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PIPE-TO-SOIL POTENTIAL LIMITS FOR PROTECTIVE COATINGS

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BERNARD HUSOCK
HARCO CORPORATION
MEDINA, OHIO 44256

NOVEMBER 1980

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NOVEMBER 1977 - APRIL 1980

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Underwater Facilities	Plastic Tape
Hydrogen Evolution Damage	Asphalt

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report summarizes the results of a study undertaken to determine the limiting potential criteria for cathodic protection of coated metallic underground and underwater facilities to avoid damage from hydrogen evolution. Tests of 30 days duration were performed in Houston tap water on four coatings, i.e., fusion bonded epoxy, coal

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20. ABSTRACT (CONCLUDED)

tar, plastic tape and asphalt. Each coating was cathodically protected at polarized instant off potential levels of -1.02, -1.07, -1.12, -1.17, and -1.22 volts to copper-copper sulfate. It was found that hydrogen evolution is initiated at a polarized potential of -1.12 volts and becomes more vigorous as the applied current is increased. The polarized potential value increases as the current increases only up to a value of -1.22 volts. An increase in applied current beyond that value increases the hydrogen evolution and increases the ON potential, but there is no measurable increase in the OFF potential.

The different coatings tested reacted differently in these tests. These short term tests should not be used for comparison of disbondment resistance. One coating experienced disbondment at an OFF potential where no gas was evident, and another coating experienced no disbondment even at -1.22 volts under vigorous hydrogen evolution.

PREFACE

This report was prepared by Harco Corporation, 1055 West Smith Road, Medina, Ohio 44256 under Contract No. F08635-77-C-0248 with the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403. The work was begun in November 1977 and was completed in April 1980.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

L. M. Womack
L. M. WOMACK
Chief, Airbase Facilities
Branch

Robert E. Boyer
ROBERT E. BOYER, Lt Col, USAF
Chief, Engineering Research
Division

Francis B Crowley III
FRANCIS B. CROWLEY III, Col,
USAF
Director, Engineering and
Services Laboratory

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SECTION I

INTRODUCTION

The recommended practice for control of corrosion on underground pipelines requires "coating supplemented with cathodic protection" (Reference 1). This practice recognizes that cathodic protection is necessary to achieve complete corrosion control on coated pipe. Experience with coated pipe that is not cathodically protected has shown that corrosion is often accelerated at discontinuities (or holidays) in the coating. Because practical pipe coatings cannot be expected to be absolutely flawless, coating together with cathodic protection has been found to be "the best combination of the two means of corrosion prevention" (Reference 2).

Despite the fact that coating together with cathodic protection is acknowledged to be an ideal combination, it is also acknowledged that cathodic protection can have deleterious effects on pipe coatings. These effects result from two basic mechanisms: (1) alkalinity sufficient to "cause the deterioration" and (2) "hydrogen produced at flaws in a coating may progressively detach the coating from the surface of the metal" (Reference 3). These adverse effects do not usually create problems at the normal levels of cathodic protection, but "excessive cathodic protection can cause or accelerate deterioration of coatings" (Reference 4). Because the level of cathodic protection applied to a pipeline is determined by the value of pipe-to-soil potential, an increase in the level of cathodic protection results in more negative values of pipe-to-soil potential. Backstom and Causey (Reference 4) indicate that the adverse effects "occur primarily at cathodic protection levels which are substantially higher than normally used to protect metal structures," and the British Code of Practice states that "the effect can be minimized by avoiding the use of very negative potentials" (Reference 3).

Despite statements such as the above, there is little substantive information in the literature to indicate what is actually meant by "substantially higher than normally used."

Therefore, it can be seen that there is a basic question concerned with determining specific potential levels beyond which coatings become susceptible to damage. Thus, the objective of this study is to determine and demonstrate the limiting surface potential criteria to be measured over underground and under water facilities to avoid damage to protective coatings from hydrogen evolution.

This study is concerned only with the determination of the damage which can result from hydrogen evolution. Damage which can result from the increased alkalinity was not considered in this study.

SECTION II

HISTORY AND BACKGROUND

It is generally agreed that free hydrogen gas, generated when the cathodic protection potential exceeds the hydrogen overvoltage, exerts pressure at flaws in a coating thereby causing damage to that coating. Although the exact value of the hydrogen overvoltage potential can vary in different electrolytes, the value for iron and steel in naturally occurring electrolytes is approximately -1.20 volts to a copper-copper sulfate reference electrode (Reference 5). This potential is a polarized potential or the potential measured at the instant when the cathodic protection current is turned off; it is often referred to as the "instant off" potential.

Despite the fact that the value of hydrogen overvoltage is a polarized potential, the literature on the subject of cathodic protection disbondment almost always refers to potential measurements taken with the cathodic protection current applied with little or no attention given to consideration of IR drop. Thus, the British Code states that "structure/electrolyte potentials more negative than -2.5V should be avoided on buried structures" (Reference 6). Salt crock tests described by Hunter (Reference 7) and others (Reference 8), were conducted at pipe-to-electrolyte potentials of -3.0 volts to a calomel electrode with the current applied. Salt crock testing by the Columbia Gas System Service Company (Reference 9) used 6 volts across the test cell and protective potentials of -1.0 and -1.5 volts to a copper-copper sulfate electrode. In coating tests on buried pipes, Goose (Reference 10) describes work in which samples were maintained at pipe-to-soil potentials of -3.0 volts and -1.5 volts to copper-copper sulfate with the cathodic protection current applied. Backstrom and Causey (Reference 11) describe work on a variety of coatings conducted presumably in fresh water (no information about the water is given) in which the copper-copper sulfate reference electrode was positioned remote from both the anode and the test specimen, and cathodic protection levels were maintained at values of -1.10, -1.25, -1.35, and -1.50 volts with the current applied. The standard methods for testing for cathodic coating disbondment issued by ASTM (References 12 and 13) describe tests performed with the cathodic protection current applied.

