FINAL REPORT

ON

FOAM MORPHOLOGY AND TRANSPORT TESTS FOR THE LA SALLE NUCLEAR PLANT

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San Francisco

September 1996

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EXECUTIVE SUMMARY

In May/June 1996 approximately 160 gallons of polyurethane foam mixture were accidentally injected into a concrete service water tunnel which is part of the Emergency Service Water System (ESWS) for the LaSalle Nuclear Plant. The foam was being used to repair cracks in the tunnel. In July 1996 a series of tests were performed at the Iowa Institute for Hydraulic Research (IIHR) to obtain information on the behavior of the injected foam, including foam morphology, material strength and transport characteristics. The focus of this report is the potential for ingestion and catastrophic blocking by larger pieces of foam of major supply lines to key pumps in the Emergency Service Water System.

The laboratory tests indicated the following:

- Foam injection tests showed that after injection, the uncured foam mixture extruded from the cracks falls to the bottom of the tunnel, and about 10-20% stays there, adhering tightly to the bottom. The remaining 80-90% rises to the surface as a buoyant foam. The curing process generates small foam particles (like BBs) and distributes them through the water volume.
- The saturated bulk density of all debris samples measured at IIHR was less than 1 gm/cm^3, i.e. all samples were buoyant. Observations at the plant by divers implied that the bulk density of a large piece of foam (approximately 8 ft. X 15 ft. X 1 ft.) found on the floor of the tunnel was greater than 1 gm/cm^3, but samples from this piece of debris were tested at IIHR and found to have a bulk density less than 1 gm/cm^3.
- A large buoyant foam piece (d ≥ 8 in.) which initially adheres to the bottom has about a 10% chance of being ingested in the ESWS if it is assumed that it becomes detached during emergency operations.
- A large buoyant foam particle (d ≥ 8 in.) that is floating against the ceiling of the tunnel prior to the onset of emergency conditions has a very small chance (< 2%) of being ingested in the ESWS.

- Large foam particles generated at one end of the tunnel are unlikely to be transported to the other end, i.e. foam injected at the Unit 2 end of the tunnel is very unlikely to affect Unit 1.
- If a large buoyant foam piece (d > 8 in.), initially attached to the floor, is postulated to become detached in the vicinity of the nonessential service water outlet during normal operations (i.e. the nonessential service water system (N-ESWS) operating, the chance of ingestion into the N-ESWS is relatively great (65-80%). However, once the sample is trapped against the ceiling of the tunnel, the probability of ingestion drops significantly with a less than 2% probability of being ingested by the ESWS and less than 5% probability of ingestion by the N-ESWS.
- As the particle size decreases, the chances of being ingested by either the ESWS or the N-ESWS system increases, with fist-size samples being several times as likely to be ingested as large (d > 8 in.) samples. The BB-size pellets are most likely to travel with the flow similar to a passive tracer.
- The behavior of large (d > 8 in.) negatively buoyant ($\rho > 1$ gm/cm^3) foam pieces was investigated using a limited number of tests on artificial debris. The probability of ingestion by the ESWS is similar to that for buoyant foam, while the probability of ingestion by the N-ESWS intake in the tunnel ceiling is much lower than for buoyant foam.
- Foam strength tests at IIHR indicate that
  - The foam debris found in the tunnel was not strong enough to fully block any of the ESWS tunnel outlets under the expected net head of about 45 feet of water.
  - The foam strength is sufficient to prevent the 8-ft. wide foam board rotating in the 7-ft. high tunnel and blocking any of the ESWS outlets.

1.0 INTRODUCTION

1.1 Background

The essential and non-essential service water systems (ESWS and N-ESWS) for both Unit 1 and 2 of the LaSalle Nuclear Plant withdraw from a common service water tunnel, which in turn withdraws from the cooling water intake structure on the plant side of the traveling screens. The tunnel consists of a concrete box conduit, 180 feet long, 13 feet wide and 7 feet deep. In May and June, 1996, cracks in the top slab of the tunnel, at the Unit 2 end, were repaired by injecting polyurethane foam adjacent to the cracks. Subsequently, the pressure differential across some of the strainers increased, and small foam nodules were found in the strainers. Further investigation showed large pieces of foam-like material in the tunnel, both on the bottom and trapped against the ceiling at the Unit 2 end of the tunnel. Foam recovered from the tunnel included one piece approximately 8 ft. X 15 ft. X 1 ft. thick which was found on the floor of the tunnel, plus enough smaller debris to fill five 55-gal. drums.

In July 1996, a series of tests were performed at the Iowa Institute for Hydraulic Research (IIHR) in an attempt to obtain further information on the foam characteristics, specifically the following:

- Effect on foam characteristics and morphology of injection parameters including injection pressure, tunnel pressure, injection rate, curing compound concentration, etc.
- Strength of saturated foam, including its ability to block an intake under a differential pressure of 25-50 feet of head.
- Foam transport characteristics in the service water tunnel.

1.2 System Description

The service water tunnel consists of a concrete box, 180 feet long, 13 feet wide, 7 feet high (internal dimensions) which is oriented north-south. Figure 1.1 shows the location of the service water tunnel, and Figure 1.2 shows a plan of the tunnel configuration. Inflow from the cooling water intake enters the tunnel through six 3-foot diameter pipes which

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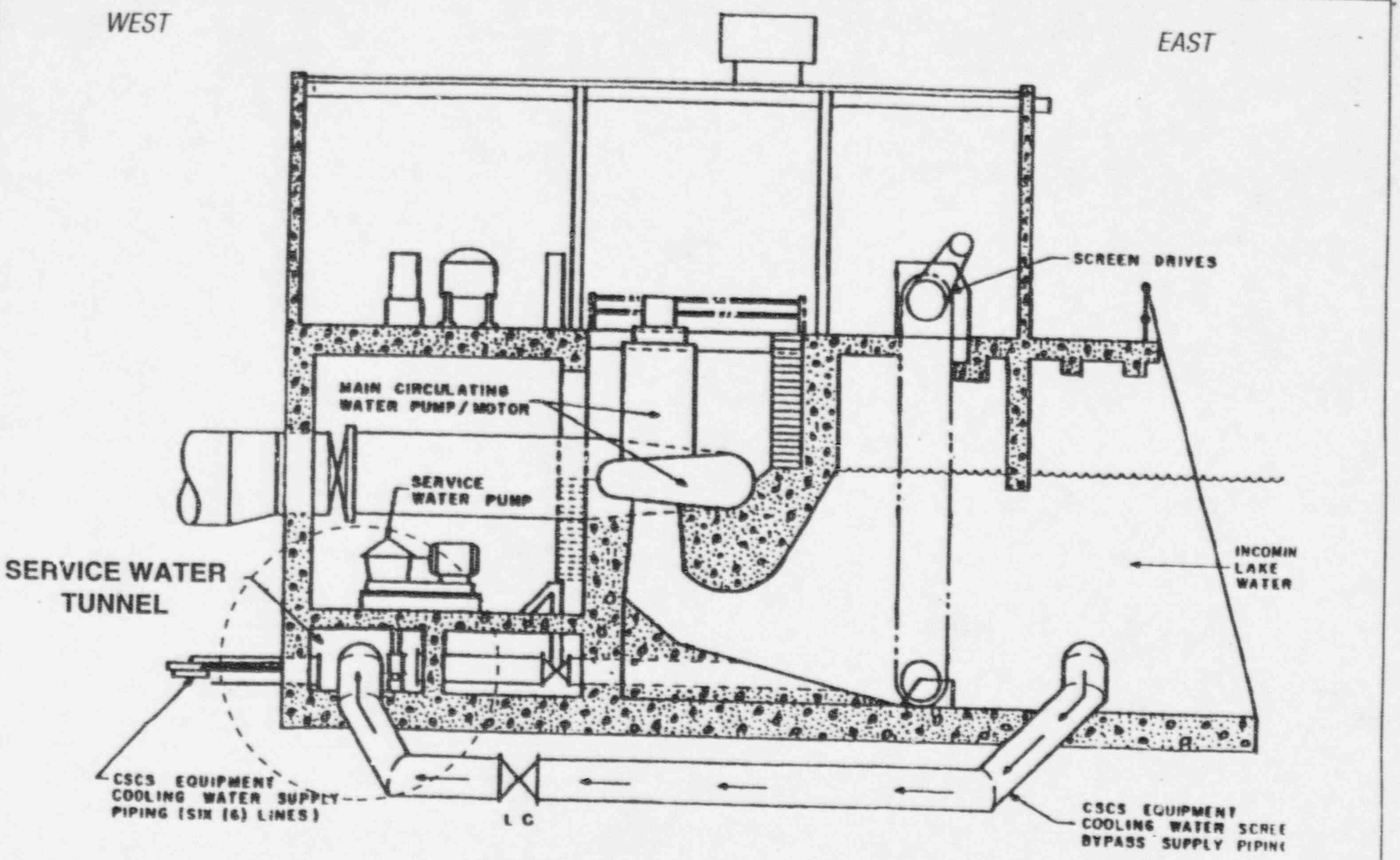

