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FOAM TRANSPORT IN THE LASALLE SERVICE WATER TUNNEL

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1.0 INTRODUCTION

In May and June of 1996 a polyurethane foam mixture was injected into the LaSalle service water tunnel. This tunnel is the supply for the emergency service water system (ESWS) as well as the Non-Essential Service Water System (N-ESWS). Subsequently, foam pieces were observed to begin plugging some of the strainers for the non-essential service water system, which take suction from the top of the tunnel. Investigations into the cause of this showed a substantial amount of foam material in the N-ESWS. Once this was determined, there were experimental investigations performed at the Iowa Institute for Hydraulic Research (IIHR) to examine the response of polyurethane foam pieces to anticipated flow conditions in the service water tunnel both during normal and emergency situations.

This report analyzes the experimental information as well as the flow distribution in the IIHR experiments in relationship to the LaSalle service water tunnel. In particular, the behavior observed in the Iowa experiments is characterized to determine whether the behavior overstates the likelihood that such foam particulate could enter into the ESWS. This analysis provides the technical foundation for the application of the IIHR experimental data to the Probabilistic Risk Assessment (PRA), i.e. possible increase in core damage frequency that could have been caused by the presence of this material in the service water tunnel.

2.0 ANALYSIS

The issue with the foam response in the LaSalle service water tunnel is the duration over which the material was neutrally buoyant. As the material is introduced into the tunnel, it is negatively buoyant with a density of approximately 1.04 gm/cm^3. After the curing process the expanded material has a density typically in the range of 0.9 - 0.95 gm/cm^3, with some small samples observed to be about 0.98 gm/cm^3. This curing process appears to be complete within approximately ten minutes and, during this time, the material is essentially neutrally buoyant as the experiments have illustrated that samples rise and sink multiple times during the curing interval. Only small particles exhibit this behavior. Once these become attached to a significant piece they are then either positively buoyant with a specific gravity in the range of 0.98 to 0.8

or negatively buoyant and remain on the bottom. Once the curing process is completed, the material is either floating on the upper surface or negatively buoyant if the curing process was water starved.

It is helpful to develop a perspective of the effective rise velocities for those pieces which are positively buoyant and compare these to the calculated flow distribution within the Iowa Institute of Hydraulic Research (IIHR) experiments, as well as the flow distribution in the service water tunnel. The rise velocity for a piece of foam can be assessed by comparing the buoyant forces with the turbulent drag forces as given by

$$g\,(\rho_w - \rho_F)\,V_F = C_D\,A_F\,\frac{\rho_w\,U_R^2}{2} \tag{1}$$

In this expression, g is the acceleration of gravity, ρ_w is the water density, ρ_F is the foam density, V_F is the volume of the foam particle and A_F is the effective cross-sectional area of the rising piece. As a conservatism, let us assume that this foam mass has a disk-like configuration such that the volume of the foam can be expressed by

$$V_F = A_F\,L_F \tag{2}$$

where L_F is the effective thickness. Using this, the rise velocity is given then by

$$U_R = \left\{\frac{2\,g\,L_F}{C_D}\left(1 - \frac{\rho_F}{\rho_w}\right)\right\}^{1/2} \tag{3}$$

where C_D is the drag coefficient for the rising disk. As illustrated in Figure 1, which is taken from Vennard (1954), the drag coefficient for a disk aligned perpendicular to the velocity is essentially unity. This is true for Reynolds numbers of about 1000 or greater and for the applications of interest here the Reynolds numbers are 30,000 - 40,000. Thus, the rise velocity calculation reduces to:

$$U_R = \left\{2\,g\,L_F\left(1 - \frac{\rho_F}{\rho_w}\right)\right\}^{1/2} \tag{4}$$

Using this relationship and assuming a four inch (0.1 m) effective thickness of the example foam particle, with a specific gravity of 0.95, the rise velocity is approximately 1 ft/sec (0.3 m/sec). As illustrated by the above equation, this rise velocity only changes as the square root of the effective length and the effective buoyancy. For example, if we were to consider the specific gravity to be 0.98, the rise velocity would be 0.67 ft/sec (0.2 m/sec).

These rise velocities can be compared with the transverse velocities in the flow for both the IIHR experiments and the LaSalle service water tunnel. These systems were evaluated assuming a two-dimensional flow field (potential flow solution) to determine the relevance (and the level of conservatism) in the IIHR experiments in relation to the LaSalle tunnel behavior (Epstein, 1996). These two-dimensional calculations were performed by assuming that the incoming flow is through a slit configuration. In reality, the system is three-dimensional which would result in the flows having somewhat higher velocities along the central core which is approximately a straight line between the incoming location and the discharge port. However, these two-dimensional analyses are sufficient to illustrate the fundamental relationship of the IIHR experiments to the LaSalle service water tunnel configuration.

The results of the two-dimensional flow application to the IIHR tests for a dimensionless incoming flow of unity and an exit flow of unity is illustrated in Figure 2. These values can be multiplied by a specified inlet flow, which would be 3 ft/sec in the Iowa test (approximately 1 m/sec). This approximates the flow velocity distribution in the experiments. In particular, the results shown in Figure 2 are for no transverse flow and only flow coming in through the suction port (designated A in the experiments) and out through the discharge port (designated C in the experiments).

As illustrated in Figure 2, the dimensionless velocity vectors have magnitudes typically in the range of .4 to .6 which means that for an assumed incoming velocity of 3 ft/sec the transverse velocity is about 1.2 to 1.8 ft/sec (0.4 to 0.6 m/sec). These velocities are comparable to but greater than the rise velocities for typical foam pieces used in the experiments. As a result, buoyant material released from the floor could be effectively transported in a lateral direction toward the discharge port.

With the combination of rise velocity calculation and the approximate transverse velocity created in the IIHR experiments, we can calculate the zone where foam particles release from the floor would have a strong possibility of being swept into the discharge piping. In particular, using the vector addition illustrated in Figure 3 we can calculate the distance away from the discharge pipe where particles would not rise sufficient fast to avoid being swept into the discharge flow. Taking the rise velocity to be 1 ft/sec as calculated previously in the transverse velocity to be about 1.2 ft/sec (which corresponds to a dimensionless velocity vector of 0.4), the angle θ in Figure 3 becomes approximately 40°. In the IIHR test, the top of the discharge pipe is 4 ft above the bottom of the hydraulic tank. Consequently, the region of influence to find in Figure 3 would be approximately 5 ft. As a note of caution, the velocity vectors shown in Figure 2 indicate that the transverse velocity could be greater than 1.2 in some regions and it is also possible that the rise velocity is less than 1 ft/sec. Either of these would extend the region of influence. However, the simple vector addition shown in Figure 3 enables one to identify those locations where foam particles submerged to the floor would not rise sufficiently rapidly to escape the discharge flow. This region of influence is in agreement with that deduced by the experimenters.

Similar two-dimensional calculations are shown in Figure 4 for the LaSalle service water tunnel. In the case addressed, flow comes in through one location and is exhausted through another location that is almost directly across the channel. Here again, the calculations were performed in a two-dimensional manner and represent the flow in and out of slit openings as dimensionless values that are multiplied by the incoming velocity. As illustrated in the calculation, the dimensionless flow velocities are less in the central configuration and in fact less than the rise velocity that would be anticipated for significant size pieces. Therefore, the region of influence would be smaller than that observed in the IIHR tests. Hence, from this configuration we conclude that these experiments are a conservative representation of the foam behavior segments in the LaSalle service water tunnel.

