FIVE YEAR REPORT
CHLORIDE SEALANT ON THE
COLUMBIA RIVER BRIDGE (ASTORIA)
CONTRACT NO. C09738

by

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INTRODUCTION

In 1983 chloride analysis was performed on spans 41, 84, and 119 on the Astoria bridge. The need for sealing the concrete from future chloride intrusion was identified. Shortly thereafter, a contract was let to seal the bottom of the deck and the beams. The sealing was completed by October 1984. At the time the project was initiated, it was decided that a five year program to evaluate the effectiveness of the sealer should be undertaken.

A limited chloride analysis in 1986 indicated the overall rate of chloride intrusion had probably been reduced. Because of the relatively short time of exposure and the limited sampling, the results were not clear cut. The recommendation to do a 1988 sampling that parallelled the 1983 sampling was made.

The 1988 sampling was identical to the 1983 sampling with respect to the spans and areas of each span checked. The sampling procedures and Laboratory analysis were also in keeping with the 1983 methods. This was done to minimize variations in the data.

CONCLUSIONS AND RECOMMENDATIONS

The chloride ion concentration in the structure is increasing. The apparent rate of increase is estimated to be 1/2 of what it was before sealing.

The area with the greatest rate of increase is the web of the beams.

The chloride ion concentration, for areas where the steel has 1 inch of concrete cover (bottom of deck), may reach the corrosion threshold value, in localized areas, in the next 3 to 5 years.

The chloride ion concentration, for areas where the steel has 1 1/2 inches of concrete cover (beams), may reach the corrosion threshold value, in localized areas, in the next 15 to 20 years.

The bottom of the deck should be surveyed in five years. The beams, with 1 1/2 inches of concrete cover over the steel, should have an in-depth survey within ten years.

STATISTICAL METHODS

When the chloride barrier was placed in 1983 it was hoped that migration of chlorides from the environment into the structure would be stopped. If that objective was to be realized the net chloride ion content of the structure would remain constant. At the 0 to 1 inch level the measured chloride ion content would drop. Correspondingly the 1 to 2 inch level should increase.

To test for change in chloride content with time, the paired difference "t" test[1] was used. This was chosen since there was a one to one correspondence between the 1983 and 1988 data.

This method requires a hypothesis be made about the data. The statistical test is applied to find out whether to "not reject" ("accept") the hypothesis and treat it as true or whether to "reject" the hypothesis and treat it as false.

The hypothesis used through out is:

> "The net chloride content of the structure in 1983 is the same as it was in 1988."

The alternative hypothesis is:

> "The net chloride content of the structure in 1983 is not the same it was in 1988."

If the hypothesis can be rejected with a high probability then the alternative hypothesis should be treated as true.

To test the hypothesis, "t" was calculated using the following equation:

$$t = \frac{\sqrt{N}\,(\bar{X} - X_o)}{s} \qquad 1.$$

Where: N = the number of samples

$\bar{X}$ = the mean of the differences between the 1983 and 1988 sampling

X_o = the mean dictated by the hypothesis; eg. 0

s = the standard deviation of the differences

[1] Advanced Engineering Mathematics by Erwin Kreyzig, Fifth Edition, John Wiley & Sons, 1983, Section 23.15, "Testing of Hypothesis, Decisions."

To determine the significance of the t value, the value T critical (T_c), is determined from the t-distribution for (N - 1) degrees of freedom at the desired confidence level.

If ($t < -T_c$ or $t > +T_c$) the hypothesis is rejected. The probability that the hypothesis is rejected in error is reflected by the confidence level used to select T_c.

If ($t < -T_c$) there is a statically significant decrease in the chloride content. For ($t > +T_c$) an increase in the chloride content is indicated.

Sampling contaminated concrete that has had a high performance chloride barrier placed should result in ($t < -T_c$) in the 0 to 1 inch level and ($t > +T_c$) for the 1 to 2 inch level at some future time after placement.

ANALYTICAL METHODS

Frick's equation for diffusion of ions through a media is generally accepted as the equation that describes the diffusion of chloride ions into a concrete structure. This equation is:

$$\frac{d^2C(x,t)}{dx^2} = \frac{1}{D}\frac{dC(x,t)}{dt} \qquad 2.$$

where: $C(x,t)$ = the chloride ion concentration
x = the depth in the concrete (inches)
t = time (years)
D = the diffusion coefficient.

The solution[2] used for this analysis is:

$$C(x,t) = C_o \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}} \right) \right] \qquad 3.$$

where: C_o = the chloride concentration at the surface of the concrete
$\mathrm{erf}(p)$ = the error function with argument p.

With boundary conditions:

$C(0,t) = C_o$ at $x = 0$ 4.
$C(x,0) = 0$ when $t = 0$ 5.

[2] Advanced Mathematics in Physics and Engineering by Arthur Bronwell, First Edition, McGraw-Hill Book Company, Inc., 1953, Section 12.7 "Linear Heat Flow in Semi-infinite Solid - Fourier Integral Solution."

STATISTICAL RESULTS

BY SPANS

The results from the chloride analysis from 1983 and 1988 are tabulated by span and the results of the calculations are in appendix 1. Table 1 and Table 2, below, summarizes these results.

TABLE 1

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
1/8 INCH TO 1 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	41	18	41	82	100
AVERAGE DIFFERENCE (MEAN)	0.17	0.61	0.22	0.19	0.27
STANDARD DEVIATION	0.64	0.65	0.67	0.66	0.67
t-SCORE	1.66	4.01	2.11	2.67	4.00
T CRITICAL (T_c)	1.68	1.74	1.68	2.38	3.17
CONFIDENCE LEVEL	95	95	95	99.0	99.9

TABLE 2

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
1 INCH TO 2 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	41	18	41	82	100
AVERAGE DIFFERENCE (MEAN)	0.15	0.14	0.12	0.13	0.13
STANDARD DEVIATION	0.18	0.16	0.10	0.14	0.15
t-SCORE	5.44	3.66	7.47	8.34	9.08
T CRITICAL (T_c)	3.31	3.65	3.31	3.21	3.17
CONFIDENCE LEVEL	99.9	99.9	99.9	99.9	99.9

Examination of the t-scores of the individual spans, at both sampling levels, indicates ($t > T_c$) in all but one case. When all 3 spans are taken together, at the 99.9% confidence level, it is clear that the chloride content of the structure is increasing at both levels.