FIGURE 1.1 LOCATION OF SERVICE WATER TUNNEL

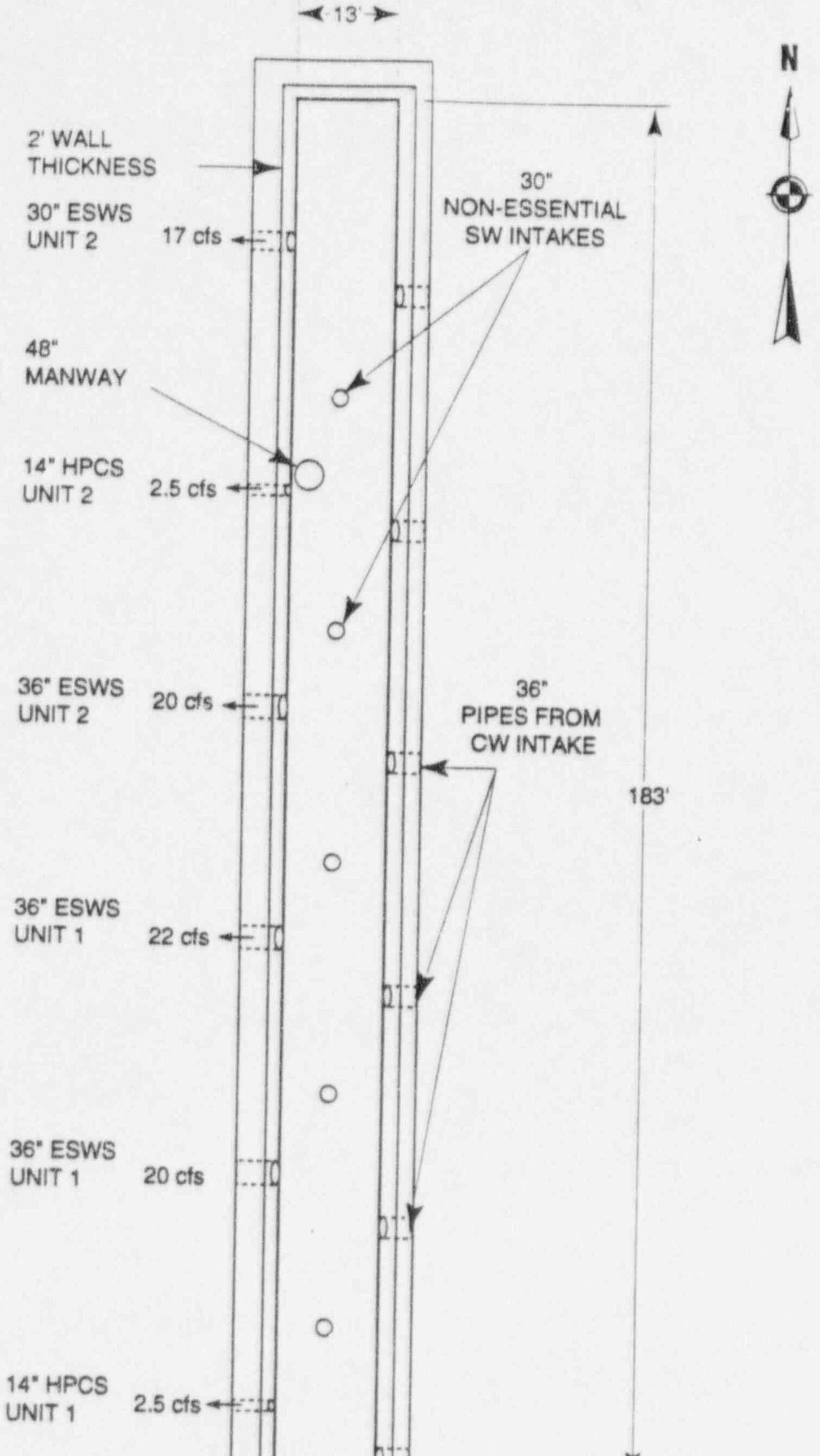

FIGURE 1.2 PLAN OF CONCRETE HEADER

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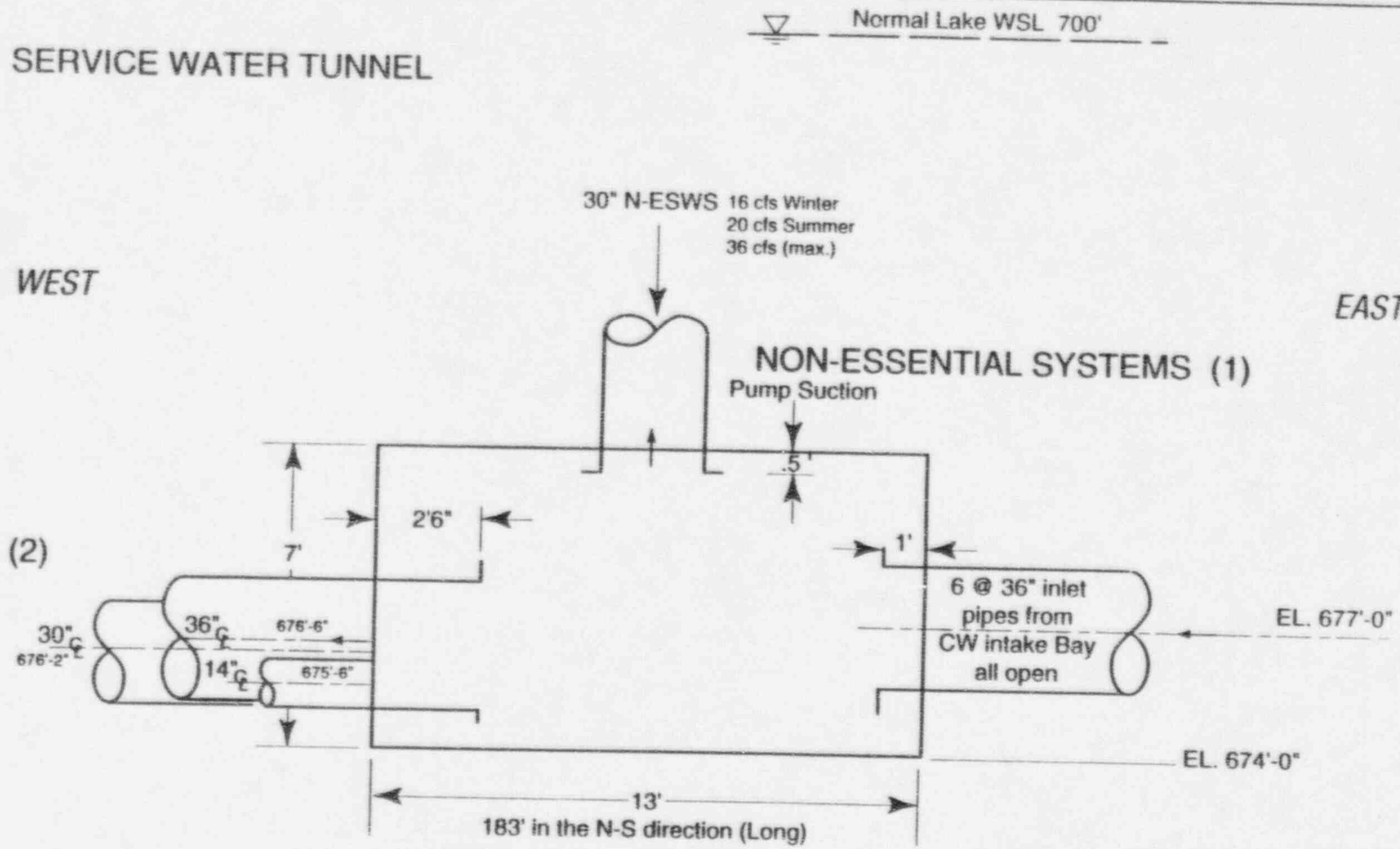
penetrate the east wall of the tunnel. The ESWS withdraws through 6 pipes, ranging from 14 inches to 36 inches which exit through the west wall as shown. ESWS flows range from 2.4 - 22 cfs. The non-essential service water system (N-ESWS) draws from the top of the tunnel through five 30-inch pipes, two for each unit, plus a common intake which can be diverted to either unit. Typical flows for the N-ESWS range from 16 cfs/pipe (winter) to 20 cfs/pipe (summer), with a maximum flow/pipe of 36 cfs. Under normal operating conditions the N-ESWS is operating in the 16-20 cfs/pipe range, and the ESWS is in a standby condition. A 54-in. bypass pipe supplies water to the tunnel in the event of clogging of the traveling screens, but normally the bypass line is closed.

The ceiling of the tunnel is at elevation 681 feet, compared to a normal lake level of 700 feet. Pipe elevations are as shown on Figure 1.3, and terminate in the tunnel in flanges as shown.

The cracks were in the northern (Unit 2) end of the tunnel, and all large foam pieces were found in the northern (Unit 2) end of the tunnel.

The injection procedure consisted of drilling a series of 5/8-inch diameter holes at an angle of 45° to the tunnel surface so as to intercept the cracks. The holes were spaced about 6-12 inches apart on either side of the cracks. A total of over 160 gallons of foam mixture was injected. Over 90% of the foam injected was Hydro Active Grout - HA CUT. The specifications are given in Table 1.1.

SERVICE WATER TUNNEL



(1) Non-essential systems include Diesel Fire Water Pump, Fire Jocky Pump and Service Water Pumps.

(2) Essential safety-related systems - focus of this investigation.

FIGURE 1.3 ELEVATION OF CONCRETE HEADER

HYDRO ACTIVE GROUT

HA CUT

DATA SHEET

Description

HYDRO ACTIVE CUT is designed to fill large voids such as rock fissure, crushed fault, gravel layer, joints/cracks in concrete structures and for the cut-off of gushing water with high pressure and speed. In its uncured form, HYDRO ACTIVE CUT is a blackish-brown transparent nonflammable liquid. When it comes into contact with water the grout expands and then depending on temperature and amount of accelerator used (Hydro Active Cut Cat) quickly cures to a rigid closed cell polyurethane foam that is resistant to most organic solvents, mild acids, alkali and micro-organisms.

Physical properties

Uncured			
HYDRO ACTIVE CUT	Solids	100 %	ASTM D-1010
	Viscosity	120 cps at 68°F	ASTM D-1638
	Color	blackish - brown	
	Density	9.30 lbs/gal	ASTM D-1638
	Flash point	C.O.C. 365°F	ASTM D-93
	Corrosiveness	Non-corrosive	
HYDRO ACTIVE CUT CAT	Appearance	pink transparent liquid	
	Viscosity	15 cps at 68°F	
	Flashpoint	C.O.C. 320°F	
Cured	Density	8.75 - 9.17 lbs/gal	ASTM D-3574
	Tensile strength	56 psi	ASTM C-190-1963
	Compressive strength	896 psi	
	Bending strength	213 psi	
	Bond strength to Mortar Joints	Bending bond strength: 99 psi Shearing bond strength: 255 psi	
	Toxicity	Non-toxic	

Storage

Store in dry area using original Resealable Containers.

Availability

HYDRO ACTIVE Cut: 5 gal metal pails, closed head with flexspout, filled and sealed under dry nitrogen.
HYDRO ACTIVE CUT CAT: 32 oz. bottle.