Another calculation was performed to parametrically investigate the influence of an adjacent intake port. In these calculations, the incoming flow was specified for the two ports and was parametrically varied from 0.8 - 0.2 for the distribution between the favored and more

removed location to a situation in which the flow is evenly distributed, i.e. 0.5 and 0.5. These parametric calculations are illustrated in Figures 5, 6 and 7 respectively. As expected, these show that the result of some flow coming through an adjacent port is to further reduce the flows in the central region of the tunnel near the discharge port. In particular, the transverse velocities are now in the range of one-half of the rise velocity. Therefore, even those pieces with marginal buoyancy (0.98) rise to the surface before they could be transported across half of the channel width.

As discussed previously, some of the foam material was found on the floor of the service tunnel and was thus negatively buoyant. It is interesting to perform calculations on the extent of lift that would be created by the induced service water tunnel flows to assess the extent of negative buoyancy that would be necessary to impose these lift forces. Using the information in Figure 4, there is a dimensionless velocity of 0.22, as a reasonable average in the central region which corresponds to an upward lift pressure

$$\left(\Delta P = \frac{\rho_w U^2}{2}\right) \tag{5}$$

of 3.5×10^3 psi (24 Pa). We can use this to determine the extent of negative buoyancy required to impose the lift using the expression

$$\Delta P = \frac{F}{A} - \Delta\rho \, L_\mu \, g \tag{6}$$

or solving for the density difference

$$\Delta\rho = \frac{\Delta P}{L_\mu \, g} \tag{7}$$

Using an effective thickness for the foam of 4 in. (0.1 m) we determine that a specific gravity of 1.024 is sufficient to oppose the lift configuration assuming a perfect lift geometry.

3.0 CONCLUSIONS

From the analyses carried out with respect to rise velocities for foam pieces, the two-dimensional velocity distribution in the IIHR test, the velocity distributions in the LaSalle service water tunnel and the lift calculations for pieces that could be lying on the floor of the service tunnel, the following conclusions can be drawn.

1. The rise velocities for foam pieces that are of sufficient size to plug the suction ports or the strainer intake for the emergency service water system have rise velocities of approximately 1 ft/sec and would rise to the top of the service water tunnel in about 10 secs.

2. The IIHR experiments were performed in a way that is a conservative representation of the LaSalle service water tunnel flow distribution. More specifically, the potential for ingesting foam particulate in the discharge port is greater in the IIHR experiments than would be the case for the LaSalle service water tunnel. Therefore, information taken directly from the Iowa experiments and used in the PRA analyses overstates the likelihood that material could be ingested into the emergency service water system.

3. The observations from the Iowa tests are readily understandable in terms of the transverse and rise velocities and the possible path that a foam particle would follow if it was submerged to the floor of the test apparatus and released in the flow stream. These analyses tend to show that there would be a region of influence of approximately 5 ft. around the discharge port. This is in agreement with the observations from the Iowa test.

4. Given the substantial rise velocity and the two-dimensional velocity vectors in the Iowa test, those particles which rise to the top of the apparatus will remain there. This was also observed in the experiments.

5. The assessment of the potential flow for the LaSalle service water tunnel indicates that the velocity vectors from the entry of the water into the service water tunnel and out through the discharge port are considerably less than those observed in the Iowa test. Thus, the Iowa experiments conservatively represent the transverse flow in the LaSalle system. As a result, there is an even smaller region of influence for foam particulate in the LaSalle service water system than was observed in the Iowa test. Furthermore, with the reduced velocities, there is a greater potential for particles which rise to the top of the service water tunnel and remain there.

6. Parametric analyses for varying incoming velocities through parallel inlet ports show that the participation of an adjacent inlet port further reduces the velocities in the service water tunnel even if only 20% of the incoming flow is entering through the adjacent port.

7. Analyses of the lift forces on negatively buoyant pieces must be less than approximately 1.02 before lift forces would move the configuration off the floor of the service water tunnel given a perfect lift configuration.

In summary, the analyses of the LaSalle service water tunnel and the IIHR test show that the examinations which have been performed overstate the likelihood of foam particles being drawn into the discharge port. Thus, the analyses that have been performed with respect to the likelihood of initiating a core damage event are a conservative representation (overstatement) of the likelihood of such an event could being initiated.

4.0 REFERENCES

Epstein, 1996 memo to R. E. Henry on the Two-dimensional Potential Flow Solution.

Vennard, J. K., 1954, Elementary Fluid Mechanics, Third Edition, John Wiley & Sons, New York.

