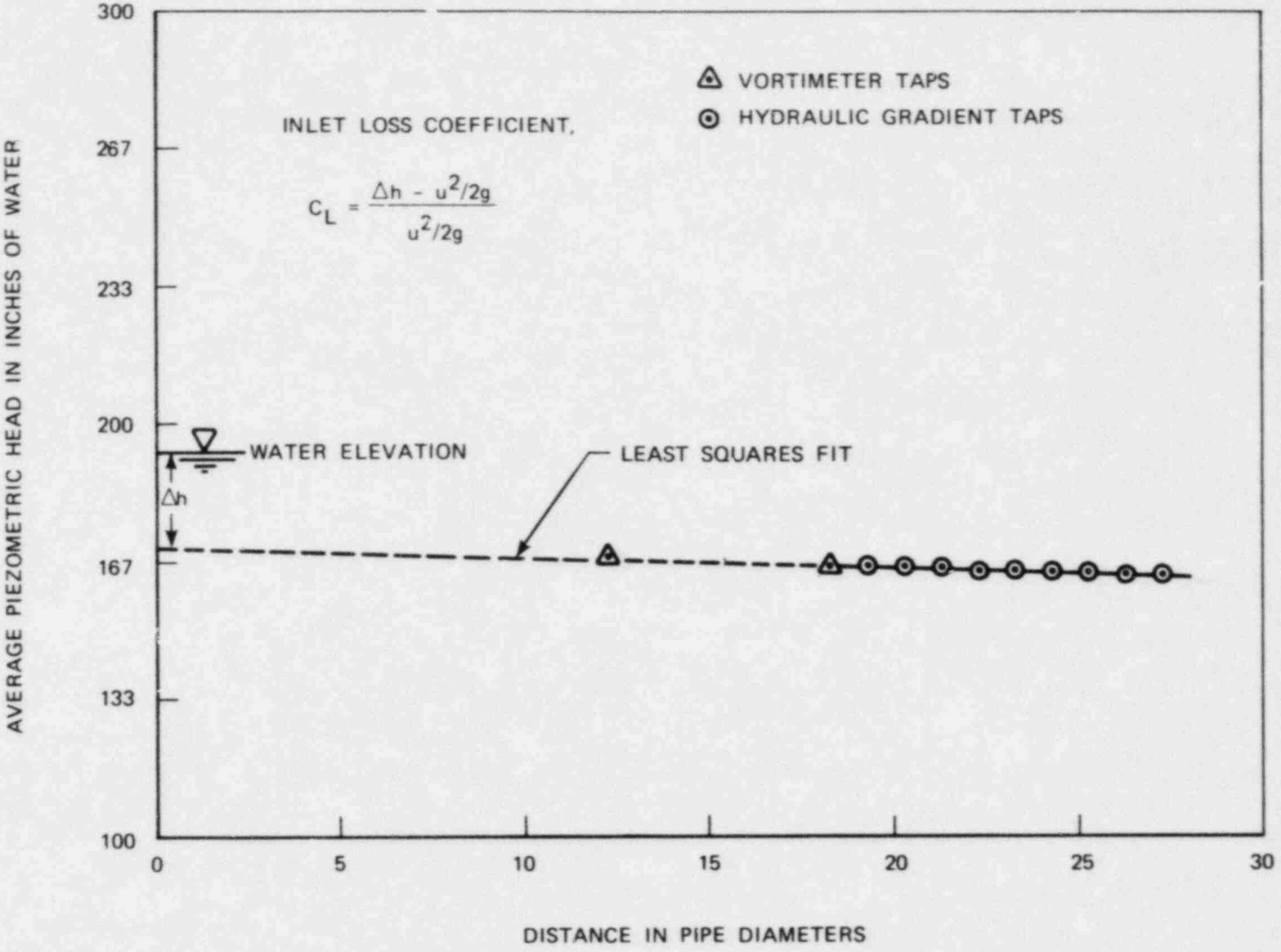


FIGURE A4 INLET LOSS COEFFICIENT DETERMINATION

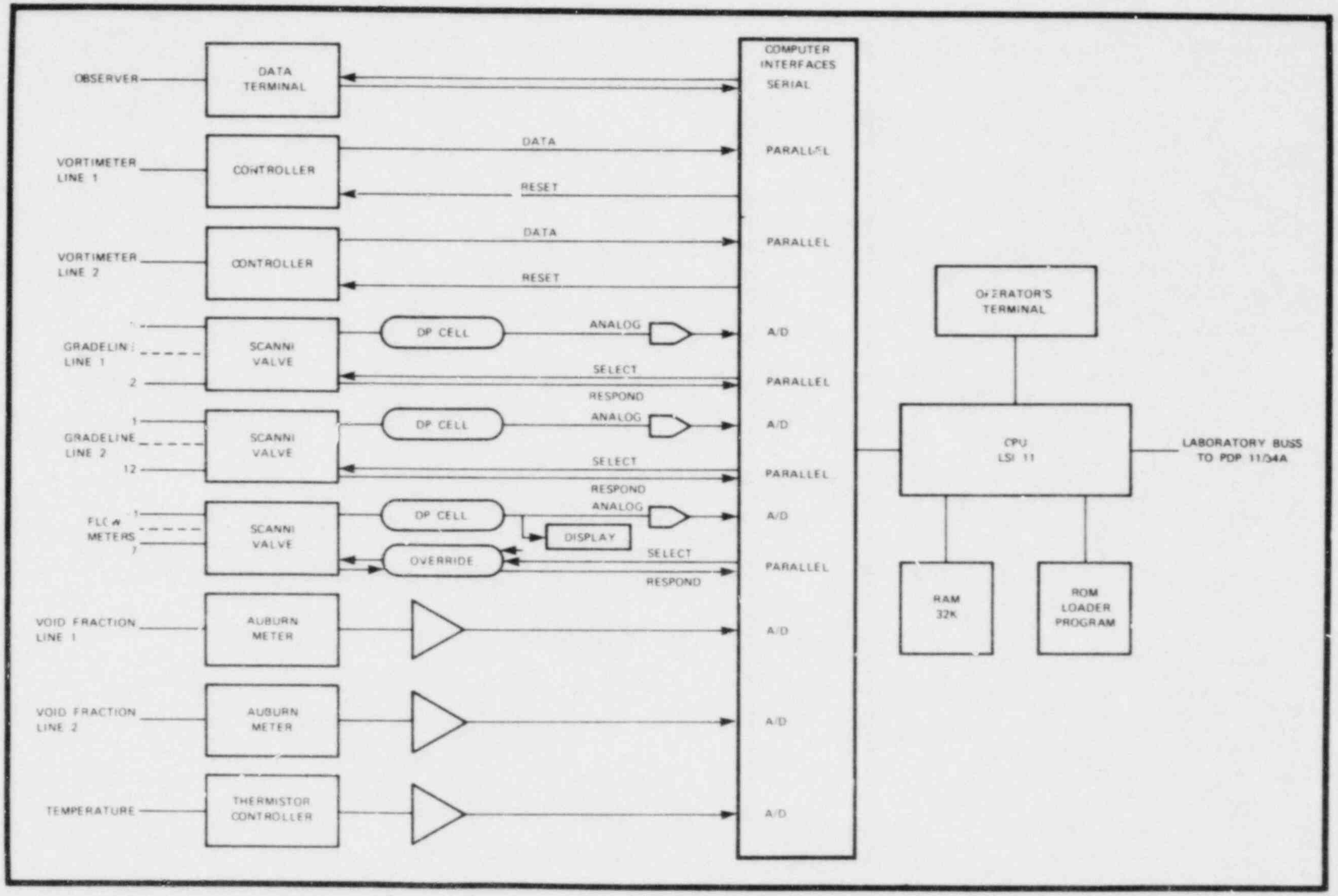


FIGURE A5 DATA ACQUISITION SCHEME

APPENDIX B

CONTAINMENT SUMP RELIABILITY STUDIES TEST PLAN

APPENDIX B
CONTAINMENT SUMP RELIABILITY STUDIES
TEST PLAN

The test plan described herein corresponds to the jointly agreed-upon program worked out by ARL and Sandia in consultation with the DOE and NRC at various stages of the study.