Reactivity

*at 50°F	% HYDRO ACTIVE CUT CAT	Geltime in min-sec
	2%	19'00"
	6%	7'40"
	10%	4'30"
* at 68°F	% HYDRO ACTIVE CUT CAT	Geltime in min-sec
	2%	9'50"
	6%	4'05"
	10%	2'24"
*at 86°F	% HYDRO ACTIVE CUT CAT	Geltime in min-sec
Example - 1%=1.3 oz./GM	2%	6'00"
	6%	2'25"
	10%	1'33"

Table 1.1 Foam Grout Specifications

2.0 FOAM MORPHOLOGY TESTS

The foam recovered from the tunnel had a variety of morphologies ranging from the standard closed cell (rice-cake) structure, to a glassy fiberglass-like structure, to BB-like pellets. Some of the foam was found trapped against the tunnel ceiling, but large segments of foam were also found on the bottom of the tunnel, implying either a specific gravity (S.G.) greater than 1 or that the foam is adhering to the bottom. The following tests were performed to better understand the foam characteristics:

- Bulk density tests
- Observations on foam formation/curing behavior
- Foam injection tests

2.1 Bulk Density Tests

Since the foam absorbs water, the saturated bulk density is the relevant parameter. Bulk density tests were performed on 29 samples of foam recovered from the tunnel, including 10 samples from each of the two 55-gallon barrels of foam debris supplied by Commonwealth Edison, and 9 samples selected from the foam transport tests (see Section 4). All samples were saturated for at least 12 hours prior to the tests. Table 2.1 shows the values obtained from the larger samples (1-4 liters) taken from the barrels. It is immediately apparent that all samples have a bulk density of less than 1 gm/cm^3, with most samples less than 0.95 gm/cm^3. The values from the smaller samples which were ingested by either the ESWS or N-ESWS outlets during the foam transport tests are shown in Table 2.2 and are in the same range, except that one sample slightly exceeds 0.98 gm/cm^3.

Observations on all samples recovered from the tunnel and immersed in water indicated that all the samples floated, i.e. the samples had a saturated bulk density of less than 1 gm/cm^3.

Density of Samples

Barrel No.	Series	Weight W_{sr} (g)	Volume V_{sr} (ml)	Bulk Density ρ (g/ml)
1	SL1	1267	1328	0.954
1	SL2	1843	2029	0.908
1	SL3	1380	1545	0.893
1	SL4	2547	2847	0.895
1	SL5	1730	1965	0.880
1	SL6	916	978	0.937
1	SL7	1889	1989	0.950
1	SL8	2810	3242	0.867
1	SH1	3540	3923	0.902
1	SH2	4126	4279	0.964
2	SN1	2008	2138	0.939
2	SN2	2379	2594	0.917
2	SN3	2502	2741	0.913
2	SN4	1041	1104	0.943
2	SN5	1726	1801	0.958
2	SN6	1717	1894	0.907
2	SN7	2808	3074	0.913
2	SN8	1285	1363	0.943
2	SN9	2796	3126	0.894
2	SN10	3789	4118	0.920

Table 2.1 Bulk Density of Saturated Foam Samples Recovered from Tunnel

Density of Foam Samples

Water Temperature = 24°C

Series	Weight W_{sr} (gm)	Volume V_{sr} (ml)	Bulk Density ρ gm/ml
R2P1	220	228	0.966
R2P2	103	115	0.893
R3W1	110	115	0.954
R3W2	191	221	0.966
R3W3	85	90	0.942
R3W4	497	507	0.981
R3W5	53	56	0.944
R3W6	49	56	0.872
R3W7	54	61	0.883

Table 2.2 Bulk Density of Saturated Foam Samples from Compound Transport Tests

2.2 Observations on Foam Formation/Curing Behavior

A simple test apparatus consisting of a 3 ft. 6 in.-long, 4.5 in.-diameter Lucite pipe was set up and filled with water. The foam mixture (S.G. = 1.04) was poured slowly (100 cc/min.) into the top of the pipe in a continuous stream through a 3/16 in. nozzle. The mixture fell through the water column as a series of droplets, approximately 3/8 in. long, 3/16 in. diameter, and gathered on the bottom in a pool about 1 in. thick. The top of the pool of mixture retained its bead-like structure and the original mixture color (a dark, oily brown). After a few minutes, a few pieces of flexible, foam-like material about 1/2 in. long moved to the surface and began forming a surface layer. Then groups of brown beads, about 1/8 inch in diameter and in clusters of 3-10 beads, began to move upwards, usually attached to one or more clear (gas) bubbles. Most of these reached the surface and became attached to the surface layer. Others lost their gas bubbles and descended. Soon there was a continuous rain of both upward and downward moving particles, and both the underside of the top surface and the top of the lower surface had a characteristic stalactite-like configuration. After about 15 minutes, the surface layer had expanded to about 6 in. thick with the characteristic foam structure. However, the underside of the top layer appeared to contain some "partly cured" glass-like beads. The bottom layer (~ 1/4-3/4 in. thick) changed color from a dark brown to yellow and adhered strongly to the bottom of the pipe section.

The above observations provide a basis for explaining the buildup of foam (with a bulk density less than 1 gm/cm^3) on the ceiling of the tunnel. It is also possible to explain the development of a thick, relatively dense layer, since if injection through one crack results in a layer of foam on the ceiling, later injections through adjacent holes may lead to a buildup of uncured foam (with a relatively high density) between the ceiling and the initial foam layer. After some time, saturation of the initial buoyant foam layer by the surrounding water could result in an overall bulk density approaching 1 gm/cm^3.

The observations also explain the foam BBs found in the ESWS strainers, since the currents caused by the N-ESWS system operating during the injections will deposit these small particles throughout the tunnel.

A simple test was performed to determine the effect of restricted contact with water on the foam characteristics. The foam mixture with 5% curing compound was placed in a dry beaker and allowed to react. The test showed that apart from a thin layer of foam on the surface, which presumably cured due to contact with the moisture in the air, most of the liquid was unaffected. However, if the mixture is poured into a shallow container with a depth of about 1/4 inch, a foam is formed with a bulk density less than 1 gm/ cm^3.

2.3 Foam Injection Tests

A series of foam injection tests were performed using the apparatus shown in Figure 2-1 and varying the injection pressure, tank (tunnel) pressure, injection rate, hole (crack) size, curing compound concentration, and tank bottom surface.

The test apparatus consisted of a 55 gallon steel tank which could be pressurized to 0-8.5 psig (0-20 feet of water). The tank pressure could be varied as required. The foam was injected through the commercial type of nozzle used at LaSalle. After exiting the nozzle the foam had to pass through a steel cap with a small hole (1/32 in.-1/16 in.) to allow the "crack" size to be varied. The foam injection apparatus, also shown in Figure 2.1, allows quantities of the foam mixture to be injected at a controlled injection rate and pressure. The test procedure involved filling the test tank with water at a nominal temperature of 85°F, establishing the required tank pressure, injecting the foam mixture, waiting until all foam expansion activity ceased (as shown by the cessation of expansion overflow from the standpipe, and examining both the top (lid) and bottom foam deposits in the test tank. Table 2.3 shows the test parameters for the 10 tests performed. Tables 2.4 and 2.5 show the dry and saturated bulk densities of the resulting foam.

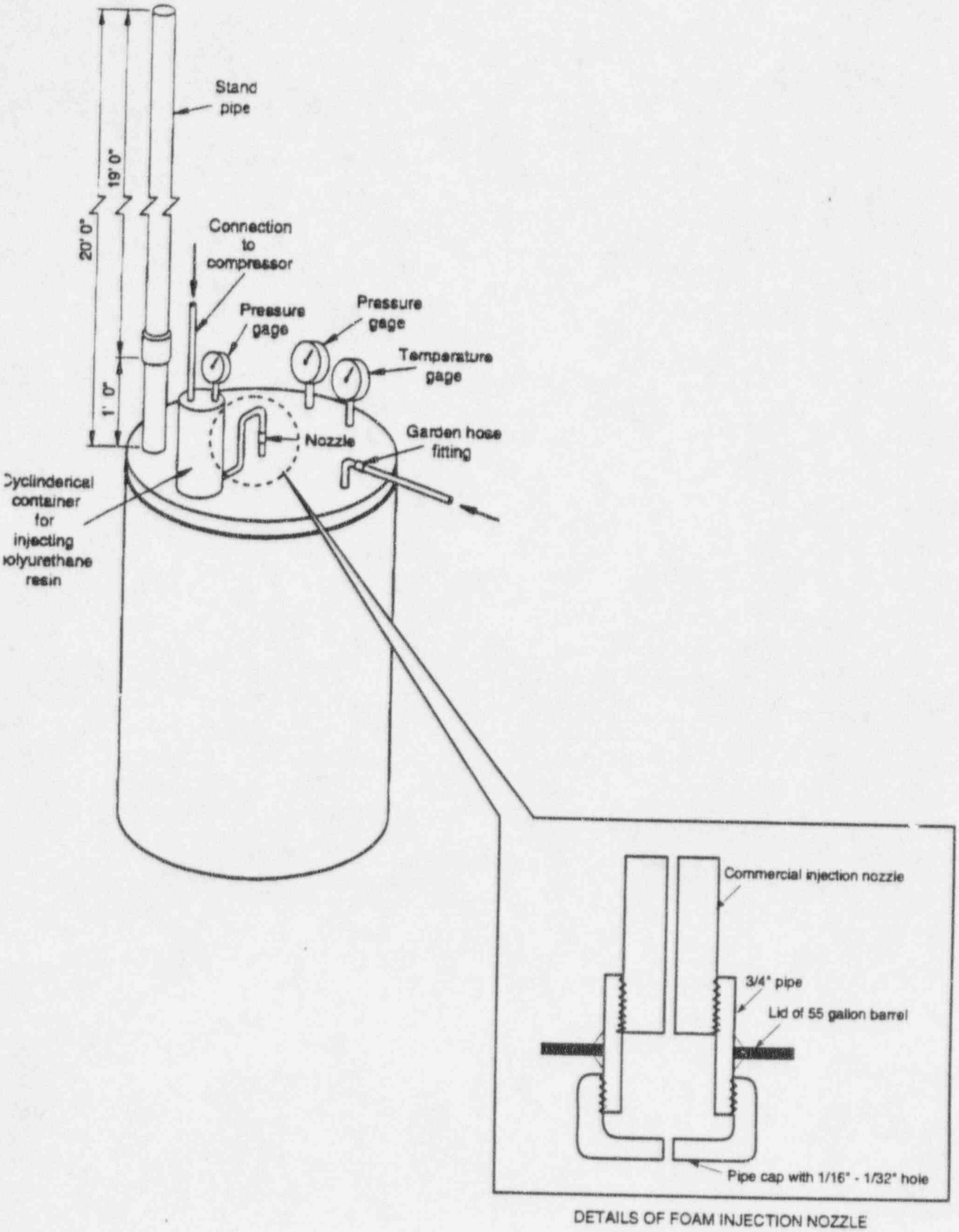


FIGURE 2.1 FOAM INJECTION TEST APPARATUS

Test No. [3]	Injection Pressure (psi)	Tank Pressure (psi)	Tank Temp (°F)	Vol. of Injection (liters)	Injection Time (min.)	Hole Size (inches)	Curing Compound (%)
2	40	8.5	86	0.1	5	1/32	5
3	9-15	8.5	83	0.4	30	1/16	5
4	35	8.5	87	2	3	0.042	5
5	20	8.5	86	2	4	1/16	5
6	10-13	8.5	83	2	7	Note [1]	5
7	35	8.5	83	2	50 sec	"	5
8	35	8.5	84	2	50 sec	"	2
9	35	0	85	2	50 sec	"	2
10	50	8.5	84	2	30 sec	"	1
11 [2]	35	8.5	85	2	50 sec	"	5