The previously discussed conditions for a high performance sealer ($t < -T_c$ for the 0 to 1 inch level and $t > +T_c$ for the 1 to 2 inch level) are not being met.

ANALYSIS BY AREA

In order to better identify the areas where the chloride intrusion is occurring a similar analysis was performed on the data from the bottom flanges of the beams, the webs and the bottom of the deck. The data and results of the calculations can be found in Appendix 2. Tables 3 and 4 summarize the results for the bottom flanges.

TABLE 3

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
BOTTOM FLANGE OF THE BEAMS
1/8 INCH TO 1 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	20	6	20	40	46
AVERAGE DIFFERENCE (MEAN)	0.066	0.32	0.22	0.10	0.13
STANDARD DEVIATION	0.76	0.64	0.82	0.77	0.76
t-SCORE	0.39	1.21	0.75	0.84	1.16
T CRITICAL (T_c)	1.73	2.02	1.73	1.68	1.68
CONFIDENCE LEVEL	95	95	95	95	95

TABLE 4

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
BOTTOM FLANGE OF THE BEAMS
1 INCH TO 2 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	19	6	20	39	46
AVERAGE DIFFERENCE (MEAN)	0.21	0.18	0.14	0.14	0.21
STANDARD DEVIATION	0.23	0.27	0.13	0.19	0.20
t-SCORE	3.94	1.63	4.84	4.72	7.32
T CRITICAL (T_c)	1.73	2.02	1.73	3.31	3.28
CONFIDENCE LEVEL	95	95	95	99.9	99.9

The t-scores in table 3 ($-T_c < t < +T_c$) do not permit rejection of the hypothesis. There is no statistically significant change in chloride concentration in the bottom flanges at the 1/8 to 1 inch level from 1983 to 1988. No strong inference can be made about the sealer on the flanges, from this data alone, at this time.

The t-scores in Table 4 indicates there was a statistically significant increase in the chloride concentration at the 1 to 2 inch level. Since the only source of chlorides for this level is the 0 to 1 inch level, there may have been a significant change in the total (0 to 2 inch) level.

Tables 5 and 6 summarize the results for the web areas of the beams.

TABLE 5

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
WEB OF THE BEAMS
1/8 INCH TO 1 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	12	6	12	24	30
AVERAGE DIFFERENCE (MEAN)	0.30	1.00	0.48	0.39	0.51
STANDARD DEVIATION	0.21	0.71	0.77	0.44	0.54
t-SCORE	4.89	3.43	2.14	4.31	5.15
T CRITICAL (T_c)	2.72	3.37	2.72	3.47	3.40
CONFIDENCE LEVEL	99	99	99	99.9	99.9

TABLE 6

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
WEB OF THE BEAMS
1 INCH TO 2 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	12	6	12	24	30
AVERAGE DIFFERENCE (MEAN)	0.11	0.15	0.17	0.14	0.14
STANDARD DEVIATION	0.11	0.12	0.06	0.09	0.09
t-SCORE	3.60	3.11	9.99	7.84	8.44
T CRITICAL (T_c)	2.72	3.37	2.72	3.49	3.40
CONFIDENCE LEVEL	99	99	99	99.9	99.9

The results for all three spans at both levels ($t > T_c$) indicate the hypothesis should be rejected. The level of confidence is high, 99.9%. There is a statistically significant increase in the chloride levels in the web areas at both depths.

Tables 7 and 8 below summarize the results for the bottom of the deck.

TABLE 7

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
BOTTOM OF DECK
1/8 INCH TO 1 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	9	6	9	18	24
AVERAGE DIFFERENCE (MEAN)	0.21	0.52	0.07	0.14	0.23
STANDARD DEVIATION	0.79	0.39	0.31	0.58	0.55
t-SCORE	0.80	3.30	0.65	1.00	2.09
T CRITICAL (T_c)	1.86	2.02	1.86	2.11	2.07
CONFIDENCE LEVEL	95	95	95	97.5	97.5

TABLE 8

ANALYSIS OF THE DIFFERENCES OF THE MEANS USING THE t-DISTRIBUTION
(1988 RESULTS - 1983 RESULTS) BY SPAN
BOTTOM OF DECK
1 INCH TO 2 INCH SAMPLE DEPTH

SPAN	41	84	119	41 & 119	ALL 3
NUMBER OF POINTS SAMPLED	9	6	9	18	24
AVERAGE DIFFERENCE (MEAN)	0.10	0.14	0.09	0.10	0.11
STANDARD DEVIATION	0.11	0.08	0.03	0.08	0.08
t-SCORE	2.87	4.31	8.08	5.40	6.81
T CRITICAL (T_c)	1.86	2.02	1.86	3.85	3.49
CONFIDENCE LEVEL	95	95	95	99.9	99.9

The results for all three spans at the 0 to 1 inch level ($t > T_c$) indicate the hypothesis could be rejected. The level of confidence is 97.5%. There is a statistically significant increase in the chloride levels in the bottom of deck, at this depth, though it is not as strongly supported as it was for the web.

The 1 to 2 inch depth have t-scores indicating there was a very statistically significant increase in the chloride concentration. Since the only source of chlorides for this level is the 0 to 1 inch level, there may have been a significant change in the total (0 to 2 inch) level.

ANALYTICAL RESULTS

CHLORIDE DIFFUSION

Frick's diffusion equation is the theoretical relationship that describes the chloride ion concentration, C(x,t), in terms of the chloride concentration at the surface of the concrete, C_o, the diffusion coefficient, D, the depth, as measured from the surface of the concrete, and time. For the calculations, the 1988 surface chloride concentration was estimated and the 1983 diffusion coefficient was used. The values predicted for 1988 using this solution to Fricks equation, at the mean depths, matched the 1988 average chloride concentrations to within 1%.

The selected solution to the equation is:

$$C(x,t) = C_o \left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}} \right) \right] \qquad 3.$$

Where x = depth in inches
t = time in years

The initial values of C_o (1983) and D were determined from the 1983 data. C_o (1988) was found by taking the average total increase in chlorides from 1983 to 1988, at the 1/8 to 1 inch level, and estimating the C_o (1988) value from the 1983 curve. The chloride concentration for the mean of the 1/8 to 1 inch level and the mean of the 1 to 2 inch level was calculated using the 1983 value for D, C_o (1988) and a structure age of 20 years.

The sampling technique used on this project required concrete powder samples to be taken from an interval of 1/8 inch to 1 inch and of 1 inch to 2 inches in depth. Therefore, it is necessary to relate the reported chloride concentration for each interval to a specific depth, x_i, within that interval.