Several geometric configurations of the sump as listed in Table B1 are included in the test program so as to cover a range of geometric parameters and other desired variables such as pipe orientation. The test plan contains the following test series and the tests are to be conducted in two phases involving one or more of the test series in part or full, as described in the following pages:

Series 1 Factorial Tests
Series 2 Sensitivity Tests
Series 3 Perturbed Flow Tests and Limited Vortex Suppressor Tests
Series 4 Detailed Vortex Suppressor Tests
Series 5 Scale Model Tests
Series 6 Debris and Fiberous Insulation Blockage Tests
Series 7 BWR Sump Tests

Phase 1*

A. Test Series 1 - Factorial Tests

Configuration 2 to 11
20 to 23, 24, and 25

For each Configuration: Two full (30 minute) Tests/Submergence
8 Survey (5 minutes) Tests/Submergences
4 Submergences
10 Flow settings

B. Tests Series 2(partly) - Sensitivity Tests

Item of Investigation	Configuration
(i) Top Cover Plate Elevation Changes	1, 52
(ii) Pipe Projection, e_y	12, 13, 14
(iii) Floor to Pipe Clearance, C	15, 16
(iv) Unsymmetrical Sumps (also variable f, e_x)	17, 18, 19
(v) Depth to pipe centerline, b	23A, 23B
(vi) Water temperature	62 to 66

For each Configuration: Two full (30 minute) Tests/Submergence
8 Survey (5 minutes) Tests/Submergence
4 Submergences
10 Flow settings

*See Table B2 for values of test flows and submergences.

TABLE B1

Details of Sump Geometry

Configuration⁺ Number	Pipe Orientation*	Sump Size (ft) (L x B)	Geometric Variables** d (ft)	b (ft)	e_x (ft)	g (ft)	f (ft)	c (ft)	a (ft)	x (ft)	e_y (ft)	Remarks
1	H	8 x 10	1	3	2	1	4	1.5	3	7.5	1	
2	H	8 x 10	1	3	2	1	4	1.5	6	7.5	1	
3	H	16 x 4	1	3	2	1	12	1.5	6	7.5	1	
4	H	16 x 10	1	3	2	1	12	1.5	6	7.5	1	
5	H	16 x 10	1	3	6	3	4	1.5	6	7.5	1	
6	H	16 x 15	1	3	6	1	4	1.5	6	7.5	1	
7	H	16 x 15	1	3	2	3	12	1.5	6	7.5	1	
8	H	20 x 10	1	3	6	1	8	1.5	6	7.5	1	
9	H	20 x 10	1	3	2	3	16	1.5	6	7.5	1	
10	H	20 x 15	1	3	2	1	16	1.5	6	7.5	1	
11	H	20 x 15	1	3	6	3	8	1.5	6	7.5	1	
12	H	20 x 15	1	3	6	3	8	1.5	6	7.5	3	
13	H	20 x 15	1	3	6	3	8	1.5	6	7.5	6	
14	H	20 x 15	1	3	6	3	8	1.5	6	7.5	10	
15	H	20 x 15	1	3	6	3	8	0.5	6	7.5	1	
16	H	20 x 15	1	3	6	3	8	2.5	6	7.5	1	
17	H	20 x 15	1	3	6	3	12	1.5	6	7.5	1	
18	H	20 x 15	1	3	10	3	8	1.5	6	7.5	1	
19	H	20 x 15	1	3	14	3	4	1.5	6	7.5	1	
20	H	8 x 4	1	6	2	1	4	1.5	6	7.5	1	
21	H	8 x 15	1	6	2	1	4	1.5	6	7.5	1	
22	H	16 x 15	1	6	2	1	12	1.5	6	7.5	1	
23	H	20 x 10	1	6	2	1	16	1.5	6	7.5	1	
23A	H	8 x 10	1	6	2	1	4	1.5	6	7.5	1	
23B	H	8 x 10	1	10	2	1	4	1.5	6	7.5	1	
24	H	16 x 10	1	1	2	1	12	1.5	6	7.5	1	
25	H	20 x 4	1	1	2	1	16	1.5	6	7.5	1	
33	H	20 x 10	2	3	2	1	16	3.0	6	7.5	2	Prototype of models
34	H	20 x 10	2	3	2	1	16	3.0	6	7.5	2	With solid partition wall
35	H	8 x 10	2	3	2	1	4	3.0	6	7.5	2	
36	H	8 x 10	2	3	2	1	4	3.0	6	7.5	2	With solid partition wall

TABLE B1
(continued)