Note (1) Internal injection hole size control removed for tests 5-10.
Note (2) Concrete block placed in tank to observe effect of bottom material on adhesion of bottom deposit.
Note (3) The initial test with a very fine nozzle did not succeed in injecting foam.

Table 2.3 Foam Injection Test Parameters

Density of Foam Samples
(Dry Conditions)

Water Temperature = 24°C

Series	Weight W_{ar} (g)	Volume V_{ar} (ml)	Bulk Density ρ gm/ml
2B	57	56	1.012
3T	25	301	0.083
4B	43	103	0.416
5T	146	489	0.298
5B	55	164	0.334
6T	32	313	0.102
6B	40	111	0.359
7T	38	419	0.091
7B	50	184	0.272
8T	103	214	0.482
8B	31	58	0.533
9T	75	461	0.163
10T	55	120	0.457
10B	79	126	0.625
11**	---	---	---
12T*	29	438	0.066
12B*	43	78	0.550
13T*	49	470	0.104
13B*	8	74	0.108

Note:
B represents samples from the bottom of the tank
T represents samples from the top of the tank
* Tests performed in an open container
**No density measurements performed

Table 2.4 Dry Density of Foam Samples from Injection/Curing Tests

Density of Foam Samples
(Saturated Condition)

Water Temperature = 24°C

Series	Weight W_{sr} (g)	Volume V_{sr} (ml)	Bulk Density ρ gm/ml
2B	67	66	1.015
3T	98	369	0.266
4B	74	116	0.636
5T	198	518	0.383
5B	77	186	0.415
6T	120	368	0.326
6B	66	127	0.518
7T	160	502	0.319
7B	85	208	0.409
8T	138	236	0.585
8B	55	78	0.703
9T	186	533	0.349
10T	126	192	0.658
10B	89	128	0.693
11**	---	---	---
12T*	70	446	0.157
12B*	65	84	0.771
13T*	137	476	0.288
13B*	34	85	0.399

Note:
B represents samples from the bottom of the tank
T represents samples from the top of the tank
* Tests performed in an open container
**No density measurements performed

Table 2.5 Saturated Bulk Density of Foam Samples from Injection/Curing Tests

The results of the injection tests were as follows:

a. Five different foam morphologies were observed:

1) For very small injection quantities (Test #2), a very thin, heavy material resulted. The thin layer broke down into a gritty material which sank in water (i.e. specific gravity S.G. >1). This material may explain the heavy foam observed in the tunnel since the foam was injected into the tunnel at high pressure through very narrow cracks.

2) For larger quantities, tank pressures (20-ft head) and curing compound concentration (5%) (Tests #3-7), about 85 % of the material rose to the surface, adhered to the lid of the tank, and formed a typical foam-like structure (rice-cake). The remaining 15% adhered to the bottom and had a more glassy appearance with a peanut brittle-like texture. The bottom material was also buoyant (bulk density < 1 gm/cm^3) but the adhesion to the tank bottom was sufficient to keep it submerged. Tables 2.4 and 2.5 give the bulk densities for both the top (T) and bottom (B) layers of foam.

3) For reduced curing compounds concentration, the foam expansion was decreased, resulting in a glassier looking material with a different (less bead-like) structure (Tests #8-10).

4) For tank (tunnel) pressure close to atmospheric (Test #9), the foam at the surface expanded more, resulting in a more open, sponge-like structure. Comparison with Test #8 indicates that higher tank pressures may result in more dense foam, but comparison with other tests indicates a lot of variability, and hence no firm conclusions can be drawn

5) The BBs which were observed in the Lucite column test (Section 2.2) were not found as a separate entity in these injection tests but became part of the stalactite-like surfaces either at the surface or the bottom of the tank. This is reasonable since no horizontal currents were present to remove the BBs from the injection site.

b. Injection rate, injection pressure, and hole (crack) size seemed to have relatively little effect, except in the case of Test No. 2 where small quantities were injected.

c. For all cases, with the exception of the very small quantities (after breakdown), the resulting foam was buoyant (bulk density < 1 gm/cm^3). In fact, as shown in Table 2.5, the saturated bulk densities of this foam are much less than for the tunnel debris, possibly due to a different foam structure which resulted in a lower degree of saturation, or perhaps due to a shorter period of saturation (~ 1 day compared to several weeks in the tunnel).

d. Test #11, which investigated the effect of the bottom material on the adhesion of the bottom foam deposit, gave interesting results. A standard 10 in. X 6 in. X 4 in. concrete block was placed on the tank bottom. The concrete block itself adhered strongly to the bottom of the tank, but the foam deposits on top of the block were removed relatively easily. The probable explanation is that the original foam mixture flowed off the top of the block to the bottom of the tank, with some mixture flowing in the narrow crack between the block and the tank bottom, resulting in the adhesion of the block. The deposits on top of the block were from the secondary deposits described in Section 2.2. The test implies that the original, uncured, foam mixture can lead to strong adhesion, but the partly cured foam droplets are less effective in causing adhesion.

2.4 Conclusions From Foam Morphology Tests

The foam morphology tests explained the somewhat paradoxical behavior of the foam debris in the tunnel, including the different foam morphologies, plus the fact that foam was observed on both the ceiling and the bottom of the tunnel. In summary, the explanations are:

- Excess foam mixture, after passing through the cracks in the concrete, falls to the bottom of the tunnel. (The mixture has a S.G. of 1.045.)
- During the curing reaction much of the foam floats to the ceiling and forms typical foam deposits against the ceiling.

- Some material adheres to the bottom and multiple injections in adjacent locations could result in relatively thick bottom deposits which can continue to adhere to the bottom even though their bulk density is less than 1 gm/cm^3, i.e. they are buoyant.
- If an initial foam layer is formed against the ceiling and further foam mixture is injected between the foam and the tunnel surface, the curing reaction may be inhibited, and the resulting uncured material may be denser than water. This is a possible explanation for the very large, relatively dense foam slab observed on the tunnel bottom.
- Foam BBs formed during the curing process and will be carried throughout the tunnel by currents caused by the N-ESWS flows.
- Ceiling and bottom deposits tend to have a different structure. In addition, changes in the curing compound concentration result in different foam appearance.

Further information on the foam injection tests is given in the IIHR Report No. 247 (Reference 1).

3.0 FAILURE LOAD TESTING OF FOAM PLUGS

Due to the large size of foam pieces in the tunnel, the possibility existed that a piece of foam could block off the mouth of one of the major ESWS inlets (14-36 in. diameter), or that downstream of the inlets smaller pieces of foam could completely block the entrances to the safety-related pumps. The head differential across the foam plug could be as high as 45 feet (23 ft. of positive head, and 22 ft. of suction head). Tests were performed on samples of the debris foam to determine if and how the foam plug would fail.

3.1 Test Procedure/Analysis

Tests were conducted at a scale ratio of 1:12 to determine the load required to fail a 1 in. thick piece of foam, across a 3 in. ID pipe with flange dimensions geometrically similar to those at the LaSalle Plant. A special jig was constructed for these tests. Testing was conducted using the IIHR MTS servohydraulic testing machine. The loading jig was constructed in the IIHR machine shop. A number of tests were conducted to determine variability in the failure load as this gave an insight into the probability of failure in field conditions. Tests were conducted at room temperature and at a suitable loading rate. The foam was under water during testing.

In conjunction with the mechanical testing, an elastic analysis was conducted (using thick plate theory) to predict the stress in a piece of foam that covers the pipe entrance under a 20-40 ft. head pressure difference. This stress was compared with the failure data found from the mechanical testing, and on the basis of this comparison, it was possible to determine whether a piece of foam which blocks the entrance to the pipe would fail, or would remain in place and thus restrict flow.

Tests were also conduced to establish the failure stress in bending and compression for the foam so that the behavior of the large foam board (approximately 8 ft. X 15 ft. X 1 ft.) in the flume could be determined. Specifically, since the board is 8 feet wide, and the tunnel is only 7 feet high, the only way that the board could turn into the vertical plane and block one of the ESWS outlets is for the for the board to fail in bending, compression or shear.

The initial 1:12 scale tests resulted in shear failure, but specific tests were required to give bending and compression values. Further information on all the tests is given in the IIHR Report No. 246 (Reference 2).

3.2 Results

3.2.1 Plate Tests

These tests involved testing a disk of foam, 1 in thick and 5-6 in. in diameter, as discussed in Section 3.1. A 2-in. diameter indenter was used. The loads required to fail the foam are shown in Figure 3.1. The mean failure load is 47.2 lbs, with a standard deviation of 17.25 lbs. This is equivalent to a head of 15.5 feet of water for a 1-ft. thick foam sample covering a 36-in. diameter pipe outlet. Since the net head across the outlet for a blocked condition can be as high as 45 feet, it appears that the foam board will not be strong enough to block the outlet.