To approximate x_i, the average chloride content of all the 1983 samples, for each interval, was used. The structures approximate age, 15 years, was assumed for the constant time solution of equation 3. The parameters C_o and D were estimated from the 1983 data and a plot C(x,t) versus x was made.

From the plot a point in each interval (x_1 in the 1/8 to 1 inch interval and x_2 in the 1 to 2 inch interval) was found so that the area under the curve to the left of the point was equal to the area under the curve to the right of the point in the interval. (see Figure 1) These points were used for the depth that the chloride content of the sample and the concentration versus depth were equal. The x_1 value was found to be 0.45 inches and x_2 was 1.3 inches.

Using the x_1 and x_2 values found above, C_o for 1983 and D were refined by successive approximation.

C_o, the chloride concentration at 0^+inches, is known to increase with time. To estimate C_o for 1988, the increase in chlorides at 0.45 inches was used and the 1988 C_o value was estimated from the 1983 curve. Using the new C_o and a structure age of 20 years, the concentration was calculated for the 1.3 inch depth. The calculated concentration was exactly the same as the average for the 1 to 2 inch interval. The 1983 and 1988 curves are shown in figure 2.

THE CHLORIDE BARRIER

Once the concentrations at the 0^+ depth have been determined it is possible to estimate the effectiveness of the chloride barrier. From figure 2, take the 15 and 20 year values for C_o:

C_{o15} = 1.75 #Cl^-/yd^3, or approximately .12# Cl^-/year (first 15 years)

C_{o20} = 2.05 #Cl^-/yd^3, or approximately .06# Cl^-/year (last 5 years)

This indicates that some good is being realized from the chloride barrier since the rate of intrusion has apparently been reduced by about 1/2. The goal to stop chloride intrusion has not been realized.

TIME TO CORROSION

The estimate of time to corrosion is based on the time dependent relationship given by the solution to Frick's equation. The chloride concentration at the surface was assumed to be increasing at the same rate that has prevailed over the last five years. The diffusion coefficient used was the one found for the 1983 data and used with the 1988 data.

The depth of concrete cover over the steel in the beams is nominally 1.5 inches and 1.0 inches for the deck. The estimated mean chloride concentration, for x = 1.0 inch and 1.5 inches, was calculated for a structure age of 15 to 50 years and is shown on Figure 3.

The curves designated "+2 Std. dev" in Figure 3 are based on the 1983 and 1988 data having a standard deviation of approximately 1/2 the mean. At 2 standard deviations approximately 2.5% of the chloride concentration values will be greater than the "+2 Std. Dev." curves shown in figure 2.

The chloride concentration, for steel at the 1 inch level, could reach corrosion threshold concentration within the next 3 to 5 years. For the steel at the 1.5 inch level threshold concentration (1.2 #Cl^-/yd^3) could be reached in 15 to 20 years.