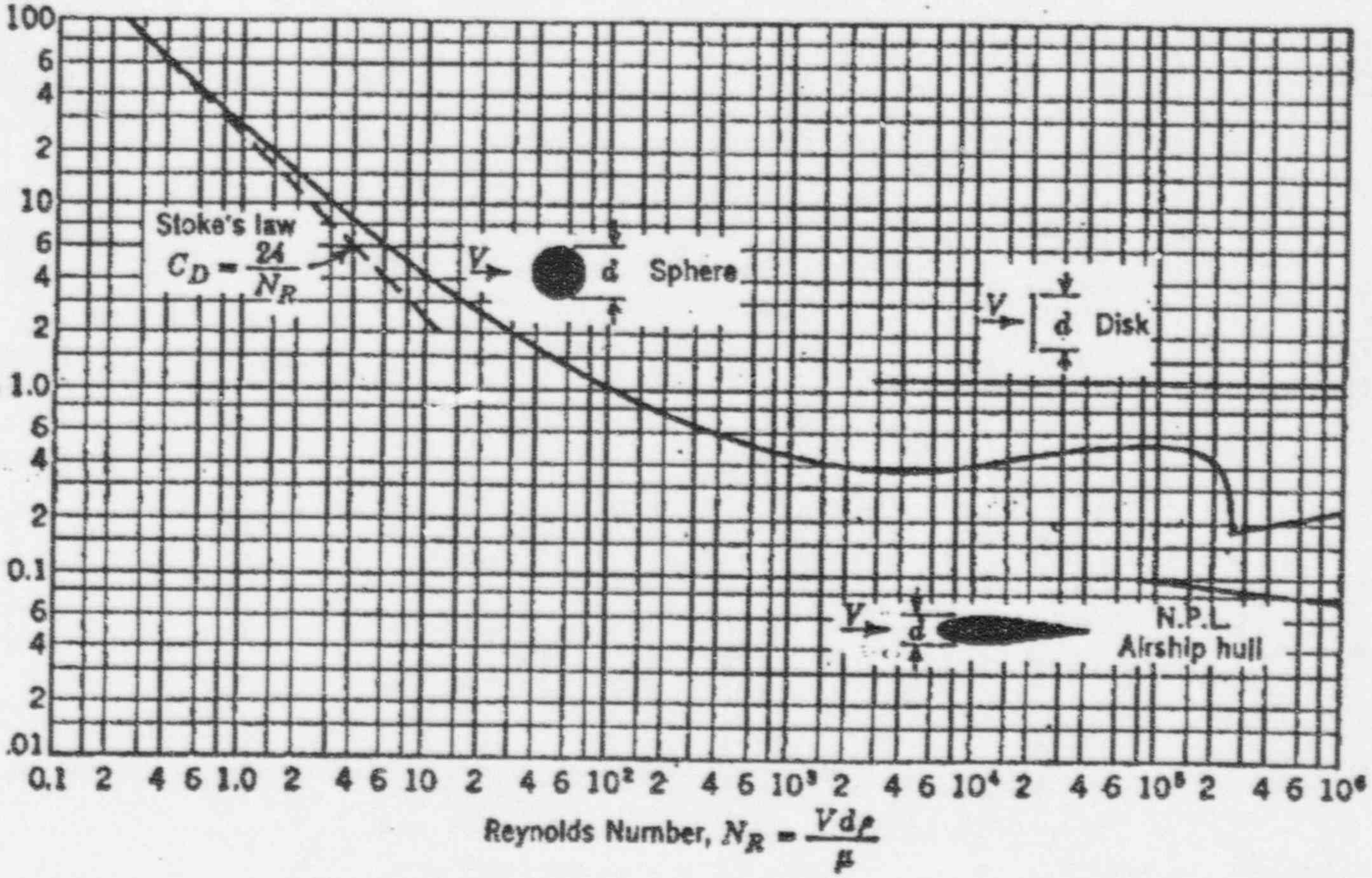

Figure 1 Drag coefficients for sphere, disk, and streamlined body.

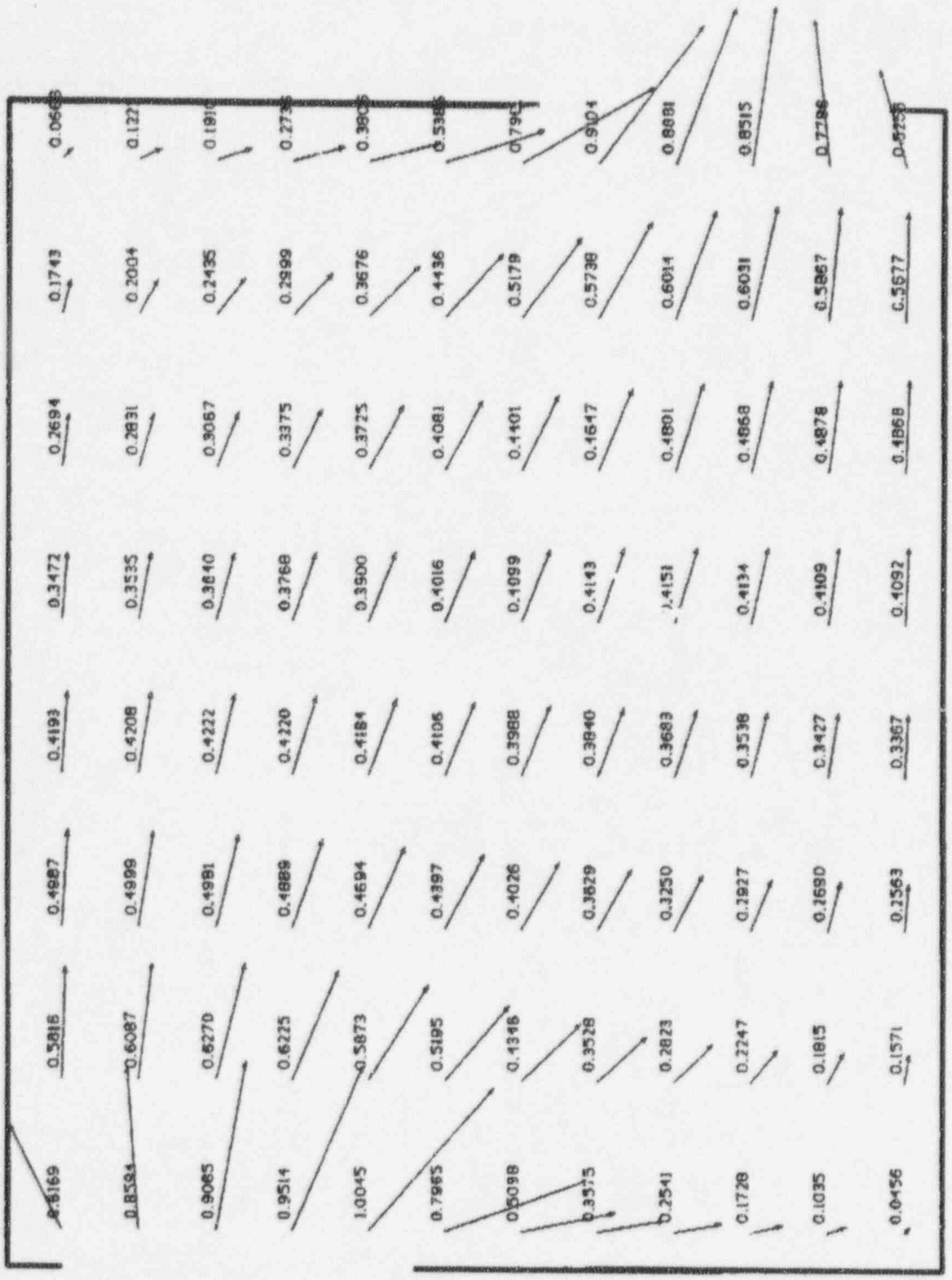

Figure 2 Plan view showing the two-dimensional velocity distribution for the IIHR test configuration.