All potential measurements taken with cathodic protection applied include a voltage (IR drop) component which is added numerically to the absolute value of the polarized instant off potential (the reading is more negative than the polarized potential). The value of the voltage (IR drop) or the difference between the ON potential and the "instant off" potential is a function of the coating conductance, the electrolyte resistivity, the position of the reference electrode with respect to the pipe, and the magnitude of the applied current. In testing work such as that described in the above references, in which only the ON potentials are of concern, identical ON potentials in different tests would not necessarily be indicative of identical polarized potentials. Because hydrogen evolution is a function of the "instant off" potential, testing work to determine the limiting potential to avoid coating damage from hydrogen evolution would be of little value unless the potentials measured were the actual polarized potential of the structure.

Therefore, tests using various values of ON potentials, as in the referenced work, were not considered to be appropriate for this study. This study tested the coatings using rectifier units which are automatically controlled to deliver the current necessary to maintain given, pre-set polarized or OFF potentials. This was accomplished using TASC (Total Automatic Sampling Controller), as described in Section III, Testing Procedures.

SECTION III

TESTING PROCEDURES

It was decided to test four types of coatings as follows:

1. Fusion bonded epoxy (thin film)
2. Coal-tar
3. Plastic
4. Asphalt

These types were selected because most of the underground coated pipe is coated with one of these types. The particular commercial coatings used in this work to represent each of these types are as follows:

1. Scotchkote 212 (fusion bonded epoxy).
2. Koppers Bitumastic 70-B Standard Enamel (coal-tar).
3. Servi-Wrap P-400 (plastic).
4. Somastic (asphalt).

These coatings are described in Appendix A. The Scotchkote 212, Bitumastic 70-B, and Servi-Wrap P-400 were applied on pipe specimens each of which was 2 inches in diameter by 12 inches long, schedule 40, standard steel pipe. The Somastic was applied to specimens 4 inches in diameter by 12 inches long, schedule 40, standard steel pipe. All coatings were applied in accordance with the manufacturer's recommendations by commercial coating applicators who are experienced in the application of the particular coating.

On each specimen, an intentional holiday was cut through the coating to expose bare steel. The size of this holiday was 3/4 inches in diameter. This is considerably larger than the 1/4 inches in diameter minimum holiday called for in ASTM G8-72 (Reference 12). The reason for using the larger exposed area is to increase the current needed to maintain a given level of potential. The use of larger values of current than ordinarily used in tests such as these, make it easier to monitor the current changes required to maintain the potential level of interest.

The specimens were tested in Houston tap water, an analysis of which is given in Appendix B. The physical arrangement of the components is shown schematically in Figure 1. The cathodic protection was applied using a TASC IV controlled rectifier as shown in Figure 2.