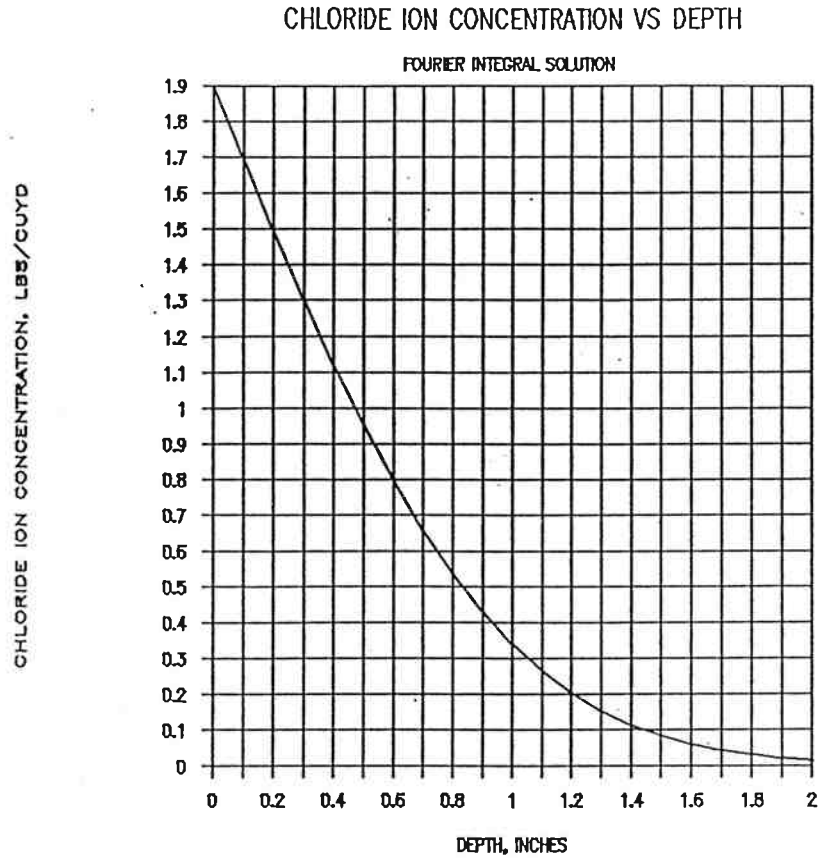


Figure 1

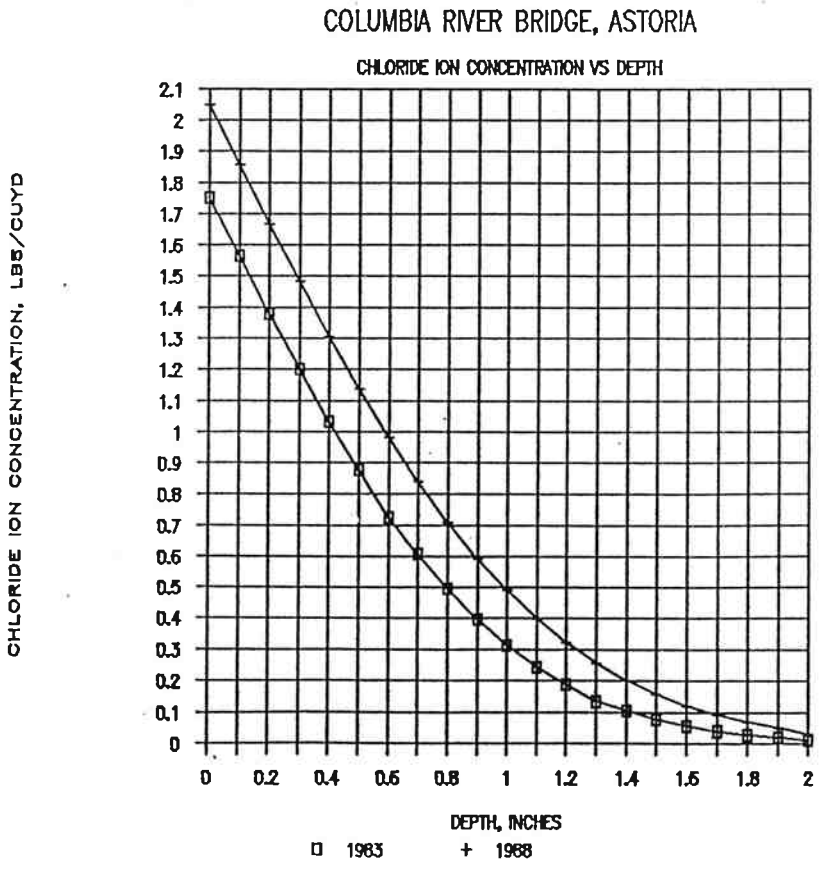
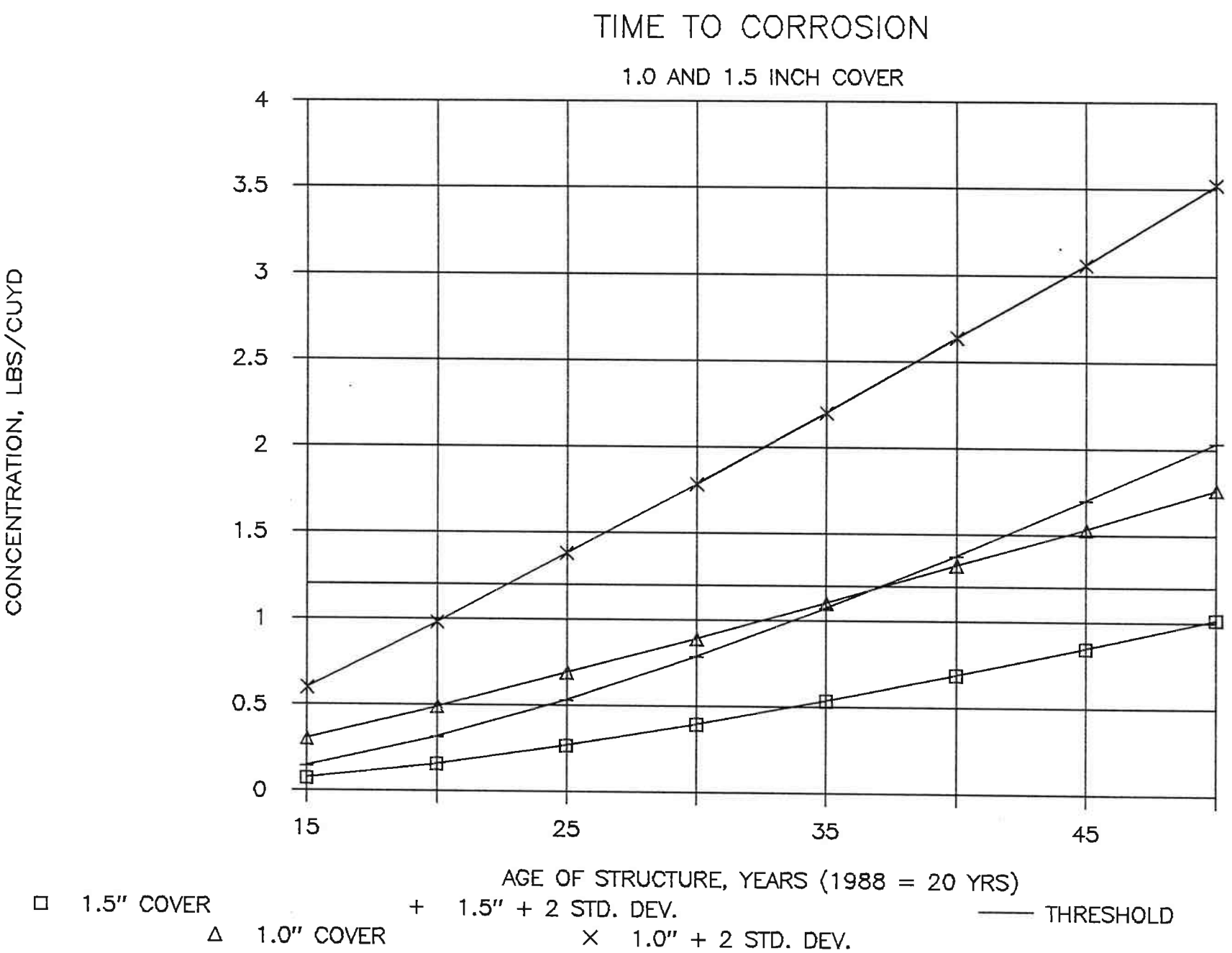


Figure 2

Figure 3


TIME TO CORROSION
1.0 AND 1.5 INCH COVER
CONCENTRATION, LBS/CUYD
4
3.5
3
2.5
2
1.5
1
0.5
0
15
25
35
45
AGE OF STRUCTURE, YEARS (1988 = 20 YRS)
□ 1.5" COVER
+ 1.5" + 2 STD. DEV.
THRESHOLD
△ 1.0" COVER
× 1.0" + 2 STD. DEV.