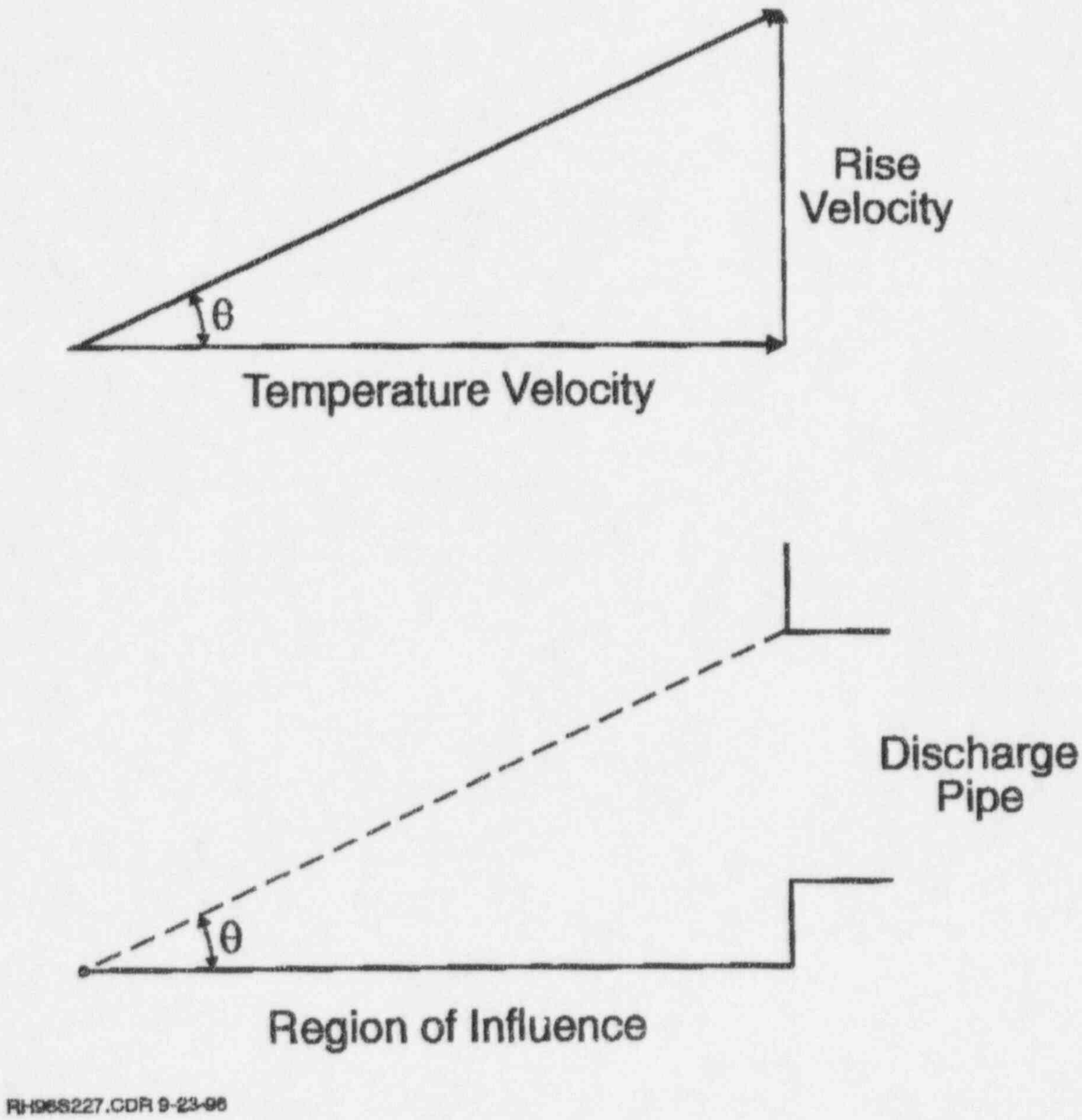

Figure 3 Region of influence where foam particles would be pulled into the discharge piping.

	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	
	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	
	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	
	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0000
	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	
	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0006	
0.0000	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	
	0.0014	0.0014	0.0014	0.0014	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	
	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	
	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	
	0.0053	0.0053	0.0053	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	0.0054	
	0.0075	0.0075	0.0075	0.0075	0.0076	0.0076	0.0076	0.0077	0.0077	0.0077	0.0078	
	0.0105	0.0105	0.0106	0.0106	0.0107	0.0108	0.0109	0.0109	0.0110	0.0111	0.0111	
	0.0147	0.0147	0.0148	0.0149	0.0151	0.0152	0.0154	0.0156	0.0158	0.0159	0.0160	
	0.0205	0.0205	0.0207	0.0209	0.0212	0.0215	0.0719	0.0223	0.0227	0.0230	0.0232	
	0.0283	0.0284	0.0287	0.0291	0.0296	0.0303	0.0310	0.0319	0.0327	0.0335	0.0340	
	0.0389	0.0390	0.0395	0.0401	0.0411	0.0424	0.0439	0.0457	0.0475	0.0492	0.0505	
	0.0528	0.0531	0.0538	0.0549	0.0565	0.0588	0.0618	0.0654	0.0696	0.0737	0.0769	
	0.0711	0.0715	0.0724	0.0740	0.0766	0.0808	0.0857	0.0930	0.1022	0.1129	0.1225	
	0.0947	0.0951	0.0960	0.0979	0.1013	0.1070	0.1158	0.1290	0.1487	0.1766	0.2112	
	0.1254	0.1253	0.1254	0.1266	0.1300	0.1369	0.1492	0.1699	0.2050	0.2678	0.3963	
	0.1667	0.1648	0.1617	0.1595	0.1605	0.1668	0.1797	0.2048	0.2510	0.3417	0.5456	
	0.2279	0.2197	0.2065	0.1950	0.1888	0.1896	0.1994	0.2213	0.2630	0.3417	0.5105	1.0000
	0.3420	0.3050	0.2606	0.2285	0.2094	0.2014	0.2033	0.2156	0.2410	0.2822	0.3394	
	0.7422	0.4333	0.3113	0.2491	0.2153	0.1981	0.1919	0.1943	0.2040	0.2192	0.2351	
1.0000	0.8709	0.4841	0.3181	0.2413	0.2014	0.1798	0.1690	0.1651	0.1660	0.1697	0.1737	
	0.7928	0.3827	0.2620	0.2029	0.1701	0.1510	0.1400	0.1341	0.1316	0.1310	0.1313	
	0.2615	0.2232	0.1814	0.1516	0.1317	0.1188	0.1102	0.1049	0.1019	0.1003	0.0995	
	0.1388	0.1311	0.1186	0.1063	0.0963	0.0888	0.0834	0.0796	0.0772	0.0757	0.0749	
	0.0845	0.0823	0.0781	0.0731	0.0685	0.0645	0.0614	0.0591	0.0574	0.0564	0.0558	
	0.0547	0.0539	0.0523	0.0503	0.0481	0.0461	0.0445	0.0431	0.0421	0.0414	0.0410	

Figure 4 Plan view showing the two-dimensional distribution for the LaSalle service water tunnel with flow in one port and out one port.