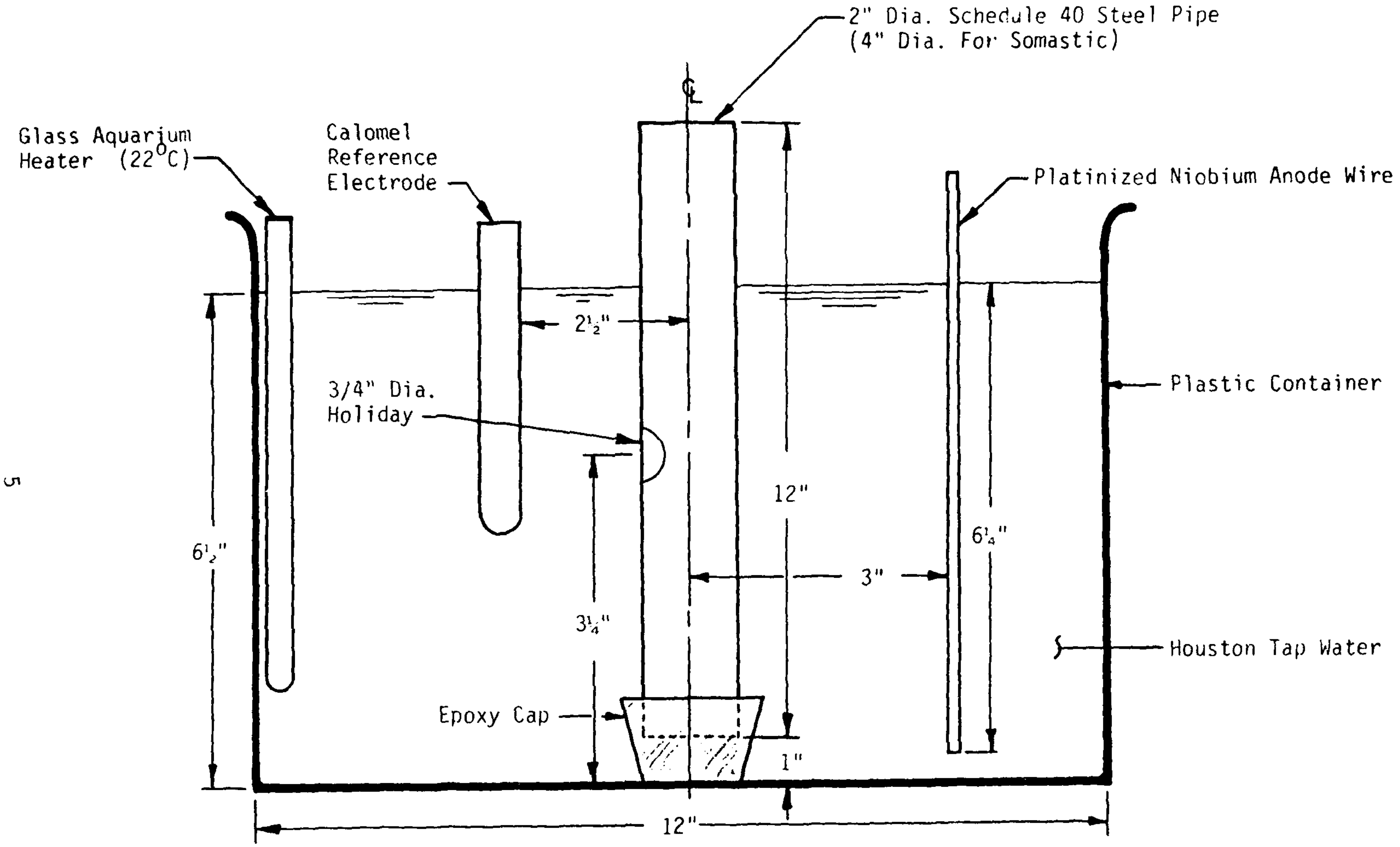

Figure 1. Physical Arrangement of Components in Coating Disbondment Tests

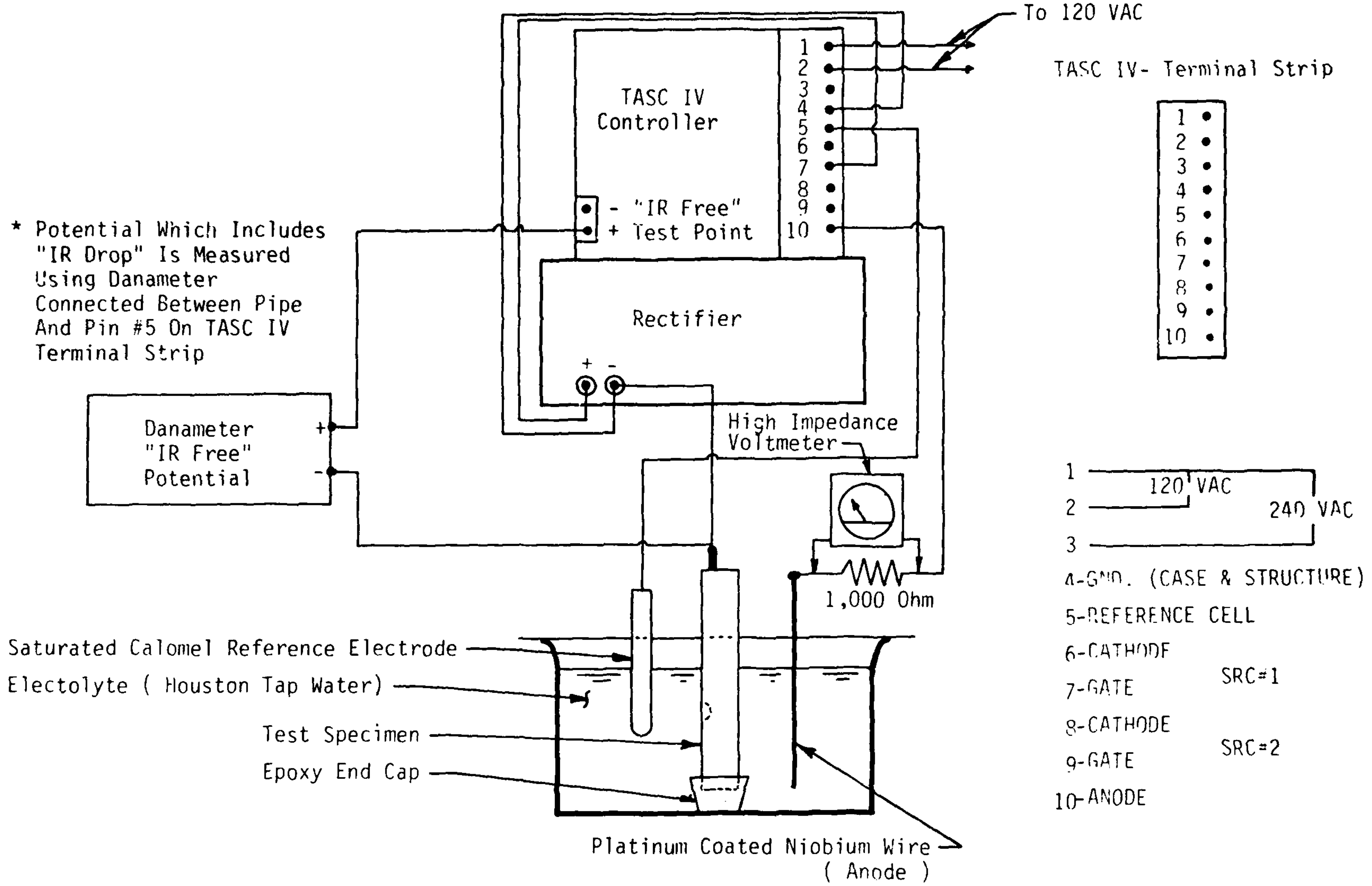

Figure 2. Electrical Schematic-Coating Disbondment Tests

The TASC IV unit used in this study is able to control automatically the applied cathodic protection current necessary to maintain a given level of pipe-to-water potential. The pipe-to-water potentials maintained by this unit are polarized potentials or "instant off" potentials free of IR drop. The TASC IV unit is able to read the polarized potential because the potentials are measured while the current is interrupted for a period of less than 10 milliseconds and the potential is measured at the instant of interruption. If the pipe-to-water potential thus measured is less negative than the potential desired, the rectifier current is automatically increased so that the potential becomes more negative. If the pipe-to-water potential is more negative than desired, the rectifier output current is automatically decreased or turned off entirely, so that the potential becomes less negative. The controller is sufficiently sensitive to maintain a polarized pipe-to-water potential within a range of ±5 millivolts from a given set value. Because the polarized potentials are measured with the current off, the exact position of the reference electrode with respect to the specimen is not critical.

It was originally intended to run six specimens of each coating for a period of 30 days; one specimen would be unprotected (freely corroding) and the others would be run at the following levels of polarized pipe-to-water potential ($Cu-CuSO_4$ reference):

-1.00 volts

-1.10 volts

-1.20 volts

-1.30 volts

-1.40 volts

It was found that the value of polarized potential "leveled off" at a value of -1.22 volts and that polarization to potentials more negative than that value were not possible. Therefore, the testing procedure was modified so that specimens were run at the following values of polarized pipe-to-water potential ($Cu-CuSO_4$ reference):

-1.02 volts

-1.07 volts

-1.12 volts

-1.17 volts

-1.22 volts

One specimen of each coating was immersed without cathodic protection.

Potentials were actually measured using a calomel reference electrode, but the equivalent copper-copper sulfate will be given throughout this report. The copper-copper sulfate reading equivalent to calomel is 70 millivolt more negative than the calomel reading. Thus, -1.02 volts to copper-copper sulfate corresponds to -0.95 volts to calomel.