APPENDIX 1

DATA ELEMENTS, EACH SPAN, ALL AND 41 + 119

SPAN 41				SPAN 119				SPAN 84	
beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 2 ^1983	beam 3 ^1983
0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"
0.6	1.0	1.2	1.2	1.1	1.8	0.4	0.4	1.6	1.3
2.1	1.0	1.1	1.1	0.7	1.9	1.0	0.5	2.3	1.9
1.6	1.1	1.7	1.4	0.8	1.9	1.3	0.7	1.9	1.0
1.4	0.7	1.9	1.3	1.4	2.0	1.6	0.8	1.1	0.6
1.8	1.6	2.2	1.3	1.3	1.7	1.4	0.4	0.7	0.9
0.3	0.7	0.7	0.4	0.4	0.8	0.3	0.2	1.2	0.8
0.4	0.7	0.9	0.3	0.4	1.0	0.5	0.4	1.1	0.3
0.4	1.2	0.3	0.4	0.6	0.7	0.4	0.5	0.5	0.3
	0.3	1.0	0.9		0.5	0.4	0.4	0.8	0.3
	0.3	1.3	0.6		0.4	1.1	0.5		
	0.4	1.7	0.7		0.5	0.5	0.7		
		1988							
1.80	0.90	1.88	0.70	1.21	0.51	3.05	0.67	1.88	2.62
0.90	1.14	1.64	1.02	1.14	0.82	2.07	0.74	1.92	1.88
1.06	1.53	0.86	0.78	1.25	2.11	1.61	0.82	1.64	1.96
2.39	1.96	2.82	0.98	1.25	1.52	2.11	0.39	1.84	2.39
0.78	1.41	3.10	0.98	0.59	1.41	1.76	0.82	2.47	1.92
0.63	1.10	1.17	0.67	1.41	1.10	1.41	0.51	1.10	1.57
0.55	0.86	0.74	0.67	2.04	0.47	0.94	0.63	1.14	1.21
0.74	1.41	1.02	0.70	1.14	0.51	1.10	0.67	1.37	0.98
	1.33	0.63	0.86		0.43	0.74	0.86	0.86	0.86
	1.21	0.67	1.49		0.74	0.55	0.67		
	1.14	0.55	1.21		0.36	0.47	0.78		
1.20	-0.10	0.68	-0.50	0.11	-1.29	2.65	0.27	0.28	1.32
-1.20	0.14	0.54	-0.08	0.44	-1.08	1.07	0.24	-0.38	-0.02
-0.54	0.43	-0.84	-0.62	0.45	0.21	0.31	0.12	-0.26	0.96
0.99	1.26	0.92	-0.32	-0.15	-0.48	0.51	-0.41	0.74	1.79
-1.02	-0.19	0.90	-0.32	-0.71	-0.29	0.36	0.42	1.77	1.02
0.33	0.40	0.47	0.27	1.01	0.30	1.11	0.31	-0.10	0.77
0.15	0.16	-0.16	0.37	1.64	-0.53	0.44	0.23	0.04	0.91
0.34	0.21	0.72	0.30	0.54	-0.19	0.70	0.17	0.87	0.68
	1.03	-0.37	-0.04		-0.07	0.34	0.46	0.06	0.56
	0.91	-0.63	0.89		0.34	-0.55	0.17		
	0.74	-1.15	0.51		-0.14	-0.03	0.08		
NUMBER IN SAMPLE, N			41				41		18
SUM			6.78				9.08		11.01
MEAN			0.17				0.22		0.61
STANDARD DEVIATION			0.64				0.67		0.65
VARIANCE			0.41				0.45		0.42
T SCORE			1.66				2.11		4.01
DEGREES OF FREEDOM			40				40		17
T CRITICAL @95%			1.68				1.68		1.68
NUMBER IN SAMPLE, N			100				82		
SUM			26.87				15.86		
MEAN			0.27				0.19		
STANDARD DEVIATION			0.67				0.66		
VARIANCE			0.45				0.43		
T SCORE			4.00				2.67		
DEGREES OF FREEDOM			99				81		
T CRITICAL @99.9%			3.17			AT 99%	2.38		

1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.1	0.1	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2
0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.5
0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0
0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.2	0.1
	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	0.1	0.1	0.1		0.1	0.1	0.1	0.1	0.1
	0.1	0.1	0.4		0.1	0.1	0.4		
	0.1	0.4	0.1		0.1	0.1	0.1		
		1988							
0.25	0.20	0.59	0.14	0.15	0.20	0.43	0.20	0.58	0.27
0.16	0.22	0.30	0.16	0.14	0.13	0.17	0.39	0.32	0.16
0.16	0.16	0.39	0.14	0.18	0.36	0.15	0.25	0.34	0.18
0.25	0.27	0.74	0.86	0.12	0.16	0.36	0.21	0.29	0.16
0.16	0.39	0.86	0.16	0.18	0.23	0.15	0.18	0.47	0.20
0.14	0.39	0.23	0.21	0.23	0.32	0.20	0.32	0.32	0.18
0.13	0.27	0.27	0.18	0.34	0.23	0.36	0.35	0.32	0.21
0.21	0.18	0.25	0.31	0.21	0.34	0.23	0.21	0.30	0.16
	0.18	0.23	0.20		0.18	0.18	0.25	0.30	0.14
	0.34	0.25	0.39		0.18	0.18	0.43		0.23
	0.29	0.29	0.24		0.23	0.20	0.21		0.18
0.15	0.10	0.39	0.04	-0.05	-0.20	0.33	0.10	0.48	0.07
-0.04	0.12	0.20	-0.04	-0.06	0.03	0.07	0.29	0.12	-0.34
0.06	0.06	0.19	0.04	0.08	0.26	0.05	0.15	0.24	0.18
0.15	0.17	0.34	0.76	0.02	0.06	0.26	0.11	0.09	0.06
0.16	0.29	0.76	-0.04	0.08	0.13	0.05	0.08	0.37	0.10
-0.16	0.29	0.13	0.11	0.13	0.22	0.10	0.22	0.22	0.08
0.03	0.17	0.17	0.08	0.24	0.13	0.16	0.25	0.22	0.11
0.11	0.08	0.15	0.21	0.11	0.24	0.13	0.11	0.20	0.06
	0.08	0.13	0.10		0.08	0.08	0.15	0.20	0.04
	0.24	0.15	-0.01		0.08	0.08	0.03		
	0.19	-0.11	0.14		0.13	0.10	0.11		
NUMBER IN SAMPLE, N			41				41		18
SUM			6.14				4.72		2.5
MEAN			0.15				0.12		0.14
STANDARD DEVIATION			0.18				0.10		0.17
VARIANCE			0.03				0.01		0.03
T SCORE			5.44				7.47		3.55
DEGREES OF FREEDOM			40				40		17
T CRITICAL @95%			1.68				1.68		1.68
NUMBER IN SAMPLE, N			100				82		
SUM			13.36				10.86		
MEAN			0.13				0.13		
STANDARD DEVIATION			0.15				0.14		
VARIANCE			0.02				0.02		
T SCORE			9.08				8.34		
DEGREES OF FREEDOM			99				81		
T CRITICAL @99.9%			3.17				3.21		