	0.0019	0.0019	0.0019	0.0018	0.0018	0.0018	0.0018	0.0017	0.0017	0.0017	0.0017	
	0.0027	0.0027	0.0027	0.0026	0.0026	0.0025	0.0025	0.0024	0.0024	0.0024	0.0023	
	0.0039	0.0039	0.0039	0.0038	0.0037	0.0036	0.0035	0.0034	0.0033	0.0033	0.0033	
	0.0058	0.0057	0.0056	0.0055	0.0053	0.0051	0.0049	0.0047	0.0046	0.0045	0.0045	
	0.0087	0.0086	0.0083	0.0079	0.0075	0.0072	0.0068	0.0066	0.0063	0.0062	0.0061	
	0.0136	0.0132	0.0125	0.0117	0.0108	0.0101	0.0094	0.0090	0.0086	0.0083	0.0082	
	0.0225	0.0213	0.0193	0.0172	0.0154	0.0140	0.0128	0.0120	0.0114	0.0110	0.0107	0.0000
	0.0422	0.0369	0.0303	0.0252	0.0215	0.0189	0.0170	0.0157	0.0148	0.0142	0.0136	
	0.1211	0.0668	0.0461	0.0352	0.0287	0.0248	0.0218	0.0199	0.0186	0.0178	0.0173	
0.2000	0.1724	0.0942	0.0606	0.0446	0.0357	0.0302	0.0267	0.0243	0.0227	0.0216	0.0211	
	0.1862	0.0950	0.0652	0.0498	0.0407	0.0349	0.0311	0.0285	0.0267	0.0256	0.0250	
	0.0862	0.0741	0.0605	0.0503	0.0431	0.0382	0.0347	0.0322	0.0305	0.0294	0.0288	
	0.0623	0.0591	0.0536	0.0482	0.0436	0.0400	0.0373	0.0354	0.0340	0.0330	0.0325	
	0.0514	0.0503	0.0480	0.0455	0.0430	0.0409	0.0383	0.0380	0.0371	0.0364	0.0361	
	0.0447	0.0444	0.0437	0.0428	0.0420	0.0413	0.0407	0.0403	0.0399	0.0397	0.0396	
	0.0395	0.0396	0.0400	0.0404	0.0409	0.0414	0.0420	0.0425	0.0429	0.0432	0.0434	
	0.0347	0.0352	0.0364	0.0379	0.0398	0.0416	0.0434	0.0449	0.0462	0.0472	0.0478	
	0.0294	0.0304	0.0326	0.0355	0.0387	0.0421	0.0452	0.0480	0.0504	0.0522	0.0533	
	0.0231	0.0240	0.0284	0.0331	0.0382	0.0432	0.0481	0.0524	0.0561	0.0589	0.0607	
	0.0151	0.0185	0.0245	0.0315	0.0387	0.0458	0.0526	0.0589	0.0643	0.0686	0.0714	
	0.0052	0.0132	0.0226	0.0322	0.0416	0.0509	0.0600	0.0687	0.0765	0.0830	0.0874	
	0.0093	0.0166	0.0268	0.0376	0.0486	0.0599	0.0715	0.0832	0.0949	0.1054	0.1130	
	0.0264	0.0307	0.0389	0.0493	0.0609	0.0738	0.0882	0.1043	0.1223	0.1410	0.1570	
	0.0482	0.0514	0.0580	0.0674	0.0790	0.0930	0.1103	0.1322	0.1609	0.1985	0.2424	
	0.0761	0.0784	0.0834	0.0912	0.1018	0.1160	0.1355	0.1635	0.2062	0.2778	0.4173	
	0.1127	0.1133	0.1153	0.1196	0.1272	0.1395	0.1586	0.1889	0.2398	0.3350	0.5431	
	0.1052	0.1609	0.1548	0.1509	0.1517	0.1585	0.1729	0.1985	0.2424	0.3218	0.4889	1.0000
	0.2599	0.2332	0.2022	0.1811	0.1702	0.1682	0.1745	0.1898	0.2164	0.2576	0.3134	
	0.5837	0.3412	0.2474	0.2007	0.1767	0.1656	0.1636	0.1686	0.1797	0.1954	0.2112	
0.8000	0.6961	0.3881	0.2568	0.1968	0.1663	0.1505	0.1434	0.1419	0.1443	0.1487	0.1530	
	0.6395	0.3105	0.2138	0.1669	0.1411	0.1285	0.1184	0.1145	0.1132	0.1134	0.1141	
	0.2138	0.1829	0.1493	0.1254	0.1096	0.0994	0.0930	0.0891	0.0870	0.0860	0.0856	
	0.1143	0.1082	0.0982	0.0883	0.0804	0.0745	0.0703	0.0674	0.0656	0.0645	0.0640	
	0.0701	0.0683	0.0649	0.0609	0.0572	0.0541	0.0517	0.0499	0.0487	0.0478	0.0474	
	0.0455	0.0449	0.0436	0.0420	0.0403	0.0387	0.0374	0.0364	0.0356	0.0351	0.0348	

Figure 5 Plan view showing the two-dimensional distribution for the LaSalle service water tunnel with 80% flow in one port and 20% flow in an adjacent port.

	0.0037	0.0037	0.0037	0.0036	0.0036	0.0035	0.0035	0.0034	0.0034	0.0034	0.0033	
	0.0053	0.0053	0.0053	0.0052	0.0051	0.0050	0.0049	0.0048	0.0047	0.0047	0.0047	
	0.0078	0.0077	0.0076	0.0074	0.0073	0.0071	0.0068	0.0067	0.0066	0.0065	0.0065	
	0.0114	0.0113	0.0111	0.0108	0.0104	0.0100	0.0097	0.0094	0.0092	0.0090	0.0089	
	0.0172	0.0170	0.0164	0.0157	0.0149	0.0142	0.0135	0.0130	0.0126	0.0123	0.0121	
	0.0269	0.0262	0.0248	0.0231	0.0214	0.0199	0.0187	0.0177	0.0170	0.0165	0.0162	
	0.0445	0.0422	0.0382	0.0341	0.0305	0.0276	0.0254	0.0237	0.0225	0.0217	0.0212	0.0000
	0.0839	0.0733	0.0602	0.0500	0.0426	0.0374	0.0336	0.0310	0.0291	0.0279	0.0272	
	0.2416	0.1332	0.0917	0.0699	0.0569	0.0486	0.0430	0.0392	0.0368	0.0349	0.0340	
0.4000	0.3447	0.1883	0.1209	0.0887	0.0708	0.0598	0.0526	0.0478	0.0445	0.0424	0.0412	
	0.3735	0.1906	0.1306	0.0994	0.0809	0.0691	0.0613	0.055[illegible]	0.0523	0.0500	0.0486	
	0.1743	0.1497	0.1217	0.1008	0.0860	0.0756	0.0683	0.0631	0.0595	0.0571	0.0558	
	0.1273	0.1204	0.1066	0.0871	0.0872	0.0793	0.0733	0.0689	0.0657	0.0636	0.0624	
	0.1066	0.1039	0.0986	0.0924	0.0863	0.0811	0.0768	0.0735	0.0711	0.0694	0.0684	
	0.0947	0.0935	0.0911	0.0880	0.0848	0.0818	0.0792	0.0772	0.0757	0.0746	0.0740	
	0.0865	0.0861	0.0852	0.0841	0.0830	0.0819	0.0810	0.0803	0.0798	0.0794	0.0792	
	0.0798	0.0799	0.0802	0.0806	0.0811	0.0818	0.0825	0.0832	0.0838	0.0843	0.0847	
	0.0734	0.0740	0.0752	0.0770	0.0791	0.0815	0.0839	0.0863	0.0883	0.0896	0.0909	
	0.0665	0.0675	0.0696	0.0730	0.0770	0.0813	0.0858	0.0900	0.0938	0.0968	0.0987	
	0.0583	0.0599	0.0634	0.0685	0.0746	0.0814	0.0883	0.0951	0.1012	0.1061	0.1094	
	0.0480	0.0506	0.0560	0.0635	0.0723	0.0820	0.0921	0.1022	0.1117	0.1197	0.1251	
	0.0352	0.0394	0.0478	0.0585	0.0708	0.0840	0.0979	0.1125	0.1270	0.1402	0.1499	
	0.0192	0.0275	0.0407	0.0555	0.0713	0.0882	0.1066	0.1270	0.1495	0.1727	0.1924	
	0.0047	0.0223	0.0400	0.0578	0.0761	0.0959	0.1184	0.1457	0.1801	0.2242	0.2748	
	0.0271	0.0362	0.0513	0.0682	0.0865	0.1071	0.1322	0.1654	0.2136	0.2918	0.4400	
	0.0587	0.0639	0.0739	0.0868	0.1019	0.1703	0.1445	0.1789	0.2333	0.3315	0.5427	
	0.1025	0.1032	0.1057	0.1108	0.1192	0.1319	0.1507	0.1791	0.2246	0.3038	0.4681	1.0000
	0.1777	0.1621	0.1452	0.1358	0.1336	0.1376	0.1479	0.1656	0.1932	0.2339	0.2877	
	0.4252	0.2496	0.1843	0.1536	0.1392	0.1344	0.1363	0.1438	0.1561	0.1720	0.1874	
0.6000	0.5215	0.2925	0.1960	0.1528	0.1318	0.1218	0.1183	0.1191	0.1227	0.1278	0.1324	
	0.4863	0.2385	0.1658	0.1310	0.1124	0.1022	0.0970	0.0850	0.0949	0.0958	0.0969	
	0.1662	0.1427	0.1172	0.0993	0.0877	0.0809	0.0759	0.0734	0.0722	0.0718	0.0717	
	0.0900	0.0853	0.0777	0.0704	0.0645	0.0602	0.0572	0.0552	0.0540	0.0534	0.0531	
	0.0556	0.0543	0.0517	0.0488	0.0460	0.0437	0.0420	0.0407	0.0399	0.0393	0.0390	
	0.0364	0.0350	0.0349	0.0337	0.0324	0.0313	0.0303	0.0296	0.0291	0.0287	0.0285	