All specimens were run for 30 days and readings were taken each day (except Saturdays and Sundays) of: (1) the polarized pipe-to-water potential (IR drop free) referred to in this report as OFF potential, (2) pipe-to-water potential with the current on (includes IR drop) referred to in this report as ON potential, and (3) the protective current. It was expected that the changes in current required to maintain a given polarized potential would be the indicator of coating deterioration. The original thinking was that if the coating remained undamaged, the current required to maintain a given level of protection would remain constant, but if the coating disbonded the current would increase.

After each run was completed, the specimens were removed, rinsed with distilled water, and examined for coating damage. After the specimens were cleaned, the percent disbondment was estimated by visually comparing the disbonded area with the area of the intentional holiday.

SECTION IV

RESULTS AND DISCUSSION

A. GENERAL

As indicated in Testing Procedures, it was not possible to achieve a pipe-to-water OFF potential of -1.30 volts and -1.40 volts as was originally intended. The maximum OFF potential obtainable was -1.22 volts. Although evolution of hydrogen was observed at lower negative values, the evolution at -1.22 volts become noticably more vigorous. When that potential was reached, an increase in the applied cathodic protection current produced an increased quantity of hydrogen, but there was no significant increase in potential. The potential can be said to level off at that value and more negative OFF potentials could not be obtained even at substantially higher values of current.

This phenomenon was totally unanticipated. Although the cathodic protection literature refers to a polarized potential of approximately -1.20 volts as the value of the hydrogen overvoltage, there was no reference found in the literature search which indicated that there is leveling off at that value.

Because of the unanticipated leveling off of OFF potentials at -1.22 volts, each of the coatings were tested at revised OFF potential levels of -1.02, -1.07, -1.12, -1.17, and -1.22 volts, yielding the results described below.

B. TEST RESULTS

The potential and current values measured during the testing of these coatings are listed in Tables 1, 2, 3, and 4.

Review of the data in these tables shows that all four of the coating followed similar patterns of behavior. In the first three specimens of each coating, (those at OFF potentials of -1.02, -1.07, and -1.12 volts), the ON potentials remained reasonably constant throughout the test. The corresponding current values on those same specimens decreased as the test progressed. These are the results that would be expected on specimens where the coating remains intact. Film formation at the holiday in the coating is considered responsible for the reduction in the current required to maintain a given level of OFF potential.