APPENDIX 2

DATA ELEMENTS, BOTTOM FLANGE

span 41				span 119				span 84	
beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 2 ^1983	beam 3 ^1983
0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"
0.6	1	1.2	1.2	1.1	1.8	0.4	0.4	1.6	1.3
2.1	1	1.1	1.1	0.7	1.9	1	0.5	2.3	1.9
1.6	1.1	1.7	1.4	0.8	1.9	1.3	0.7	1.9	1
1.4	0.7	1.9	1.3	1.4	2	1.6	0.8		
1.8	1.6	2.2	1.3	1.3	1.7	1.4	0.4		

ASTORIA BRIDGE CHLORIDE MONITORING PROGRAM - 1988 DATA ANALYSIS

BENT 41 1/8 TO 1 INCH				BENT 119 1/8 TO 1 INCH				BENT 84 1/8 TO 1 INCH	
BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 2	BEAM 3
1.80	0.90	1.88	0.70	1.21	0.51	3.05	0.67	1.88	2.62
0.90	1.14	1.64	1.02	1.14	0.82	2.07	0.74	1.92	1.88
1.06	1.53	0.86	0.78	1.25	2.11	1.61	0.82	1.64	1.96
2.39	1.96	2.82	0.98	1.25	1.52	2.11	0.39		
0.78	1.41	3.10	0.98	0.59	1.41	1.76	0.82		
1.20	-0.10	0.68	-0.50	0.11	-1.29	2.65	0.27	0.28	1.32
-1.20	0.14	0.54	-0.08	0.44	-1.08	1.07	0.24	-0.38	-0.02
-0.54	0.43	-0.84	-0.62	0.45	0.21	0.31	0.12	-0.26	0.96
0.99	1.26	0.92	-0.32	-0.15	-0.48	0.51	-0.41		
-1.02	-0.19	0.90	-0.32	-0.71	-0.29	0.36	0.42		
NUMBER IN SAMPLE, N			20				20		6
SUM			1.33				2.75		1.90
MEAN			0.066				0.137		0.317
STANDARD DEVIATION			0.76				0.82		0.64
VARIANCE			0.57				0.68		0.41
T TEST		T =	0.393				0.747		1.207
DEGREES OF FREEDOM			19				19		5
T CRITICAL @ 95%			1.73				1.73		2.02
NUMBER IN SAMPLE, N			46				40		
SUM			5.98				4.08		
MEAN			0.130				0.102		
STANDARD DEVIATION			0.76				0.77		
VARIANCE			0.57				0.60		
T TEST		T =	1.163				0.836		
DEGREES OF FREEDOM			45				39		
T CRITICAL @ 95%			1.68				1.68		

DATA ELEMENTS, BOTTOM FLANGE 1983 1988 1 TO 2 INCHS

SPAN 41				SPAN 119				SPAN 84	
beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 1 ^1983	beam 2 ^1983	beam 3 ^1983	beam 4 ^1983	beam 2 ^1983	beam 3 ^1983
1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.1	0.1	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2
0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.5
0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0
0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1		
	0.1	0.1	0.2	0.1	0.1	0.1	0.1		

ASTORIA BRIDGE CHLORIDE MONITORING PROGRAM - 1988 DATA ANALYSIS

BENT 41 1 TO 2 INCHES				BENT 119 1 TO 2 INCHES				BENT 84 1 TO 2 INCHES	
BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 2	BEAM 3
0.25	0.20	0.59	0.14	0.15	0.20	0.43	0.20	0.58	0.27
0.16	0.22	0.30	0.16	0.14	0.13	0.17	0.39	0.32	0.16
0.16	0.16	0.39	0.14	0.18	0.36	0.15	0.25	0.34	0.18
0.25	0.27	0.74	0.86	0.12	0.16	0.36	0.21		
0.16	0.39	0.86	0.16	0.18	0.23	0.15	0.18		
0.15	0.10	0.39	0.04	-0.05	-0.2	0.33	0.1	0.48	0.07
-0.04	0.12	0.20	-0.04	-0.06	0.03	0.07	0.29	0.12	-0.34
0.06	0.06	0.19	0.04	0.08	0.26	0.05	0.15	0.24	0.18
0.15	0.17	0.34	0.76	0.02	0.06	0.26	0.11		
	0.29	0.76	-0.04	0.08	0.13	0.05	0.08		
NUMBER IN SAMPLE, N			19				20		6
SUM			3.70				1.84		0.75
MEAN			0.21				0.14		0.18
STANDARD DEVIATION			0.23				0.13		0.27
VARIANCE			0.05				0.02		0.07
T TEST		T =	3.94				4.84		1.63
DEGREES OF FREEDOM			18				19		5
T CRITICAL @ 95%			1.73				1.73		2.02
NUMBER IN SAMPLE, N			45				39		
SUM			6.29				5.54		
MEAN			0.21				0.14		
STANDARD DEVIATION			0.20				0.19		
VARIANCE			0.04				0.04		
T TEST		T =	7.32				4.72		
DEGREES OF FREEDOM			44				38		
T CRITICAL @ 99.9%			3.28				3.31		

DATA ELEMENTS, WEBB 1983 1988

SPAN 41				SPAN 119				bent 84	bent 84
beam 1 ^1983 0 to 1"	beam 2 ^1983 0 to 1"	beam 3 ^1983 0 to 1"	beam 4 ^1983 0 to 1"	beam 1 ^1983 0 to 1"	beam 2 ^1983 0 to 1"	beam 3 ^1983 0 to 1"	beam 4 ^1983 0 to 1"	beam 2 ^1983 0 to 1"	beam 3 ^1983 0 to 1"
0.3	0.7	0.7	0.4	0.4	0.8	0.3	0.2	1.1	0.6
0.4	0.7	0.9	0.3	0.4	1	0.5	0.4	0.7	0.9
0.4	1.2	0.3	0.4	0.6	0.7	0.4	0.5	1.2	0.8
1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