Figure 6 Plan view showing the two-dimensional distribution for the LaSalle service water tunnel with 60% flow in one port and 40% flow in an adjacent port.

	0.0046	0.0046	0.0046	0.0045	0.0045	0.0044	0.0043	0.0043	0.0042	0.0042	0.0042	
	0.0066	0.0066	0.0065	0.0065	0.0063	0.0062	0.0061	0.0060	0.0059	0.0059	0.0058	
	0.0097	0.0096	0.0095	0.0093	0.0091	0.0088	0.0086	0.0084	0.0083	0.0081	0.0081	
	0.0143	0.0141	0.0138	0.0134	0.0130	0.0125	0.0121	0.0117	0.0114	0.0112	0.0111	
	0.0215	0.0212	0.0205	0.0196	0.0186	0.0177	0.0169	0.0162	0.0157	0.0153	0.0151	
	0.0335	0.0327	0.0309	0.0288	0.0267	0.0248	0.0233	0.0221	0.0212	0.0205	0.0201	
	0.0556	0.0527	0.0477	0.0425	0.0381	0.0344	0.0317	0.0296	0.0280	0.0270	0.0264	0.0000
	0.1047	0.0915	0.0751	0.0623	0.0532	0.0466	0.0419	0.0386	0.0363	0.0348	0.0339	
	0.3018	0.1663	0.1145	0.0873	0.0710	0.0606	0.0536	0.0489	0.0456	0.0435	0.0423	
0.5000	0.4309	0.2353	0.1510	0.1108	0.0884	0.0746	0.0656	0.0595	0.0554	0.0528	0.0513	
	0.4672	0.2303	0.1633	0.1242	0.1011	0.0863	0.0764	0.0697	0.0651	0.0621	0.0605	
	0.2183	0.1875	0.1524	0.1260	0.1074	0.0943	0.0851	0.0785	0.0739	0.0710	0.0693	
	0.1598	0.1511	0.1364	0.1218	0.1089	0.0990	0.0914	0.0857	0.0816	0.0789	0.0774	
	0.1342	0.1307	0.1239	0.1158	0.1080	0.1012	0.0957	0.0913	0.0881	0.0859	0.0846	
	0.1197	0.1101	0.1148	0.1106	0.1062	0.1021	0.0986	0.0957	0.0935	0.0920	0.0911	
	0.1100	0.1093	0.1079	0.1061	0.1041	0.1022	0.1006	0.0993	0.0983	0.0976	0.0972	
	0.1024	0.1023	0.1022	0.1021	0.1020	0.1020	0.1022	0.1024	0.1027	0.1030	0.1032	
	0.0955	0.0958	0.0967	0.0981	0.0997	0.1017	0.1037	0.1056	0.1074	0.1088	0.1097	
	0.0882	0.0891	0.0910	0.0937	0.0972	0.1012	0.1053	0.1093	0.1129	0.1158	0.1177	
	0.0799	0.0812	0.0843	0.0888	0.0943	0.1006	0.1073	0.1140	0.1201	0.1251	0.1285	
	0.0697	0.0718	0.0763	0.0828	0.0910	0.1002	0.1102	0.1203	0.1301	0.1384	0.1441	
	0.0571	0.0602	0.0668	0.0761	0.0874	0.1002	0.1142	0.1291	0.1443	0.1582	0.1685	
	0.0414	0.0464	0.0564	0.0693	0.0843	0.1010	0.1198	0.1410	0.1647	0.1894	0.2104	
	0.0223	0.0320	0.0474	0.0647	0.0882	0.1035	0.1270	0.1555	0.1917	0.2381	0.2914	
	0.0055	0.0260	0.0461	0.0658	0.0862	0.1083	0.1348	0.1694	0.2195	0.3000	0.4520	
	0.0319	0.0422	0.0584	0.0759	0.0943	0.1150	0.1407	0.1764	0.2318	0.3311	0.5432	
	0.0712	0.0755	0.0835	0.0937	0.1060	0.1213	0.1418	0.1712	0.2169	0.2956	0.4582	1.0000
	0.1387	0.1271	0.1180	0.1148	0.1169	0.1238	0.1359	0.1545	0.1822	0.2224	0.2749	
	0.3460	0.2041	0.1534	0.1308	0.1213	0.1196	0.1239	0.1318	0.1446	0.1604	0.1756	
0.5000	0.4343	0.2449	0.1859	0.1312	0.1149	0.1077	0.1060	0.1079	0.1121	0.1175	0.1221	
	0.4097	0.2025	0.1420	0.1132	0.0982	0.0902	0.0864	0.0853	0.0858	0.0871	0.0883	
	0.1423	0.1225	0.1012	0.0863	0.0767	0.0708	0.0674	0.0656	0.0648	0.0647	0.0648	
	0.0778	0.0739	0.0675	0.0614	0.0565	0.0530	0.0507	0.0491	0.0483	0.0478	0.0476	
	0.0484	0.0473	0.0451	0.0427	0.0404	0.0386	0.0372	0.0361	0.0355	0.0351	0.0348	
	0.0318	0.0314	0.0306	0.0296	0.0285	0.0276	0.0268	0.0262	0.0258	0.0255	0.0253	

Figure 7 Plan view showing the two-dimensional distribution for the LaSalle service water tunnel with 50% flow in one port and 50% flow in an adjacent port.

TENERA

September 23, 1996

SFM96-029/SFM96A

Dr. Petros Antonopolous
ComEd
LaSalle County Station
2601 N. 21st Road
Marseilles, IL 61341-9757

Dear Petros:

This letter contains the summary of my assessment of the strainer issue related to the sealant injection event. It reflects my review of the strainer related sections of ComEd's "Probabilistic Risk Assessment Report of the Impact of Foam Sealant Injection in the LaSalle County Nuclear Station Service Water Tunnel."

I have provided information here which I believe supports the statement that the PRA evaluation conservatively represents the potential impact of the foam upon the core damage frequency. The potential for risk impact was small.