Configuration Number+	Pipe Orientation*	Sump Size (ft) (L x B)	Geometric Variables** d (ft)	b (ft)	e_x (ft)	g (ft)	f (ft)	c (ft)	a (ft)	x (ft)	e_y (ft)	Remarks
37	H	8 x 10	1	3	2	1	4	1.5	6	7.5	2	With solid partition wall
38	H	8 x 10	0.5	3	2	1	4	0.75	6	7.5	0.5	With solid partition wall
39	H	Single Outlet Sump - Size Undecided										
40	H	Single Outlet Sump - Size Undecided										
52	H	8 x 10	1	3	2	1	4	1.5	2	7.5	1	
56	H	10 x 5	1	1.5	1	0.5	8	1.5	3	3.75	1	1:2 scale model
57	H	5 x 2.5	0.5	0.75	0.5	0.25	4	0.75	1.5	1.875	0.5	1:4 scale model
58	V	8 x 10	1	3	2	1	4	1.5	6	7.5	5	
58A	V	8 x 10	1	3	2	1	4	1.5	6	7.5	1	
58B	V	8 x 10	1	3	2	1	4	0	6	7.5	5	
59	V	16 x 10	1	3	2	1	12	1.5	6	7.5	5	
59A	V	16 x 10	1	3	2	1	12	1.5	6	7.5	1	
50	V	16 x 10	1	1	2	1	12	1.5	6	7.5	5	
60A	V	16 x 10	1	1	2	1	12	1.5	6	7.5	1	
60B	V	16 x 10	1	1	2	1	12	0	6	7.5	5	
61	H	8 x 10	0.5	3	2	1	4	0.75	6	7.5	0.5	
62	H	16 x 10	1	1	2	1	12	1.5	6	7.5	1	At water temperature approximately 130°F
63	H	16 x 10	1	1	2	1	12	1.5	6	7.5	1	At water temperature approximately 160°F
64	H	8 x 10	1	3	2	1	4	1.5	6	7.5	1	At water temperature approximately 70°F
65	H	8 x 10	1	3	2	1	4	1.5	6	7.5	1	At water temperature approximately 130°F
66	H	8 x 10	1	3	2	1	4	1.5	6	7.5	1	At water temperature approximately 160°F

*H = Horizontal, V = Vertical
**See Figure 1
+For identification purposes only

TABLE B2

Test Flows and Submergences For Phase I Tests

Test Classification	Full Tests (30 minutes)		Survey Tests (5 minutes)	
	Flows (gpm/pipe)	Water Depths* (ft)	Flows (gpm/pipe)	Water Depths* (ft)
1. Factorial (F) and Sensitivity (S)	3000, 5300	1, 2, 3, 5	1500, 2000 2500, 3500 4000, 4500 5000, 6000	1, 2, 3, 5
2. Drain Flow (with Factorial/Sensitivity Tests)	None	None	5300	1
3. Perturbed Flow Tests and Limited Vortex Suppressor Tests (X)				
a. Screen Blockage and Obstructions	3000, 5300	2, 5	1500, 2500 3500, 4500	2, 5
b. Non-Uniform Approach Flow/Streaming	3000, 5300	1, 3	1500, 2500 3500, 4500	1, 3
c. Break Flows				
(i) Config. 24 (tested at flows of 20%, 40%, and 60% of total flow)	3000, 5300	2, 3, 4	None	None
(ii) Other config. (tested at break flows of 40% and 60% of total flow)	5300	2	None	None
d. Transients	Varied from 0 to 6000	1, 2, 3, 4, 5	None	None
e. Vortex Suppressors	3000, 5300	2	1500, 2500 3500, 4500	2

*Above containment floor.

C. Test Series 3 (Part)

Tested on Configurations 2, 9, 22, 24, and 25. The following items are covered. These configurations have been selected based on results of test series 1 (moderate to strong vortex action).

Item Description		Quantity
a.	Non-Uniform Approach/Streaming	
(i)	Number of Schemes	4
(ii)	Submergences	2
(iii)	Full Test/Submergence	2
(iv)	Survey Test/Submergence	4

	b. Break Flow		Only for Config. 24
(i)	Impact Location	1	1
(ii)	Heights	1	1
(iii)	Jet Momentum	2	3
(iv)	Submergences	1	3
(v)	Full Test/Submergence	1	2
(vi)	Survey Test/Submergence	0	0

c. Condenser Flow One survey test at 5,300 gpm flow and at lowest submergence.