Specimens 4 and 5 for all the coatings (those at instant OFF potentials of -1.17 and -1.22 volts) showed more erratic behavior in that the ON potentials and the currents varied to a greater degree as the testing progressed than was the case with the first three specimens. These results are attributed to either the effects of hydrogen gas evolution or coating damage or a combination of both. The instability encountered on Specimen 5 is understandable in view of the fact that the OFF potential remained at -1.22 volts, even when the

TABLE 1. CATHODIC PROTECTION DISBONDMENT TEST
FUSION BOND EPOXY

DAY	SP. 1 -1.02 V		SP. 2 -1.07 V		SP. 3 -1.12 V		SP. 4 -1.17 V		SP. 5 -1.22 V	
	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.
1	-1.11	.027	-1.18	.034	-1.26	.110	-2.45	2.2	-6.32	8.3
2	-1.29	.035	-1.22	.016	-1.25	.070	-2.17	1.7	-1.22	8.7
5	-1.40	.042	-1.25	.023	-1.28	.048	-1.88	1.5	-4.53	7.0
6	-1.35	.036	-1.22	.019	-1.26	.055	-1.74	1.1	-2.62	3.5
7	-1.40	.038	-1.25	.025	-1.27	.045	-1.78	1.4	-1.22	7.0
8	-1.38	.036	-1.26	.023	-1.27	.040	-1.87	1.5	-4.37	7.7
9	-1.29	.034	-1.25	.021	-1.23	.032	-1.74	1.3	-3.77	6.3
12	-1.39	.030	-1.29	.038	-1.25	.025	-2.02	2.6	-4.52	9.0
13	-1.29	.030	-1.34	.033	-1.25	.025	-1.68	1.4	-2.97	4.4
14	-1.32	.025	-1.29	.035	-1.23	.021	-1.68	1.3	-3.07	4.5
15	-1.33	.025	-1.28	.035	-1.23	.020	-1.61	1.1	-3.07	4.4
16	-1.35	.024	-1.27	.030	-1.23	.014	-1.57	0.8	-3.21	4.4
19	-1.34	.020	-1.29	.026	-1.22	.011	-1.53	0.9	-2.72	3.2
20	-1.26	.017	-1.39	.046	-1.24	.012	-1.46	0.8	-2.77	3.9
21	-1.34	.019	-1.33	.036	-1.25	.014	-1.53	1.1	-2.97	4.3
22	-1.33	.016	-1.35	.039	-1.25	.013	-1.57	1.2	-2.87	4.3
23	-1.34	.014	-1.35	.035	-1.25	.011	-1.60	1.3	-2.97	3.4
26	-1.33	.013	-1.33	.030	-1.25	.009	-1.56	0.8	-2.32	2.9
27	-1.33	.014	-1.33	.030	-1.25	.009	-1.53	0.8	-2.37	2.6
28	-1.25	.013	-1.40	.043	-1.27	.011	-1.88	2.2	-2.77	3.8
29	-1.31	.011	-1.41	.046	-1.25	.010	-1.52	0.8	-2.47	2.9
30	-1.33	.012	-1.35	.025	-1.28	.010	-1.57	0.9	-2.62	3.3

TABLE 2. COAL TAR ENAMEL

DAY	SP. 1 -1.02 V		SP. 2 -1.07 V		SP. 3 -1.12 V		SP. 4 -1.17 V		SP. 5 -1.22 V	
	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.
1	-1.10	.090	-1.18	.135	-1.28	.210	-2.52	2.0	-7.97	9.3
2	-1.10	.084	-1.16	.115	-1.32	.210	-3.49	4.4	-6.27	6.9
5	-1.07	.006	-1.15	.055	-1.28	.150	-2.67	2.0	-4.67	7.9
6	-1.05	.004	-1.11	.038	-1.26	.130	-2.01	1.0	-5.30	8.1
7	-1.05	.003	-1.11	.025	-1.23	.126	-1.92	1.3	-4.47	8.3
12	-1.10	.003	-1.10	.004	-1.24	.100	-1.74	1.1	-3.80	4.5
13	-1.13	.002	-1.10	.004	-1.14	.096	-1.78	1.3	-4.02	4.9
14	-1.21	.003	-1.19	.004	-1.25	.104	-1.75	1.3	-3.57	4.2
17	-1.13	.002	-1.08	.002	-1.23	.083	-1.85	1.4	-3.12	3.5
18	-1.22	.003	-1.17	.002	-1.23	.084	-1.57	0.9	-3.17	3.4
19	-1.21	.003	-1.19	.003	-1.24	.088	-1.77	1.2	-3.17	3.6
20	-1.21	.003	-1.15	.003	-1.24	.078	-1.67	0.9	-2.82	3.1
21	-1.24	.005	-1.17	.003	-1.25	.088	-1.59	0.9	-3.47	3.5
24	-1.22	.005	-1.21	.002	-1.24	.073	-1.97	0.1	-2.97	3.0
25	-1.23	.005	-1.19	.002	-1.25	.073	-1.53	0.8	-2.97	3.0
26	-1.20	.005	-1.18	.002	-1.24	.069	-1.62	0.1	-2.79	2.6
27	-1.22	.005	-1.15	.002	-1.23	.069	-1.57	0.9	-2.65	2.8
28	-1.22	.005	-1.12	.002	-1.24	.066	-1.55	0.7	-2.65	2.7