The resolution to the strainer issue can be capsulized as follows:

CSCS-ESW Strainer Failure Mode	Resolution
Strainer blockage due to ineffective backwash.	ESW surveillance and flow tests indicated no degradation of flow. The density of material in the tunnel that could be ingested and impact the strainers would have been highest during this time. Since degradation of flow did not occur, and no unusual amount of backwash operation occurred, it appears that the strainers were not being unduly stressed with blockage, and the backwash operation was effective. (Note: if excessive backwash frequency had been observed, the surveillance would have been terminated and the plant would have been shut down. This is because this would have invalidated the then-current assumption that the material floated; that assumption coupled with the surveillance test was used as a basis for continued operation.)

Strainer backwash lines plugged. See above.

The ComEd report indicates a small increase in core damage frequency as a result of the assumption that sealant could impact the strainer operation. The ComEd report concludes that the failure rate is near zero; however, for the purposes of its calculations an additional failure rate of 0.001 (i.e., one chance out of one thousand) for strainer failure as a result of blockage. The low failure rate is based upon interpretations of the University of Iowa studies, which indicate a nominal 10% chance of material becoming entrained during the curing process and therefore being available for ingestion by the ESW suction nozzle. From the ComEd report, only 10% of the material removed from the tunnel by divers was assumed to be available to plug strainers; this amount (~2.75 gallons) was concluded to be too small to plug the strainers to the point where the strainer operation would be impacted.

Additional support for concluding that the safety significance of the sealant injection was small prior to cleanup activities commencing can be added by noting that operation of the non-essential service water pumps acts to "dilute" the concentration of the active material[1] in the service water tunnel. Thus, a calculation can be performed to determine how many tunnel turnovers must occur before the amount of active material left in the tunnel is too low to create the amount of blockage in the strainer tubes required to inhibit design flow (blockage = 90% by volume in the tubes to inhibit design flow). In other words, we can estimate the amount of time the N-ESW pumps must have operated in order to remove a sufficient amount of active material from the service water tunnel to prevent 90% blockage of the strainer tubes.

The "dilution" of the concentration of active material in the service water tunnel is a mass balance problem involving the computation of the change in mass as a result of the volume of water/foam mixture being swept out of the tunnel by the N-ESW pumps. As the concentration decreases with time, the amount being swept out is also decreasing. This pattern is represented by an exponential decay equation.

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[1] "Active material" is defined as material which is small in size and near neutrally buoyant. This material acts like a tracer (see the IIHR report). From observations and the IIHR report, most material in the tunnel was actually larger and positively buoyant; the tests indicate that this material would not be pulled down to the ESW suction.

The following equation is used for the calculation:

$$m(t) = m_0\, e^{-[(Q/V)\, t]} \qquad \text{Eqn. 1}$$

where $m(t)$ = concentration of active material in tunnel as a function of time
m_0 = initial concentration
V = volume of service water tunnel
Q = volumetric flow rate
t = time

Assume the following:

1. Flow rate is based upon a nominal flow of 10,000 gpm through a single non-essential service water pump (ref. - conversation w/Steve Brown, 8/22/96). Four pumps were in operation at the time of the event, and therefore a total nominal flow rate of 40,000 gpm is assumed. (Note - the flow rate is conservative, in that design flow is 15,000 gpm per pump, with optimal flow in the 12,000 to 14,000 gpm per pump range).

2. No additional dilution occurs due to ESW operation, i.e., the ESW pumps do not remove any additional foam from the tunnel.

Calculation

A. Volume, V, of service water tunnel = 180' x 13' x 7' = 16,380 ft^3

B. Volumetric flow rate, Q, = 10,000 gpm/pump x (.002228 (ft^3/sec)/gpm) x 4 pumps = 89.12 ft^3/sec

__Result #1__

At this flow rate, one tunnel turnover occurs approximately every 184 seconds, or about every 3 minutes: 16,380 ft^3 / 89.1 ft^3/sec = 183.7 seconds

__Conclusion__

The "dilution" of the service water tunnel occurs rapidly due to the high volumetric flow rate provided by the N-ESW pumps. Foam sealant "particles" that are positively or neutrally buoyant would be swept out quickly by this flow.

C. Next, calculate the amount of material required to fill the strainer tubes to 90% by volume.

Strainer tubes are 2.75" in diameter, 34" long. Therefore, the volume of one tube is

$$V_T = \pi r^2 l = 3.14159 \times (2.75/2)^2 \times 34 = 201.95 \text{ in}^3 = .117 \text{ ft}^3$$

90% by volume $= .9 \times .117 = .105$ ft^3
mass of material to fill this volume $= .105$ ft^3 $\times$ 59.31 lbs/ft^3 $= 6.25$ lbs (per tube)

D. Total number of tubes (using information supplied by ComEd):

Strainer	Number of Tubes
Unit 1:	
DG 1 cooling water	13
DG 2 cooling water	10
DG 3 cooling water	10
RHR-WS 1	40
RHR-WS 2	40
subtotal	*113*
Unit 2:	
DG 2 cooling water	10
DG 3 cooling water	10
RHR-WS 1	40
RHR-WS 2	40
subtotal	*100*
TOTAL	*213*

Insufficient material to clog all strainers to 90% by volume would exist once the total mass drops below (213 tubes) x (6.25 lbs/tube), or 1,331.25 lbs. In other words, 1,331.25 lbs of foam sealant are required in the tunnel to clog all tubes to the point where their operation is significantly degraded.

Result #2

At any given time, 1,331.25 pounds of sealant must have been in the tunnel and in a form susceptible to being pulled into the ESW pumps in order to possibly plug all ESW

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strainers. If the amount of material was below this amount, the strainers could not be plugged to 90% volume.

Example Calculations

As a test of the assumptions in the ComEd PRA evaluation, sample calculations were performed to determine the susceptibility of the strainers to blockage given the dilution effect.

The following additional assumptions were employed:

i. Service water tunnel is well-mixed so that effluent concentration of active material is the same throughout. (Note: thus, this assumes all sealant is at least neutrally or slightly positively buoyant, and that none adheres to the floor surface.)

ii. Initial concentration of material is based upon a mass of 30 cubic feet of foam. This is based upon discussions with Steve Brown (ComEd, LaSalle; 8/16/96 and 8/23/96), and represents an upper bound for the amount of material removed from the tunnel by divers. The amount removed loosely filled five 55-gallon drums (275 gallons total, as used in the ComEd PRA evaluation). The amount of material actually in the tunnel at any given time cannot be estimated with certainty, since the foam was injected over different time periods and dilution was or could have been occurring throughout the time of concern. Tests performed on material from two of the drums at the IIHR facility indicate that much of the material was relatively large (>10") and positively buoyant; test results show that this material would not be pulled down to the ESW suction. Thus, the actual amount of active material that had the potential to be pulled down into the ESW suction is believed to be much less than the 30 cubic feet used in this calculation. Therefore, using 30 cubic feet as a starting point is conservative.

iii. The initial concentration of active material includes any material that would have been dislodged from the floor after initially adhering to the floor. In other words, no additional material is added to the mix from that stuck to the floor. This is supported by the divers' observations and experience regarding the difficulty in removing the adhered material from the floor.

iv. Using data supplied in the IIHR report, the density of the foam is nominally chosen to be 0.95 gm/cm^3 (which is 59.31 lbs/ft^3, using the conversion factor of 62.428 to convert to lbs/ft^3 from gm/cm^3)

v. For the baseline calculation it is assumed that flow through the ESW related strainers is equally distributed among all 9 strainers, so that there is an equal likelihood of any specific strainer receiving foam material. In actuality, the observed accumulation of material was biased

towards the Unit 2 side of the tunnel (the northern side of the tunnel), where the injection occurred. Therefore, a sensitivity analysis is included here using just Unit 2 strainers.

vi. For the baseline calculation which follows, all 275 gallons (30 cubic feet) are assumed to be available for ingestion by the ESW suction (as opposed to the 2.75 gallons used in the ComEd PRA evaluation baseline). This assumption represents the situation covered by the sensitivity analysis included in the ComEd report, in which the failure probability of the strainers is increased by a factor of 10.