ASTORIA BRIDGE CHLORIDE MONITORING PROGRAM - 1988 DATA ANALYSIS

BENT 41				BENT 119				BENT 84	
1/8 TO 1 INCH				1/8 TO 1 INCH				1/8 TO 1 INCH	
BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 2	BEAM 3
0.63	1.10	1.17	0.67	1.41	1.10	1.41	0.51	1.84	2.39
0.55	0.86	0.74	0.67	2.04	0.47	0.94	0.63	2.47	1.92
0.74	1.41	1.02	0.70	1.14	0.51	1.10	0.67	1.10	1.57
1 TO 2 INCHES				1 TO 2 INCHES				1 TO 2 INCHES	
BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 1	BEAM 2	BEAM 3	BEAM 4	BEAM 2	BEAM 3
0.14	0.39	0.23	0.21	0.23	0.32	0.20	0.32	0.29	0.16
0.13	0.27	0.27	0.18	0.34	0.23	0.36	0.35	0.47	0.20
0.21	0.18	0.25	0.31	0.21	0.34	0.23	0.21	0.32	0.18
1/8 TO 1 INCHES									
0.33	0.40	0.47	0.27	1.01	0.30	1.11	0.31	0.74	1.79
0.15	0.16	-0.16	0.37	1.64	-0.53	0.44	0.23	1.77	1.02
0.34	0.21	0.72	0.30	0.54	-0.19	0.70	0.17	-0.10	0.77
NUMBER IN SAMPLE, N			12				12		6
SUM			3.56				5.73		5.99
MEAN			0.30				0.48		1.00
STANDARD DEVIATION			0.21				0.77		0.71
VARIANCE			0.04				0.34		0.51
T TEST			4.89				2.14		3.43
DEGREES OF FREEDOM			11				11		5
T CRITICAL AT 99%			2.72				2.72		3.37
							24		
NUMBER IN SAMPLE, N			30				9.29		
SUM			15.28				0.39		
MEAN			0.51				0.44		
STANDARD DEVIATION			0.54				0.19		
VARIANCE			0.29				4.31		
T TEST			5.15				23		
DEGREES OF FREEDOM			29				3.47		
T CRITICAL AT 99.9%			3.40						

1 TO 2 INCHES

-0.16	0.29	0.13	0.11	0.13	0.22	0.10	0.22	0.09	0.06
0.03	0.17	0.17	0.08	0.24	0.13	0.16	0.25	0.37	0.10
0.11	0.08	0.15	0.21	0.11	0.24	0.13	0.11	0.22	0.08

NUMBER IN SAMPLE, N	12	12
SUM	1.37	2.04
MEAN	0.11	0.17
STANDARD DEVIATION	0.11	0.06
VARIANCE	0.01	0.00
T TEST	3.60	9.99
DEGREES OF FREEDOM	11	11
T CRITICAL AT 99%	2.72	2.72

NUMBER IN SAMPLE, N	30	24
SUM	4.33	3.41
MEAN	0.14	0.14
STANDARD DEVIATION	0.09	0.09
VARIANCE	0.01	0.01
T TEST	8.44	7.84
DEGREES OF FREEDOM	29	23
T CRITICAL AT 99.9%	3.40	3.49

DATA ELEMENTS, BOTTOM OF DECK 1983 1988

SPAN 41			SPAN 119			SPAN 84	
^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"	^1983 0 to 1"
0.3	1	0.9	0.5	0.4	0.4	1.1	0.3
0.3	1.3	0.6	0.4	1.1	0.5	0.5	0.3
0.4	1.7	0.7	0.5	0.5	0.7	0.8	0.3
1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.1	0.1	0.4	0.1	0.1	0.4	0.1	0.1
0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.1

ASTORIA BRIDGE CHLORIDE MONITORING PROGRAM - 1988 DATA

BENT 41			BENT 119			BENT 84	
1/8 TO 1 INCH			1/8 TO 1 INCH			1/8 TO 1 INCH	
bottom of deck	bottom of deck	bottom of deck	bottom of deck	bottom of deck	bottom of deck	bottom of deck	bottom of deck
1.33	0.63	0.86	0.43	0.74	0.86	1.14	1.21
1.21	0.67	1.49	0.74	0.55	0.67	1.37	0.98
1.14	0.55	1.21	0.36	0.47	0.78	0.86	0.86
1 TO 2 INCHES			1 TO 2 INCHES			1 TO 2 INCHES	
0.18	0.23	0.20	0.18	0.18	0.25	0.32	0.21
0.34	0.25	0.39	0.18	0.18	0.43	0.30	0.16
0.29	0.29	0.24	0.23	0.20	0.21	0.30	0.14
1/8 TO 1 INCH							
1.03	-0.37	-0.04	-0.07	0.34	0.46	0.04	0.91
0.91	-0.63	0.89	0.34	-0.55	0.17	0.87	0.68
0.74	-1.15	0.51	-0.14	-0.03	0.08	0.06	0.56

NUMBER IN SAMPLE, N	9	9	6
SUM	1.89	0.6	3.12
MEAN	0.21	0.07	0.52
STANDARD DEVIATION	0.79	0.31	0.39
VARIANCE	0.62	0.10	0.15
T TEST T =	0.80	0.65	3.30
DEGREES OF FREEDOM	8	8	5
F CRITICAL @95%	1.86	1.86	2.02
NUMBER IN SAMPLE, N	24	18	
SUM	5.61	2.49	
MEAN	0.23	0.14	
STANDARD DEVIATION	0.55	0.58	
VARIANCE	0.30	0.34	
T TEST T =	2.09	1.00	
DEGREES OF FREEDOM	23	17	
F CRITICAL @97.5%	2.07	2.11	

1 TO 2 INCHES

0.08	0.13	0.1		0.08	0.08	0.15		0.22	0.11
0.24	0.15	-0.01		0.08	0.08	0.03		0.2	0.06
0.19	-0.11	0.14		0.13	0.1	0.11		0.2	0.04

NUMBER IN SAMPLE, N	9	9	6
SUM	0.91	0.84	0.83
MEAN	0.10	0.09	0.14
STANDARD DEVIATION	0.11	0.03	0.08
VARIANCE	0.01	0.00	0.01
T TEST T =	2.87	8.08	4.31
DEGREES OF FREEDOM	8	8	5
F CRITICAL @95%	1.86	1.86	2.02

NUMBER IN SAMPLE, N	24	18
SUM	2.58	1.75
MEAN	0.11	0.10
STANDARD DEVIATION	0.08	0.08
VARIANCE	0.01	0.01
T TEST T =	6.81	5.40
DEGREES OF FREEDOM	23	17
F CRITICAL @99.9%	3.49	3.85

APPENDIX 3

1988 TOTAL CHLORIDE CONCENTRATION AND ESTIMATED TIME RATE OF CHANGE

SPAN 41

beam 1 0 to 1"	beam 2 0 to 1"	beam 3 0 to 1"	beam 4 0 to 1"
1.80	0.90	1.88	0.70
0.90	1.14	1.64	1.02
1.06	1.53	0.86	0.78
2.39	1.96	2.82	0.98
0.78	1.41	3.10	0.98
0.63	1.10	1.17	0.67
0.55	0.86	0.74	0.67
0.74	1.41	1.02	0.70
	1.33	0.63	0.86
	1.21	0.67	1.49
	1.14	0.55	1.21