When the foam disk failed, it broke into four to eight pie-shaped fragments. The 2-inch indenter did not just punch a hole through the disk. The implication of this failure mode in determining a shear stress for this material is being evaluated. However, an initial value of 5 psi seems reasonable to determine if shear failure of the large foam board by currents in the tunnel is possible. Internal velocities in the tunnel are of the order of 3 fps, and would generate a drag force on the foam of about 10 lbs/ft^2, and would result in a shear force of less than 0.5 psi in the foam if it were jammed across the tunnel. Hence, typical currents in the tunnel are unlikely to cause the foam board to fail in shear.

3.2.2 Bending Test

Ten foam specimens were placed in a three-point bending test rig and loaded until failure occurred. Failure in this situation was defined as the growth of a visible crack. Each specimen measured 4 in. high, 4 in. wide, and about 8 in. long. The three-point testing rig consisted of two supports 6 in. apart with the indenter located between the supports in the center. Further information is given in Reference 2. Each specimen was tested while saturated.

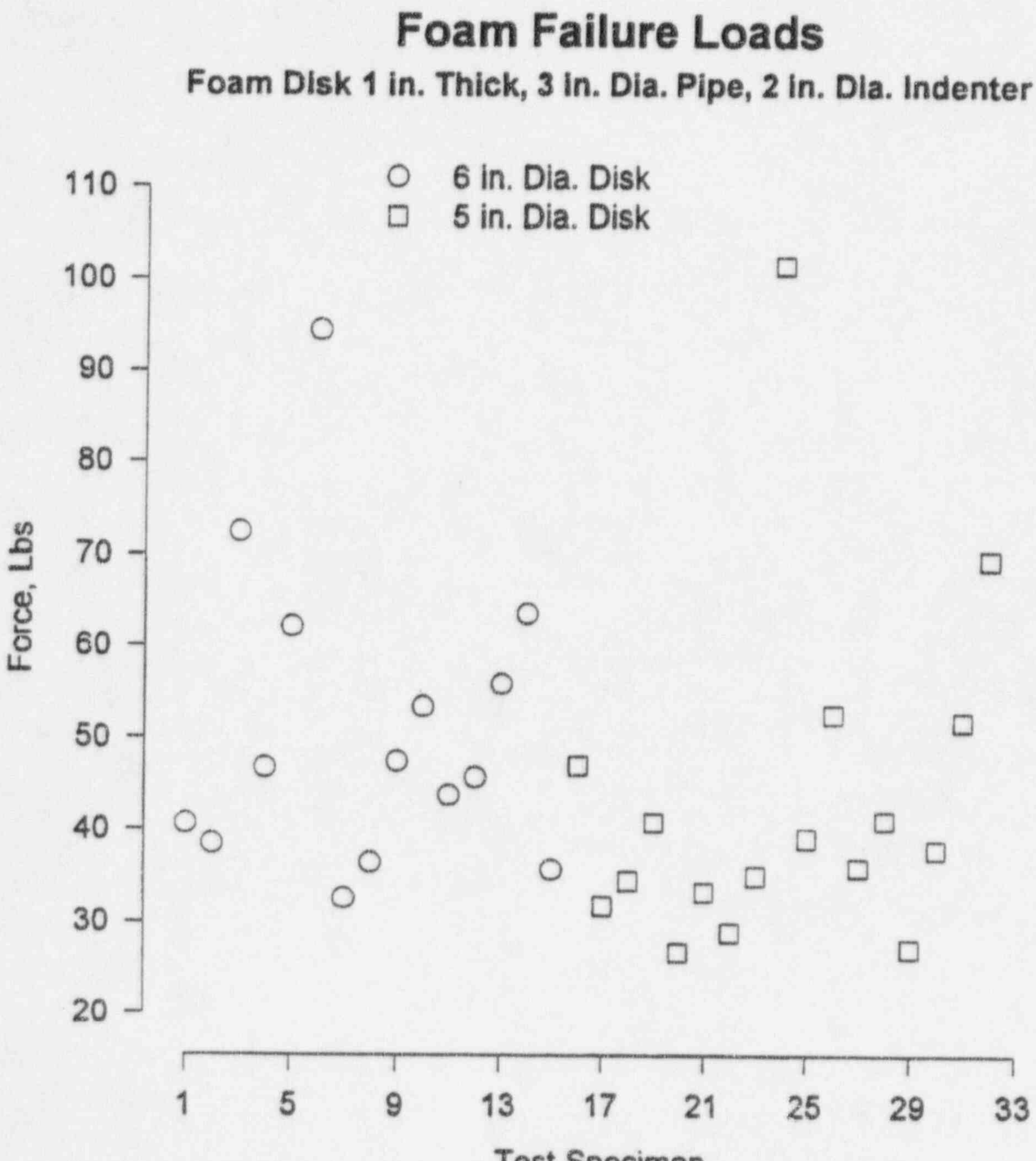


Figure 3.1 Results from Foam Failure Loads

An analysis was performed using beam theory and the failure stresses were calculated. For these 10 specimens, the mean failure stress was 12 psi., with a standard deviation of 2.9 psi. A plot of the failure stresses of the samples is shown in Figure 3.2

3.2.3 Compression Tests

Ten foam specimens 4 to 6 in. high were placed in axial compression and loaded until the final height was 2 in. In this case failure did not occur, rather the water that was in the specimens was expelled. Each of the specimens measured 4 in. wide by 4 in. deep, with a height of between 4 to 6 in. Axial compression was accomplished by placing the specimen between two flat platens and bringing the platens together at a fixed velocity. Each specimen was tested while saturated.

Converting the load into stress and the platen displacements into bulk engineering strain, a series of 10 stress-strain curves were developed, as shown in Figure 3.3. The family of curves demonstrate that all the foam specimens exhibited a similar stress-strain relationship and that high compression is possible.

3.2.4 Bulk Density Observations on Samples

The samples of foam that were part of the large foam board (approximately 8 ft. X 15 ft. X 1 ft.) were placed in a bath of water at room temperature from 8/22 until 8/26/96. The samples were submerged by means of concrete blocks and all samples stayed submerged for the entire period. None of the samples appeared to have a lost their buoyancy when the weights were removed on 8/26/96 and the specimens used in the bending and compression tests were made from randomly selected samples.