Calculation

I. Initial mass of foam, m_{o}, = (.95 gm/cm^3 x 62.428 (lbs./ft^3)/(gm/cm^3)) x 30 ft^3 = 1,779.2 lbs.

The total number of strainer tubes that could be filled to 90% by volume is therefore:
1,779.2 lbs/6.25 lbs/tube = 285 tubes

Thirty cubic feet of foam is thus enough mass to clog all strainers to 90% by volume.

II. Concentration of foam in tunnel = 1,779.2 lbs/16,380 ft^3 = .11 lbs/ft^3

The first second of pump operation removes (89.12 ft^3 x .11 lbs/ft^3) of material, which is about 9.8 lbs. Every subsequent second removes less, as the concentration in the tunnel is reduced (diluted).

With these assumptions and calculations, a total of (1,779.2 - 1,331.25), or 447.95 pounds of foam must be removed through the non-essential service water pump system to drop the amount of foam remaining in the tunnel to below the required amount for blockage.

III. We can now solve Eqn. 1 for t, the amount of time required to reduce the mass in the tunnel to 1,331.25 lbs by setting m(t) to 1,331.25.

$$1{,}331.25 = 1{,}779.2 \exp [(-89.12 \text{ ft}^3/\text{sec})/(16{,}380 \text{ ft}^3) \times t]$$

Solving for t:

$$.748 = \exp(-.0054t)$$
$$\ln(.748) = -.0054t$$
$$t = \ln(.748)/(-.0054) = (-.29005)/(-.0054) = 53.31 \text{ seconds} = < 1 \text{ minute}$$

This result means that the concentration of material in the service water tunnel would be insufficient to plug all strainer tubes to 90% by volume after less than 1 minute of operation of four N-ESW pumps at the nominal flow rate assumed. The time window of vulnerability for strainer plugging is only 1 minute (less than 1/3 of a tunnel turnover). Thus, it is extremely unlikely that the strainers would have plugged during any emergency operation required of the ESW system.

Sensitivity Analysis

The above calculation is repeated assuming that only the Unit 2 strainers receive material, i.e., that all foam flows through the Unit 2 strainers. Thus, the number of tubes susceptible to plugging drops to 100 (see Step D above), and the volume required for 90% plugging of these 100 tubes drops to 625 lbs.

Substituting 625 lbs. for 1,331.25 lbs. in the calculations, we get:

$625 = 1{,}779.2 \exp[(-89.12/16{,}380) \times t]$

Solving for t:

$.351 = \exp(-.0054\,t)$
$t = \ln(.351) / -.0054$
$t = -1.047 / -.0054 = 193.9$ seconds, or approximately 3.23 minutes.

Even in this situation, the time period is very short, and the potential for a transient event occurring during this particular time period is insignificantly small. Thus, it appears that there was very little potential for strainer plugging and loss of ESW operation.

sult #3

The amount of time required for N-ESW pump operation to dilute the concentration of material in the tunnel to below the point of strainer vulnerability is less than 3.5 minutes, even in the extreme case of (1) only Unit 2 strainers must be plugged and (2) all 30 cubic feet of foam could be ingested by the ESW pumps. If either of these conditions is relaxed (for example, if entrainment is limited to 10%, as used in the ComEd report), the time window of vulnerability decreases dramatically. A significantly higher amount of foam (much greater than the 30 cubic feet assumed for the calculations) would have been required in the service water tunnel before the time window of vulnerability became significant (e.g., a window greater than 10 minutes would have required over 500 cubic feet of foam sealant)

Conclusion

A strainer failure rate close to zero seems appropriate for use in any calculation which is performed to estimate the potential increase in core damage probability as a result of the presence of foam sealant in the service water tunnel. The use of a failure rate of 0.001, as in the ComEd PRA evaluation, appears to be conservative - a rate closer to zero would be more reasonable; a rate of 0.01 (a factor of 10 higher - which would correspond to the example calculation performed above) is even more conservative given the conservative nature of the assumptions employed (e.g., initially high concentration of foam; all foam available to be pulled in by ESW pumps).

Additional Issues

1. Reliability of backwash system - the material condition of the backwash equipment was reviewed by ComEd, and the condition of the equipment is satisfactory.

2. Backwash activity - no unusual amount of backwash activity occurring during the surveillance operation was noted, providing a data point indicating that material was not being drawn into the strainers. (Normal surveillance does not continuously monitor strainer performance - only one data point is taken in the initial surveillance, and it did not indicate a problem. When the flow tests were performed later, when the presence of the foam was known, the strainers were monitored - once again, no problem was indicated.)

3. Manual backwash capability - credit can be taken for manual backwash as a backup since (1) it can be demonstrated that the procedures are well understood, and (2) the staff is trained on them. Based upon conversations with ComEd staff (8/23/96), manual backwash can be accomplished in less than 1 hour (in fact, it can be performed in approximately 10 minutes). In addition, operation of ESW is not impeded during this procedure. Therefore, in the event of failure of the automatic system it would be possible for manual action to be successful in a short period of time. Due to the slow pace at which accumulation of material within the strainer tubes would occur (extrapolating from the calculations presented above), it is concluded that adequate time exists for manual operation well in advance of any significant impact on flow through the ESW system.

Overall Conclusions

I believe that the possibility of strainer tube plugging was very small during the time period of concern. In addition, although I haven not estimated a value, I believe that the likelihood of a transient event requiring ESW operation combined with the subsequent degradation of ESW operation as a result of sealant material in the strainers was an extremely small probability. I

base this conclusion on the results of the Iowa studies, the observations made by the plant staff during subsequent surveillance activities, and the calculations provided here.

The strainer-related conclusions reached by the ComEd PRA report appear to be reasonable and conservative. The changes in core damage probability (CDP) estimated in the PRA report are consistent with the conclusions I draw from the calculations performed above. The PRA basis using "input probabilities x 10" (Table 1 of that report) calculates a change in CDP of only 1.7E-5, which is just above the guideline for "potentially risk significant" (Table 2 of the report). Given the conservatisms in the calculation, the high degree of dilution, and the fact that no significant strainer blockage was or has been observed, I believe the actual change in CDP was much smaller (i.e., near zero), and existed for only a very short time.

Sincerely,

Wes Brinsfield
Senior Consultant
TENERA, Inc.