NUMBER OF SAMPLE POINTS	41
MEAN - SPAN 41	1.17
STANDARD DEVIATION	0.58

NUMBER OF SAMPLE POINTS	100
MEAN - ALL SPANS	1.21
STANDARD DEVIATION	0.61

SPAN 119

beam 1 0 to 1"	beam 2 0 to 1"	beam 3 0 to 1"	beam 4 0 to 1"
1.21	0.51	3.05	0.67
1.14	0.82	2.07	0.74
1.25	2.11	1.61	0.82
1.25	1.52	2.11	0.39
0.59	1.41	1.76	0.82
1.41	1.10	1.41	0.51
2.04	0.47	0.94	0.63
1.14	0.51	1.10	0.67
	0.43	0.74	0.86
	0.74	0.55	0.67
	0.36	0.47	0.78

NUMBER OF SAMPLE POINTS	41
MEAN - SPAN 119	1.06
STANDARD DEVIATION	0.59

NUMBER OF SAMPLE POINTS	82
MEAN - SPANS 41 & 119	1.11
STANDARD DEVIATION	0.59

SPAN 84

beam 2 0 to 1"	beam 3 0 to 1"
1.88	2.62
1.92	1.88
1.64	1.96
1.84	2.39
2.47	1.92
1.10	1.57
1.14	1.21
1.37	0.98
0.86	0.86

NUMBER OF SAMPLE POINTS	18
MEAN - SPAN 119	1.65
STANDARD DEVIATION	0.53

1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.25	0.20	0.59	0.14
0.16	0.22	0.30	0.16
0.16	0.16	0.39	0.14
0.25	0.27	0.74	0.86
0.16	0.39	0.86	0.16
0.14	0.39	0.23	0.21
0.13	0.27	0.27	0.18
0.21	0.18	0.25	0.31
	0.18	0.23	0.20
	0.34	0.25	0.39
	0.29	0.29	0.24

NUMBER OF SAMPLE POINTS	41
MEAN - SPAN 41	0.29
STANDARD DEVIATION	0.18

NUMBER OF SAMPLE POINTS	100
MEAN - ALL SPANS	0.26
STANDARD DEVIATION	0.14

1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.15	0.20	0.43	0.20
0.14	0.13	0.17	0.39
0.18	0.36	0.15	0.25
0.12	0.16	0.36	0.21
0.18	0.23	0.15	0.18
0.23	0.32	0.20	0.32
0.34	0.23	0.36	0.35
0.21	0.34	0.23	0.21
	0.18	0.18	0.25
	0.18	0.18	0.43
	0.23	0.20	0.21

NUMBER OF SAMPLE POINTS	41
MEAN - SPAN 119	0.24
STANDARD DEVIATION	0.08

NUMBER OF SAMPLE POINTS	82
MEAN - SPANS 41 & 119	0.26
STANDARD DEVIATION	0.14

1" to 2"	1" to 2"
0.58	0.27
0.32	0.16
0.34	0.18
0.29	0.16
0.47	0.20
0.32	0.18
0.32	0.21
0.30	0.16
0.30	0.14

NUMBER OF SAMPLE POINTS	18
MEAN - SPAN 119	0.27
STANDARD DEVIATION	0.11

APPENDIX 3, CONT.

1983 TOTAL CHLORIDE CONCENTRATION

SPAN 41				SPAN 119				SPAN 84	
beam 1	beam 2	beam 3	beam 4	beam 1	beam 2	beam 3	beam 4	beam 2	beam 3
0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"	0 to 1"
0.6	1.0	1.2	1.2	1.1	1.8	0.4	0.4	1.6	1.3
2.1	1.0	1.1	1.1	0.7	1.9	1.0	0.5	2.3	1.9
1.6	1.1	1.7	1.4	0.8	1.9	1.3	0.7	1.9	1.0
1.4	0.7	1.9	1.3	1.4	2.0	1.6	0.8	1.1	0.6
1.8	1.6	2.2	1.3	1.3	1.7	1.4	0.4	0.7	0.9
0.3	0.7	0.7	0.4	0.4	0.8	0.3	0.2	1.2	0.8
0.4	0.7	0.9	0.3	0.4	1.0	0.5	0.4	1.1	0.3
0.4	1.2	0.3	0.4	0.6	0.7	0.4	0.5	0.5	0.3
	0.3	1.0	0.9		0.5	0.4	0.4	0.8	0.3
	0.3	1.3	0.6		0.4	1.1	0.5		
	0.4	1.7	0.7		0.5	0.5	0.7		
NUMBER IN SAMPLE			41				41		18
AVERAGE - EACH SPAN			1.00				0.84		1.03
STANDARD DEVIATION			0.53				0.51		0.57
NUMBER IN SAMPLE			100				82		
AVERAGE - ALL			0.94		SPAN 41 & 119		0.92		
STANDARD DEVIATION			0.54				0.53		

1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"	1" to 2"
0.1	0.1	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2
0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.5
0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0
0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.2	0.1
	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	0.1	0.1	0.1		0.1	0.1	0.1	0.1	0.1
	0.1	0.1	0.4		0.1	0.1	0.4		
	0.1	0.4	0.1		0.1	0.1	0.1		
NUMBER IN SAMPLE			40				41		18
AVERAGE - EACH SPAN			0.14				0.12		0.13
STANDARD DEVIATION			0.09				0.07		0.10
NUMBER IN SAMPLE			99				81		
AVERAGE - ALL			0.13		SPAN 41 & 119		0.13		
STANDARD DEVIATION			0.08				0.08		

APPENDIX 4

ERROR FUNCTION VALUE BY CALCULATION

THE VALUE OF THE ERROR FUNCTION, WITH ARGUMENT X, CAN BE CALCULATED FROM THE FOLLOWING RELATIONSHIP.

$$\mathrm{erf}(X) = 1 - \left(\frac{1}{[\ 1 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4\ ]^4} \right)$$

WHERE:

$a_1 = 0.278393$

$a_2 = 0.230389$

$a_3 = 0.000974$

$a_4 = 0.078108$

AND:

$0.1 < X < 2.0$

THIS FORMULA WAS CHECKED AGAINST AN ERROR FUNCTION TABLE AND FOUND TO BE GOOD TO AT LEAST 2 SIGNIFICANT FIGURES.