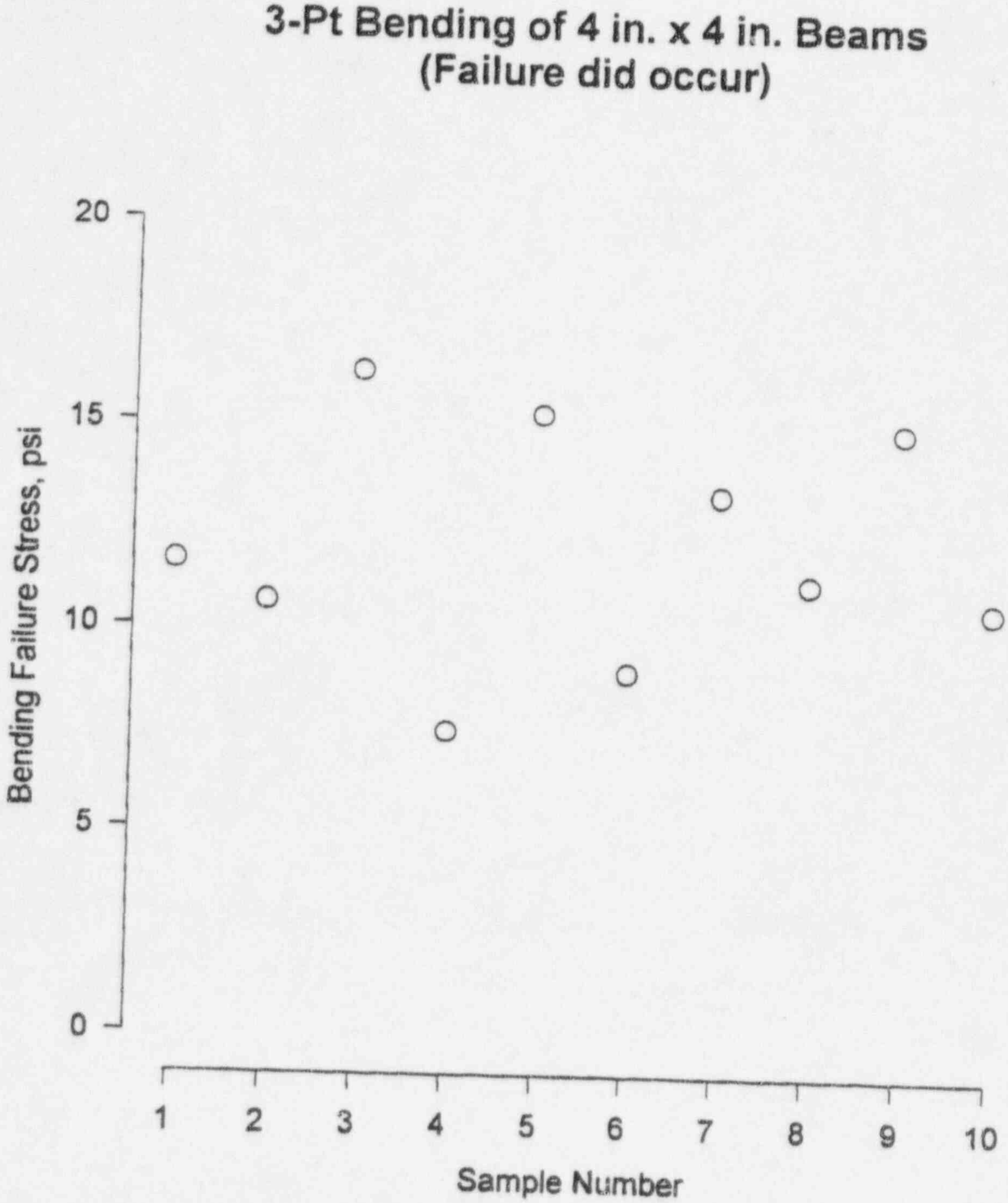


Figure 3.2 Bending Failure Tests for Samples from Large Foam Board

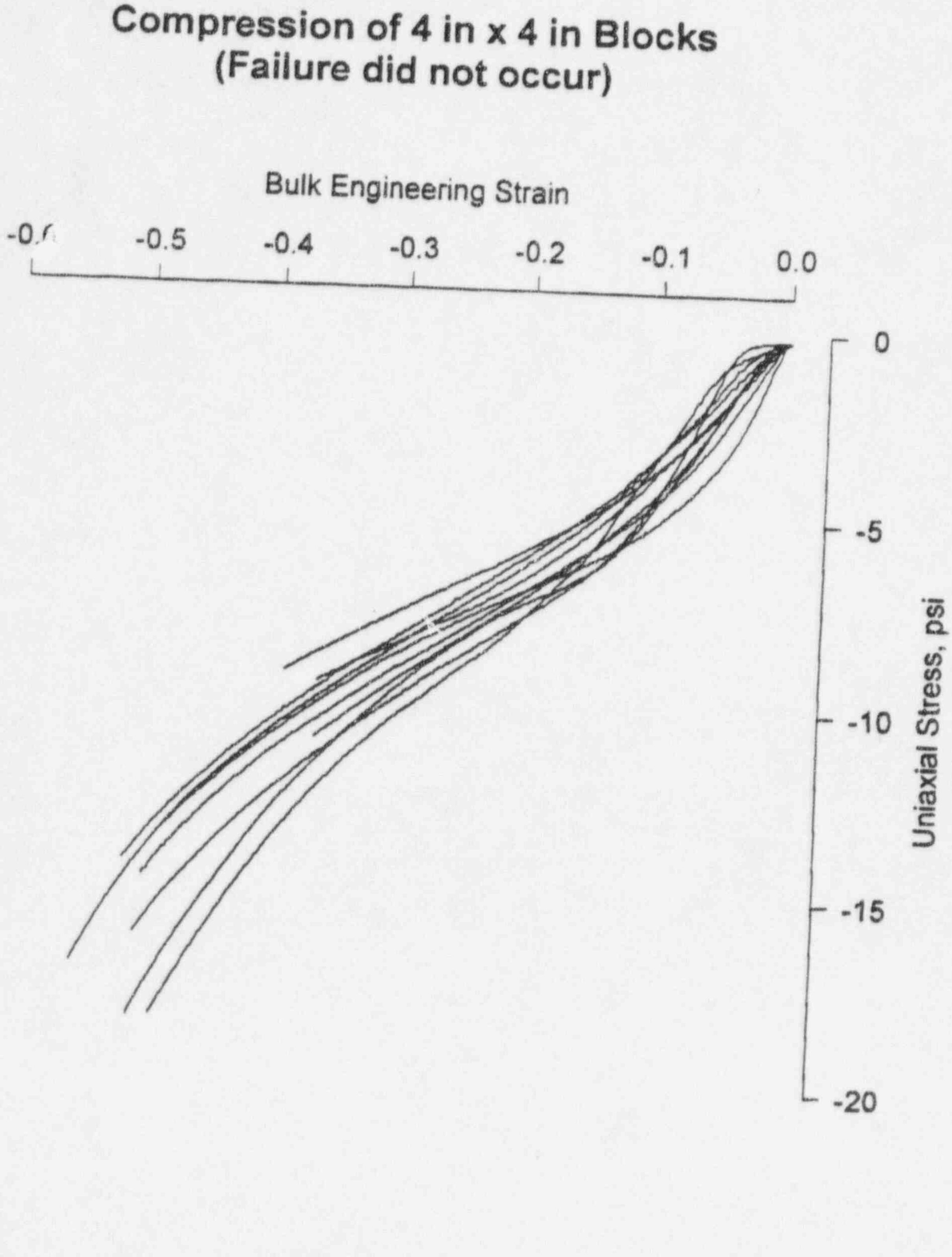


Figure 3.3 Compression Tests on Samples from Large Foam Board

3.2.5 Analysis

A simple analysis indicates that the bending stress in the foam board jammed across the tunnel between the floor and the ceiling is about 3 psi compared to an average failure value of 12 psi and a minimum value of about 7 psi (see Figure 3.2). Hence, it is very unlikely that the foam will fail in bending due to currents in the tunnel. Similarly, the compression force exerted by the tunnel floor and ceiling due to current drag is about 0.5 psi. A strain of 12% (needed to reduce the 8' wide board to 7') requires a compressive force of about 5 psi (see Figure 3.3), and hence the currents in the tunnel were not large enough to rotate the foam board and block off the ESWS outlet from the tunnel.

4.0 FOAM TRANSPORT TESTS

The probability of ingesting large pieces of foam through the ESWS intake pipes (14-36 in.) in the tunnel, or ingesting foam into the smaller diameter pipes leading to the ESWS pumps, was investigated by replicating a segment of the tunnel at full scale in the recirculating flume at the Iowa Institute for Hydraulic Research, the University of Iowa. The recirculating flume has a working section which is 65 feet long, 13 feet wide and 7 feet deep, with a flow capacity exceeding 100 cfs. An 8-foot wide segment of the tunnel was replicated as shown in Figure 4.1.

Inflow through a 3-foot pipe (A) (see Figure 4.2) and outflow through a 3-foot pipe on the west wall (C), and a 30-inch outlet on the top of the tunnel (B) are replicated. Inlet and outlet manifolds (D and E) were included to simulate longitudinal flows along the tunnel. Further details on the test configuration are given in the discussion of the Phase III tests in the IIHR Report No. 247 (Reference 1).

Four series of tests were performed as follows:

- Preliminary tests
- Detailed tests using buoyant samples
- Compound tests using multiple samples
- Additional tests to determine the behavior of negatively buoyant samples

4.1 Preliminary Tests

The following preliminary tests were performed to obtain an understanding of the behavior of the system. The tests were limited to five natural samples (recovered from LaSalle) and five fabricated foam samples.

a. Through flow tests (TF-1) with an inflow (A) of 20 cfs and an outflow (C) of 20 cfs representing ESWS operation by itself. The non-essential service water flow (B) was set to zero, and no longitudinal flow was considered (D=E=O). One reason for performing these tests was to determine the sensitivity of the results of