TABLE 3. SERVIWRAP - 400 TAPE

DAY	SP. 1 -1.02 V		SP. 2 -1.07 V		SP. 3 -1.12 V		SP. 4 -1.17 V		SP. 5 -1.22 V	
	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	Poten. mv.	Current ma.
1	-1.10	.085	-1.16	.057	-1.29	.171	-2.67	1.91	-3.87	3.5
4	-1.05	.005	-1.10	.017	-1.28	.001	-2.17	1.58	-3.50	4.9
5	-1.05	.005	-1.12	.019	-1.26	.111	-2.07	1.50	6.87	10.02
6	-1.06	.005	-1.11	.013	-1.25	.100	-1.92	1.25	-5.07	7.3
7	-1.05	.004	-1.12	.013	-1.24	.098	-1.97	1.28	-4.87	6.3
8	-1.05	.005	-1.10	.011	-1.23	.080	-1.75	1.3	-3.47	5.1
11	-1.05	.005	-1.10	.010	-1.25	.079	-2.17	1.55	-3.52	4.7
12	-1.06	.005	-1.08	.009	-1.22	.095	-1.39	1.40	—	5.1
13	-1.07	.005	-1.12	.010	-1.23	.082	-1.68	1.62	-2.93	3.1
14	-1.07	.005	-1.11	.010	-1.24	.076	-1.76	0.97	-3.15	3.2
15	-1.08	.009	-1.10	.009	-1.14	.069	-1.83	1.15	-2.67	2.4
18	-1.05	.005	-1.10	.009	-1.23	.005	-1.76	1.05	-2.67	2.6
19	-1.04	.004	-1.12	.006	-1.21	.050	-1.76	0.95	-2.67	2.1
20	-1.05	.002	-1.10	.005	-1.21	.050	-1.69	0.91	-2.72	2.3
21	-1.05	.002	-1.09	.004	-1.20	.048	-1.69	0.85	-2.57	2.2
22	-1.05	.003	-1.10	.005	-1.20	.046	-1.70	0.85	-2.87	2.6
25	-1.04	.002	-1.11	.004	-1.21	.042	-1.69	0.81	-2.77	2.2
26	-1.05	.002	-1.12	.004	-1.21	.042	-1.70	0.89	-2.77	2.4
27	-1.06	.003	-1.13	.006	-1.22	.047	-1.85	1.09	-2.71	2.6
28	-1.05	.003	-1.13	.005	-1.21	.042	-1.75	0.98	-2.72	2.6
29	-1.05	.002	-1.13	.005	-1.22	.041	-1.72	1.10	-2.72	2.5

TABLE 4. SOMASTIC

DAY	SP. 1 -1.02 V		SP. 2 -1.07 V		SP. 3 -1.12 V		SP. 4 -1.17 V		SP. 5 -1.22 V	
	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.	On Poten. mv.	Applied Current ma.
1	-1.12	.081	-1.17	.095	-1.81	.260	-2.87	1.39	-9.27	7.20
2	-1.12	.074	-1.17	.083	-1.49	.310	-3.97	3.40	-7.87	5.30
3	-1.11	.060	-1.16	.075	-1.52	.330	-3.37	3.55	-8.02	5.20
6	-1.07	.024	-1.13	.043	-1.48	.290	-4.12	4.15	-5.02	7.30
7	-1.07	.021	-1.15	.045	-1.46	.265	-3.87	3.70	-7.07	11.4
8	-1.06	.017	-1.13	.003	-1.46	.275	-3.92	4.10	-6.37	11.1
9	-1.07	.013	-1.12	.031	-1.45	.265	-3.42	3.40	-5.82	9.50
10	-1.05	.010	-1.12	.027	-1.42	.230	-2.97	2.55	-5.57	7.90
13	-1.05	.007	-1.10	.021	-1.42	.260	-3.22	3.20	-6.92	9.10
14	-1.05	.006	-1.10	.021	-1.43	.245	-2.87	2.70	-7.67	10.9
15	-1.05	.006	-1.10	.018	-1.41	.230	-3.32	2.65	-7.52	10.7
16	-1.05	.005	-1.10	.018	-1.41	.230	-2.62	2.40	-7.77	10.8
21	-1.05	.004	-1.10	.013	-1.38	.210	-2.77	2.50	-8.07	9.80
23	-1.05	.004	-1.10	.015	-1.38	.200	-2.82	2.25	-8.62	9.60
24	-1.05	.004	-1.10	.011	-1.37	.180	-2.47	1.80	-8.62	9.20
27	-1.06	.004	-1.11	.011	-1.36	.175	-2.37	1.67	-5.17	4.30
28	-1.06	.003	-1.11	.011	-1.34	.170	-2.32	1.60	-4.57	3.50
29	-1.06	.003	-1.09	.009	-1.34	.170	-2.62	1.90	-5.22	4.50
30	-1.06	.003	-1.09	.009	-1.34	.170	-2.67	2.00	-8.07	9.70

current was increased beyond that which is shown in the tables. An increase in current at -1.22 volts increased the gas generated as well as the ON potential, but did not increase the OFF potential. Thus, it can be seen that the ON potentials had no direct relationship to the OFF potential particularly on Specimens 5. This condition was also the case for Specimens 4. It can be seen that the values of ON potential vary even though the OFF potentials are maintained at a constant value. Thus, it can be stated that the value of ON potential is not a valid indicator for use in ascertaining coating disbondment under conditions where hydrogen is being evolved.

In an attempt to find correlations among the results for each of the types of coatings, the values of current and potential measured on each coating were used to calculate values of apparent resistance as follows:

$$R = \frac{E\text{ on} - E\text{ off}}{I}$$

where

R = Apparent resistance of the specimen, ohms

E_{on} = Pipe-to-water potential with cathodic protection current on, millivolts.

E_{off} = Pipe-to-water potential, instant off, millivolts.

I = Applied current, milliamperes.