	d. Obstructions	
(i)	Position Trials	1
(ii)	Submergences	2
(iii)	Full Test/Submergence	1
(iv)	Survey Test/Submergence	4

	e. Transients	
(i)	Submergences	4

	f. Screen Blockages	Subm. 1	Subm. 2
(i)	Schemes	8	4
(ii)	Full Tests	2	2
(iii)	Survey Tests	4	4

	g. Vortex Suppressor Cages	
(i)	Cage Design	1
(ii)	Submergence	1
(iii)	Full/Tests/Submergence	2
(iv)	Survey Tests/Submergence	4

PHASE 2

A. Test Series 2 (Remainder) - Sensitivity Tests

	Item of Investigation	Configuration
(i)	Vertical Outlets	58, 59, 60
(ii)	Variable C for Vertical Outlets	58B, 60B
(iii)	Variable e_x for Vertical Outlets	58A, 59A, 60A
(iv)	Pipe Diameter	35, 61
(v)	Solid Partition - Single Pipe Operation	34, 36, 37, 38
(vi)	Single Outlet Sumps	38, 40
(vii)	Pump Over Speed Tests	with Config. 2
(viii)	Bellmouth Tests	with Config. 2

See Section 2.0 for details on flows and submergences to be tested for items with configurations 34 to 40 and item (vii). The flows and submergences for other itmes or configurations are the same as for Phase I tests (Table B2), except that for itme (viii), tests are limited to one submergence.

B. Test Series 3 (Remainder)

Vertical pipe outlet configurations 58 and 60A are chosen for perturbed flow tests, the test details being the same as that for Phase I, Test Series 3. Limited perturbed flow tests (screen blockage only) are included for configurations 34 to 40, the details of which are in Section 2.0.

C. Test Series 4

Vortex suppressors, both horizontal and cage type, are included and the tests are to be performed for two configurations (configurations 2 and 58). For cases of single pipe operation, the suppressor will be tested for configuration 58. Details are included in Section 2.0.

D. Test Series 5

Scale model tests are performed for configuration 33 with a 1:2 scale model (configuration 56) and 1:4 scale model (configuration 57). See Reference 3 for details.

E. Test Series 6

The details on debris pull-down and fiberous material blockage tests are not available at this time.

F. Test Series 7

Two BWR sump configurations are to be tested. Details are included in Reference 1.

*U.S. GOVERNMENT PRINTING OFFICE: 1982 361-297/2410 1-3

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-2761
SAND 82-7065
ARL 49-8

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*

Results of Vortex Suppressor Test, Single Outlet Sump Tests and Miscellaneous Sensitivity Tests

5. DATE REPORT COMPLETED
MONTH June YEAR 1982

7. AUTHOR(S)

M. Padmanabhan

DATE REPORT ISSUED
MONTH September YEAR 1982

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

Subcontractor:
Alden Research Laboratory
Worcester Polytechnic Institute
Holden, Massachusetts

Sandia National Laboratories
Albuquerque, New Mexico

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

US Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washington, D. C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.

A1237

13. TYPE OF REPORT

Technical

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

Full scale tests of flow conditions in Containment Recirculation Sumps for nuclear power stations were conducted at the Alden Research Laboratory to provide sump hydraulic design and performance data for use in resolving the Unresolved Safety Issue, A-43 "Containment Sump Performance".

This document is a report of the results in investigations conducted as a part of Phase II of the test program, including (a) vortex suppressor tests of two commonly used suppressors, (b) single outlet sump tests and comparison to double outlet sumps, and (c) test to study the effects on the hydraulic performance of a solid partition wall in a double outlet sump, pump overspeed, outlet pipe diameter, and bellmouth entrances.

Test data on single and double outlet sumps were used for an envelope analysis so as to derive appropriate maximum bounding values for average vortex types, air-withdrawals, pipe swirl, and inlet loss coefficients versus Froude number. These bounding values are compared with the bounding values of the Phase I test. Results of the envelope analysis and an evaluation of other results would provide a data base for use in the preparation of sump design and in their evaluation, and thereby assists in the resolution of the Unresolved Safety Issue, A-43 "Containment Sump Performance".

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT

Unlimited

19. SECURITY CLASS *(This report)*
unclassified

20. SECURITY CLASS *(This page)*
unclassified

21. NO. OF PAGES

22. PRICE
$

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

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

120555078877 1 ANAI9XIS
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WASHINGTON DC 20555