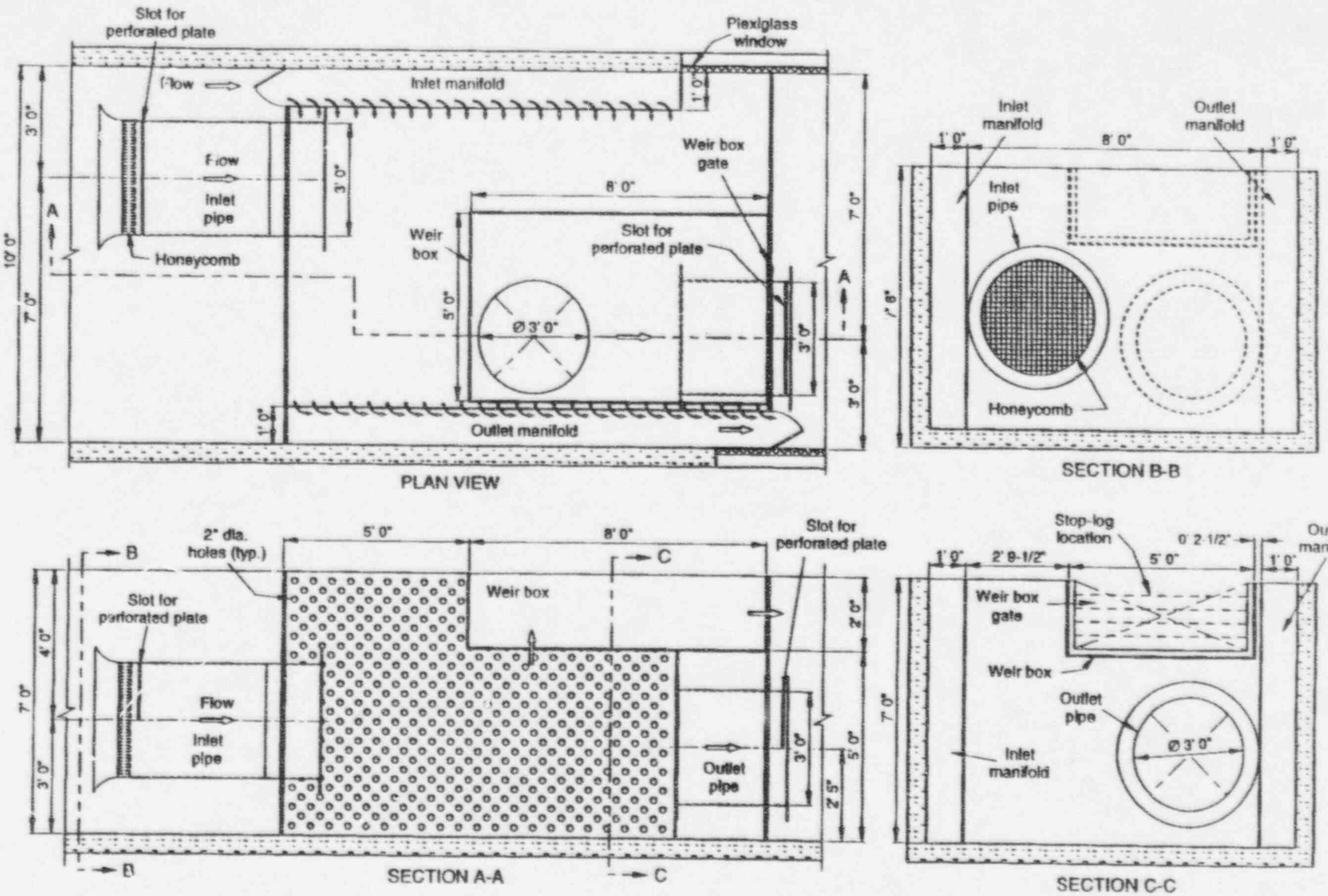


FIGURE 4.1 LAYOUT OF TEST FLUME

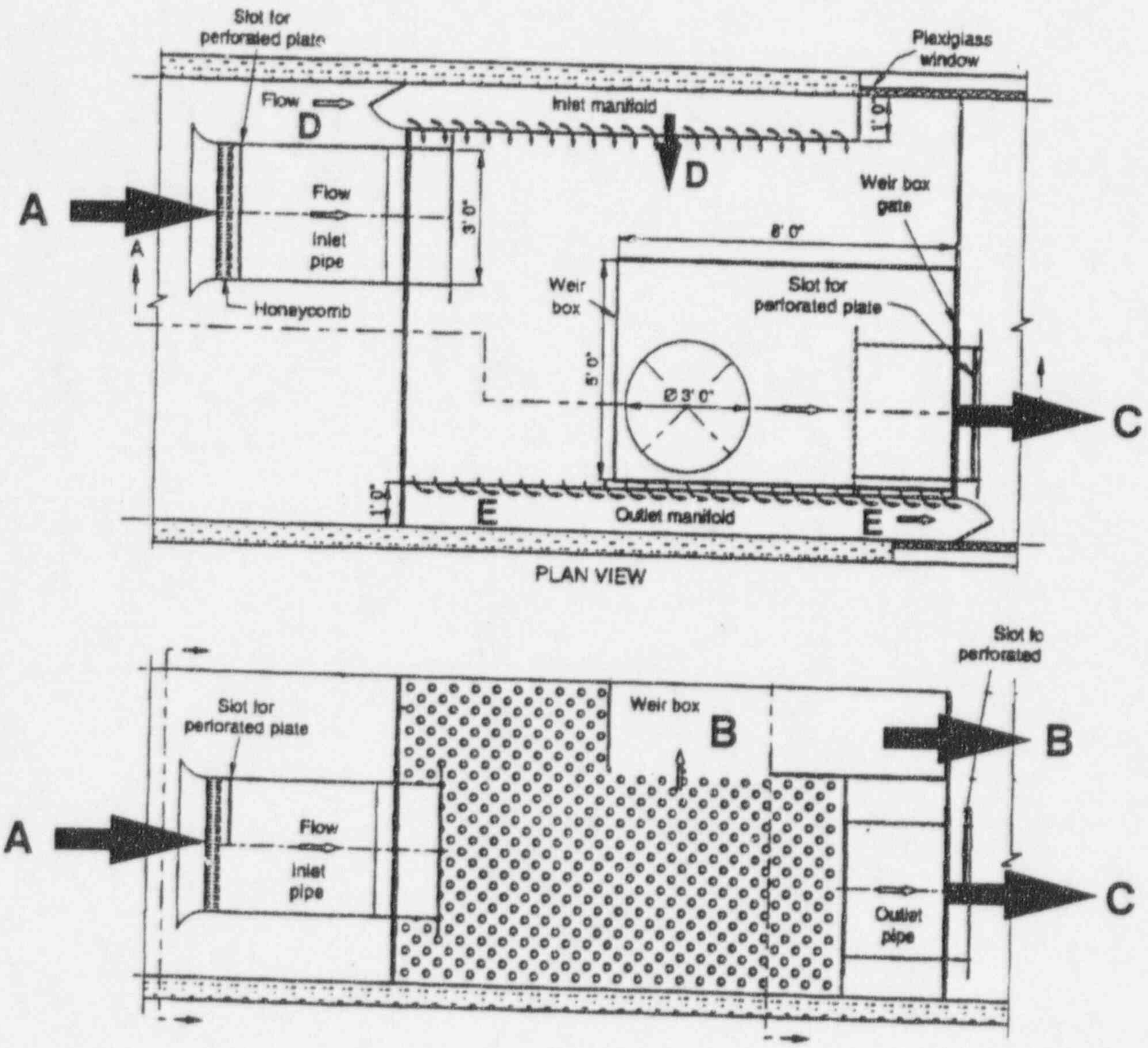


FIGURE 4.2 SCHEMATIZATION OF TEST FLOWS

the vertical withdrawal flows (B), by comparing the results with those from the Emergency Operation tests (EO-1 and EO-2).

b. Emergency Operation tests (EO-1 and EO-2) with both essential and non-essential service water flows, and limited longitudinal flows (A=B=C=D=20 cfs, E=0).

c. Normal Operation Tests (No. 1) with withdrawals from only the non-essential service water systems (N-ESWS), and inflows through the East Wall and limited longitudinal flows (A=13cfs, B=20 cfs, C=0, D=7, E=0).

d. Crossflow tests with only the longitudinal flow manifolds operating (A=B=C=0, D=E=20 cfs).

Tests were performed by releasing buoyant samples from specific locations on the bottom of the flume, or dropping negatively buoyant samples from the water surface at specific locations. Figure 4.3 shows typical release locations. Both natural samples (recovered from LaSalle) and artificial samples (made from a stiff foam with the average specific gravity adjusted with steel plates) were used. Typical natural samples were 0.5-1.25 ft^2 in area and 2 - 6 inches thick. All artificial samples were 10 inches X 10 inches X 2.5 inches (approximately). Typical specific gravities were in the 0.80 to 1.05 range. Since all debris recovered from LaSalle was found to be positively buoyant, the emphasis in these tests was on buoyant samples, with all 5 of the natural samples and 4 of the 5 artificial samples being positively buoyant. Samples in the 10 in. range were used since these are the smallest which could block the reducer to the main ESWS pump suction.

Results were as follows

a. Through flow (TF) A=C=20 cfs, B=D=E=0

A total of 34 releases were made, primarily with natural samples. Ten of the releases resulted in samples going into the ESWS outlet (C). The samples went to

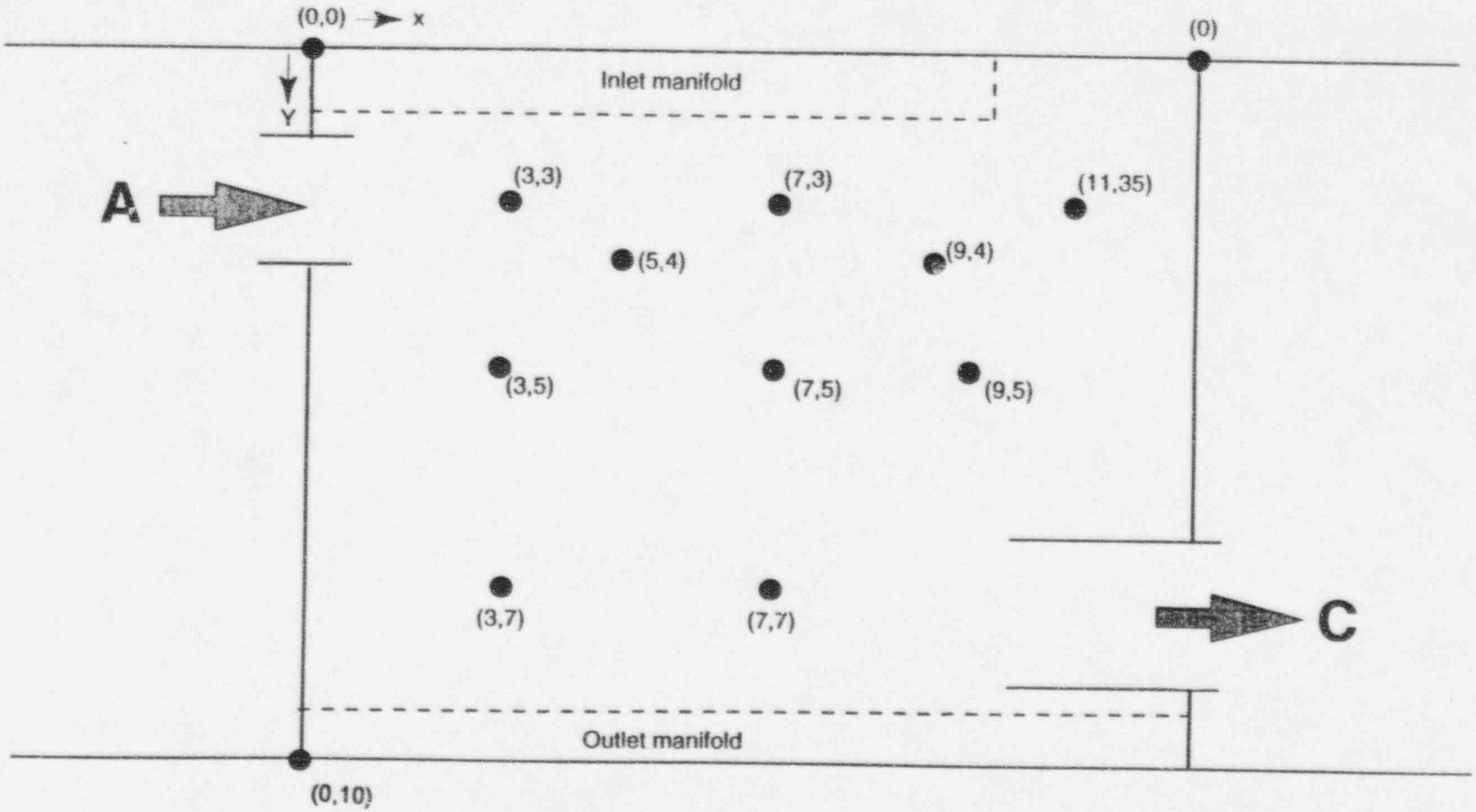


FIGURE 4.3 RELEASE LOCATIONS FOR FOAM SAMPLES

the surface in the remaining 24 tests. The tendency to go into the outlet did not seem to be strongly affected by the specific gravity of the sample.

b. Emergency Operation (EO-1) A=B=C=D=20, E=0. A total of 22 tests were performed, primarily with natural samples (17 out of 22 tests). Five of the tests resulted in samples going into the ESWS outlet (C). In most of the tests, the samples (14/22) went to the non-essential service water outlet (B). It was observed that in the bulk density range (ρ = 0.84 - 0.97 gm/cm^3), the sample density seemed to have very little effect on behavior, but as the density became very close to 1.0 gm/cm^3 the sample tended to be sucked into the ESWS.

A second series of tests (EO-2) were run using artificial samples including one sample with a $\rho \sim 1.05$ gm/cm^3. Forty-six (46) tests were performed with 8 samples going to the outlet. In general this occurred for releases within 5 - 6 feet of the outlet (7 cases out of 8).

A series of tests were run with all samples released about 30 inches from the bottom. All samples came to the surface, i.e. no samples were withdrawn by the ESWS outlet (C).

c. Normal Operation Tests (NO-1) A=13 cfs, B=20 cfs, C=0, D=7 cfs. D=0. The tests were run with the non-essential service water system (N-ESWS) running, with the required inflow split between the 36-inch inlet pipe (A) and the longitudinal flow. Seventeen tests were run, including 4 tests with samples which were slightly negatively buoyant, and it was concluded that

1) Samples with strong positive buoyancy will end up on the ceiling of the tunnel or will enter the N-ESWS and will be removed from the system. It is very unlikely that any samples will be sucked into the ESWS outlet (C) once they are on the ceiling.