The values thus calculated for the various coatings are listed in Tables 5, 6, 7 and 8. The pattern which emerges from comparing the values calculated shows that there are similarities in the results at same levels of cathodic protection for the various coatings.

For example, specimens of all coatings which were maintained at -1.02 volts showed considerable increases in resistance as the test progressed. Similarly, specimens of all of the coatings maintained at -1.07 volts, except for asphalt, also showed large increases in resistance although not in the amount seen at -1.02 volts. The resistance of the asphalt specimen also increased at that potential level, but by a lesser factor than the others. All of Specimens 3 (-1.12 volts) showed resistance values which remained relatively unchanged as the tests progressed except the fusion bonded specimen. On that coating, the resistance of Specimen 3 increased in a manner similar to that seen on Specimens 1 and 2. The resistance of Specimens 4 (-1.17 volts) and Specimens 5 (-1.22 volts) of all coating started at relatively low values and remained low or decreased as the tests proceeded. The resistances of Specimens 4 and 5 were nearly the same for every coating.

Although there were exceptions, it can be said in a very rough approximation, that at -1.02 volts and -1.07 volts there is a

TABLE 5. FUSION BONDED EPOXY - APPARENT RESISTANCE IN OHMS

DAY	SP. 1 -1.02V	SP. 2 -1.07V	SP. 3 -1.12V	SP. 4 -1.17V	SP. 5 -1.22V
1	3330	3240	1270	580	610
2	5140	9380	1860	590	510
5	9050	7830	3130	470	470
6	9170	7890	2360	520	400
7	10000	7200	3110	440	390
8	10000	8260	3500	470	410
9	7940	8570	3440	440	400
12	12330	5790	5200	330	370
13	9000	8180	5200	360	400
14	12000	8800	5240	390	410
15	12400	6000	5500	400	420
16	13750	6670	7860	480	450
19	16000	8460	9090	410	470
20	14120	6960	10000	370	400
21	16840	7220	9290	330	410
22	19380	7180	10000	330	380
23	22860	8000	11820	330	510
26	23850	8670	14440	490	380
27	22140	8670	14440	470	440
28	17690	7670	13640	320	410
29	26360	7390	13000	420	430
30	24170	11200	16000	450	420

TABLE 6. COAL TAR ENAMEL - APPARENT RESISTANCE IN OHMS

DAY	SP. 1 -1.02	SP. 2 -1.07	SP. 3 -1.12	SP. 4 -1.17	SP. 5 -1.22
1	889	815	769	675	729
2	952	782	952	527	736
5	8333	1455	1067	750	441
6	7500	1053	1077	875	506
7	10000	1600	873	577	393
12	26667	7500	1200	514	573
13	55000	7500	1250	480	571
14	63333	30000	1250	446	560
17	44000	55000	1325	504	543
18	66667	40000	1310	455	574
19	54286	40000	1364	536	542
20	54286	26667	1538	538	516
21	44000	33333	1477	452	643
24	36364	63636	1644	816	583
25	42000	48000	1781	434	583
26	36000	55000	1739	474	604
27	40000	40000	1594	471	511
28	40000	25000	1818	514	530

TABLE 7. TAPE - APPARENT RESISTANCE IN OHMS

DAY	SP. 1 -1.02V	SP. 2 -1.07V	SP. 3 -1.12V	SP. 4 -1.17V	SP. 5 -1.22V
1	882	1440	1020	785	772
4	4200	1820	1000	634	606
5	5000	2420	1225	600	566
6	6800	2920	1260	600	527
7	2230	3380	1180	549	579
8	5000	2820	1360	450	442
11	6000	2500	1380	645	495
12	7000	444	1031	153	85
13	7600	4300	1240	306	560
14	8200	3300	1510	606	603
15	6780	3220	1300	573	603
18	6000	3110	2060	559	672
19	4750	8170	1780	618	689
20	15000	5600	1800	568	650
21	16000	5000	1710	608	627
22	10330	18750	1780	620	634
25	9500	9500	2140	763	720
26	14000	*12000*	*2120*	592	658
27	10330	9330	6210	620	572
28	9330	11600	2090	590	575
29	14000	11800	2440	496	611

TABLE 8. ASPHALT - APPARENT RESISTANCE IN OHMS

DAY	SP. 1 -1.02V	SP. 2 -1.07V	SP. 3 -1.12V	SP. 4 -1.17V	SP. 5 -1.22V
1	1234	1053	1192	1223	1124
2	1351	1205	1193	824	1264
3	1500	1200	1212	620	1319
6	2083	1395	1241	711	525
7	2381	1778	1283	730	513
8	2353	1690	1236	671	464
9	3846	1613	1245	662	484
10	3000	1852	1304	706	551
13	4286	1429	1154	641	626
14	5000	1429	1265	630	592
15	5000	1667	1261	811	589
16	5455	1667	1261	604	606
21	7500	2308	1238	640	699
23	7500	2000	1300	733	771
24	7500	2727	1389	722	804
27	10000	3636	1371	719	919
28	13333	3636	1294	719	957
29	13333	2222	1294	763	889
30	1333	2222	1294	750	706

TABLE 9. DISBONDMENT RESULTS

Potential (IR Free) Volts	Disbondment Area-sq.in.				Percent Disbondment			
	Fusion Bonded	Coal Tar	Plastic Tape	Asphalt	Fusion Bonded	Coal Tar	Plastic Tape	Asphalt
-1.02	0	0	0	0	0	0	0	0
-1.07	0	0	0.020	0	0	0	5	0
-1.12	0.0437	0	0.058	0	10	0	13	0
-1.17	0.0625	0	0.095	0	14	0	21	0
-1.22	0.6830	0.0069	0.160	0	150	2	36	0

substantial increase in resistance with respect to time as the tests progressed; at -1.12 volts, the resistance remains unchanged or increases only slightly; and at -1.17 volts and -1.22 volts remains at a low value or decreases.