2) Samples which are negatively buoyant, but close to neutral, move to the bottom, often traveling 10+ feet horizontally, remaining on the bottom, or migrating to low velocity areas. Occasionally, these samples can be caught in an upwelling current and go to the N-ESWS inlet (B).

d. Cross Flow Tests (CF1, CF2) D=E=20, A=B=C=0

These tests were performed to test the probability of material moving along the tunnel due to longitudinal currents which could arise when only one unit is operating (i.e. withdrawals occur only at one end of the tunnel).

Seventeen tests were performed using primarily natural samples. The samples were released from the bottom (positively buoyant) or surface (negatively buoyant), about 2 feet from the upstream manifold (D). In five cases the samples hit the downstream manifold before hitting the surface or bottom. In all other cases the samples reached the surface or bottom after traveling less than 6 feet horizontally.

Thirty tests were performed using artificial samples. In five cases the samples hit the downstream manifold. It was observed that for cases with a bulk density $\rho \leq 0.95$ gm/cm^3 there was no further movement when the samples contacted another surface, but for $\rho \approx 1.0$ gm/cm^3 movement continued with the sample rubbing against the surface.

4.2 Detailed Transport Tests

These tests involved a much larger number of releases (150-200) than the preliminary tests. Twenty samples in the 8-15 in. diameter range were selected from the 2 barrels of foam debris. Bulk densities of saturated samples were all in the range of 0.87-0.96 gm/cm^3. The majority of the samples were in the 0.9-0.95 gm/cm^3 range (see Table 2.1). For most tests only 10 of the natural samples were used. Ten artificial samples were also

created in the range of 0.78-0.985 gm/cm^3. The artificial samples were all approximately 10 in. X 10 in. X 2.5 in.

Tests were performed for similar basic flow conditions as for the preliminary tests.

- Through Flow i.e. inflow through the east wall and out the west wall (with and without longitudinal flows)
- Normal Flow i.e. flow in the east wall and out the top of the tunnel.
- Emergency Flows i.e. flow in the east wall and out both the top (N-ESWS) and west wall (ESWS)
- Cross Flow i.e. flow in the tunnel in the north-south direction.

Flow rates were chosen which were typical for both normal and emergency operating conditions. Details are given in the IIHR Report No. 247 (Reference 1). Each test consisted of releasing multiple samples from 8-10 locations in the test section. Typically 150-200 samples were released for each test condition. For conservatism, buoyant samples were released at the bottom so they traversed the water column in front of the ESWS outlet.

The bottom of the test section was marked with a grid to assist in obtaining test repeatability. The results were as follows:

a. The sample behavior appeared to fall into two density classes as follows:
   - Light (ρ=0.85=0.97 gm/cm^3) which included all the natural debris samples
   - Near Neutral (ρ=0.97-1.00 gm/cm^3)

   The light samples tended to move towards the surface and be trapped on the surface or go out the N-ESWS outlet. When they reached the surface or were trapped against the ceiling, they were not pulled down into the ESWS outlet. However, during transit to the surface, some samples can enter the ESWS outlet.

The near neutral samples tended to continue to move around in the water column and be withdrawn by either the N-ESWS or ESWS outlet.

b. For both the through flow tests and the emergency operation tests, i.e. with the ESWS outlet operating, the probability of a sample released within 8 feet of the ESWS outlet being withdrawn into the emergency system was about 1 in 3, slightly greater than the preliminary tests indicated. Assuming that debris pieces are randomly distributed on the bottom of the tunnel, the probability of withdrawal (into the ESWS) of a light sample, initially adhering to the bottom and being released during emergency operation, will be less than 1 in 10.

c. The normal operation tests indicate that 65-80% of the buoyant material released from the bottom within 5 feet of the non-essential outlet (N-ESWS) will be drawn into that outlet. However, samples released at a greater distance will tend to be trapped against the ceiling, and in general will not enter the N-ESWS outlet.

d. Cross transport tests show that most buoyant large (larger than 8 in.) foam pieces released from the bottom will tend to travel horizontally less than 10 feet before they are trapped against the ceiling. When they reach the ceiling, it is very unlikely that they will be withdrawn into the ESWS. Hence foam injection activity at the Unit 2 end of the flume should not adversely affect Unit 1.

4.3 Compound Transport Tests

Both the preliminary and detailed transport tests involved the release and tracking of one sample at the time, and required the sample to traverse the water column in front of the intake. In contrast, in the compound transport tests a large number of samples were released into the flume, allowed to find their equilibrium condition, and observed during emergency flow conditions. The samples consisted of 56 small (1.5-5 in.) and 47 large (6-15 in.) natural debris samples, plus 5 light artificial samples. The debris density (volume of foam debris/volume of conduit) was greater than at LaSalle. Tests were run for flows

through the emergency outlet of up to 25 cfs, i.e. 10% greater than the design flow. The tests were run until it appeared that no further samples would be ingested by either the ESWS or N-ESWS outlets. The results were as follows:

- No large natural samples were withdrawn.
- A small number (3) of the small samples were withdrawn into the ESWS outlet.
- One of the artificial samples, close to neutrally buoyant, was withdrawn into the ESWS outlet.

The tests strongly indicate that once the buoyant natural samples reach the ceiling of the conduit, the probability of the large pieces being withdrawn into the ESWS is small (~<2% based on the 47 samples). The probability of the smaller pieces being ingested by the ESWS is relatively low (of the order of 5% given the results of the 56 small samples).

Tests were run both with and without the N-ESWS outlet operating, and showed little difference in behavior except that a larger number (6) of small (fist size or smaller) samples tended to exit through the N-ESWS, indicating a probability of ingestion of about 10% (based on the 56 samples).

All samples which were withdrawn into the ESWS or N-ESWS outlet were captured and their bulk density measured, as shown in Table 2.2, and discussed in Section 2. The small foam pieces had the same density range as the larger (> 8 in.) pieces

4.4 Additional Tests

4.4.1 Laboratory Tests

Although the bulk density tests performed at IIHR on the foam debris recovered from LaSalle indicated buoyant material (bulk density <1 gm/cm^3), it appears that the large foam slab (approximately 8 ft. X 15 Ft. X 0.5-1 ft.) found on the floor of the tunnel could possibly have been negatively buoyant ($\rho > 1$ gm/cm^3) at some stage, and a significant number of tests were performed on artificial samples in the 1.01-1.1 gm/cm^3 range to ensure that samples in this range did not show an increased tendency to be withdrawn into the ESWS. A total of 10 dense samples were constructed as shown in Table 4.1, and

Density of Samples

Series	W_{sr} (g)	V_{sr} (ml)	ρ g/ml
ML0	3155	4042	0.781
ML1	3290	4005	0.821
ML2	3528	4157	0.849
ML3	3729	4106	0.908
ML4	3457	4039	0.856
ML5	3623	4050	0.895
ML6	3739	4150	0.901
ML7	3756	4070	0.923
ML8	3843	4061	0.946
ML9	3875	4087	0.948
ML10	4092	4148	0.986
MH1	3972	3787	1.049
MH2	4076	3941	1.034
MH3	4208	4098	1.027
MH4	4319	4119	1.048
MH5	4192	4103	1.022
MH6	4195	4128	1.016
MH7	4420	4210	1.050
MH8	4471	4219	1.060
MH9	4551	4254	1.070
MH10	4638	4230	1.097

Table 4.1 Bulk Density of Artificial Samples

parallel tests were performed both for the detailed transport tests and compound tests discussed in the previous two sections. For these tests, the samples were released from the surface and fell slowly through the water column. In most cases they went directly to the bottom, and either remained there immobile or moved slowly to one of the corners. In some cases they would enter the influence of either the N-ESWS or ESWS outlets during their descent and be withdrawn. This was particularly true for samples with a bulk density in the near neutral range 1.0-1.03 gm/cm^3. Overall, their tendency to be withdrawn by the ESWS was consistent with the behavior of the buoyant samples, whereas the tendency to be withdrawn by the N-ESWS was significantly less which is to be expected given the location of the N-ESWS intake in the tunnel ceiling.

4.5 Conclusions from Flume Tests

Based on four series of tests on foam particle transport in a replicated segment of the concrete tunnel at LaSalle, including multiple (~980) releases of foam debris in the flume, it can be stated that:

- If a large (> 8 in.), buoyant foam piece was assumed to be released from the bottom within about 8 feet of the ESWS intake, it would have a probability of about 30% of entering the intake during emergency operations. Assuming random distribution of the sealant material on the tunnel floor, this probability drops to about 10%.
- During normal operation, a large, buoyant sample assumed to be released from the bottom within a radius of about 5 feet of the N-ESWS intake would have a high probability of being ingested by the N-ESWS intake (~ 65-80%). Assuming sealant material was randomly distributed on the tunnel floor, the overall probability of ingestion drops to the 10-15% range.
- Buoyant, large (> 8 in.) debris floating against the tunnel ceiling appears to have very low probability (< 2%) of ingestion by the ESWS, and relatively low (< 5%) of ingestion by the N-ESWS.

- Longitudinal transport of large pieces of positively or negatively buoyant foam debris will be limited. If buoyant debris were released from the bottom, or non-buoyant material released from the ceiling, the debris will contact the ceiling or bottom of the tunnel within a relatively short distance (< 10 ft.) and in most cases further movement will be restricted, although in cases where the debris has a near-neutral buoyancy, further slow movement of the debris in contact with the tunnel surface was observed.

- Tests on heavy ($\rho > 1$ gm/cm^3) debris showed that it had a similar (slightly lower) probability of entering the ESWS outlet, and a much smaller probability of entering the N-ESWS outlet as compared to the buoyant debris.

REFERENCES

1. Jain, S. C. (1996), "Laboratory Tests with Polyurethane Resin and Resultant Foam," IIHR Limited Distribution Report No. 247, Iowa Institute of Hydraulic Research, The University of Iowa, September 1996

2. Whelan, A. and Nixon, W. A. (1996), "Mechanical Testing of Expanded Polyurethane Foam," IIHR Limited Distribution Report No. 246, Iowa Institute of Hydraulic Research, The University of Iowa, September 1996