There is a rough correlation between these findings and the amount of hydrogen evolution observed. At -1.02 volts and -1.07 volts, no gas evolution was observed; at -1.12 volts, some slight evolution of gas occurred; and at -1.17 volts and -1.22 volts, there was vigorous gas evolution.

C. PHYSICAL EXAMINATION

Although all of the specimens were examined for disbondment upon the completion of each test, it should be understood that the results given here are merely informational. Conclusions should not be drawn from this information concerning the disbondment resistance of any particular coating. Although all the coatings were subjected to the same levels of cathodic protection, it must be appreciated that these are very short term tests conducted in water and that they would not necessarily be indicative of long term performance in an underground environment. In addition, the testing of only one sample of each coating at a given potential level is certainly not a sufficient sample on which to base general conclusions.

The disbondment results observed are listed in Table 9 (see page 18). These results show that the heavier coatings, i.e., asphalt and coal tar, showed better disbondment resistance than the fusion bonded epoxy and the plastic tape. The plastic tape showed disbondment even at a potential level (-1.07) where there was no apparent gas evolved. It is interesting that the asphalt and coal tar showed little or no disbondment even at -1.22 volts in the presence of vigorous gas evolution. On the basis of these tests, it can be stated that there is no value of potential which can be considered to be a limit, that is, a value of potential beyond which (more negative) disbondment always occurs and below which coatings do not disbond. For example, during these tests disbondment was found on the tape specimen at the relatively low negative OFF potential of -1.07 volts with corresponding ON potentials less negative than -1.16 volts, while no disbondment was found on the asphalt specimen at the upper limit of OFF potential, -1.22 volts, and corresponding ON potentials more negative than -8.0 volts.

The above remarks are not intended to indicate that one coating is superior to another in disbondment resistance, but merely to show that under certain conditions, disbondment can occur at relatively low negative potentials and also that coatings can be found to be resistant at potential values which are often considered to be excessive.

SECTION V

CONCLUSIONS

The results of the coating tests conducted in Houston tap water showed that:

1. Hydrogen evolution was initiated at an OFF potential of -1.12 volts to copper-copper sulfate and became vigorous at OFF potentials of -1.17 and -1.22 volts.

2. The most negative OFF potential obtainable was -1.22 volts. The OFF potential could not be made more negative than that value even with a substantial increase in applied current.

3. An increase in the current applied to a specimen at an OFF potential of -1.22 resulted in increased hydrogen evolution and an increase in the negative ON potential, but the OFF potential remain unchanged.

4. The OFF potential could not be directly related to the ON potential and, therefore, the ON potential is not considered to be a valid indicator of hydrogen evolution.

5. Hydrogen evolution by itself did not produce coating disbondment in all cases in these short term tests. On the other hand, one specimen showed disbondment even though there was no visible gas evolution.

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4. Backstrom, T.E. and Causey, F.E., "Effects of Cathodic Protection on Protective Coatings," Report No. ChE-71 United States Department of Interior, Bureau of Reclamation, February 1969, Page 1.

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11. OP. Cit. Reference 3, Page 4.

12. Standard Methods of Test for Cathodic Disbonding of Pipeline Coatings," American Society for Testing and Materials, Designation: G8-72.

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APPENDIX A

COATING SPECIFICATIONS

FUSION BONDED EPOXY

The fusion bonded epoxy coating used in this study is known commercially as "Scotchkote" Brand 212 Fusion Bonded Epoxy Coating as manufactured by the 3M Company. It is described by the manufacturer as a one-part, heat curable, thermosetting powdered epoxy coating. It is applied to pipe preheated to approximately 450°F after being cleaned by removing oil, grease and loosely adhering deposits and prepared by abrasive blast to NACE near white. The 212 powder is deposited electrostatically to a minimum thickness of 10 mils (.254mm).

The manufacturer's literature lists the properties given in Table A-1.

TABLE A-1. PROPERTIES OF FUSION BONDED EPOXY

PROPERTY	VALUE
Color	Brown
Specific Gravity	1.35
Coverage 10 mil (2.54mm) coating	14.2 ft^2/lb ($2.59m^2/kg$)
Shelf life at 80°F (27°C)	12 months
Gel time at 400°F (204°C)	9 secs.
Explosibility minimum explosive concentration	.03 oz/ft^3 30.6 gms/m^3

Test data excerpted from the manufacturer's literature is given in Table A-2.

TABLE A-2. TEST DATA

Property	Test Description	Results
Impact	ASTM G-14 1/8 in.x 3 in.x 3 in.(.32cmx7.6 cmx7.6cm)steel panel 5/8in. (1.6cm)Radius Tup	160 in.-lbs.(1.8 kg-m)

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Property	Test Description	Results
Abrasion Resistance	ASTM D-1044 CS 17,1,000 gm weight 5,000 cycles	0.0664 gm loss
Abrasion Steel(Shear)	ASTM D-1002 10 mil(0.254 mm)glue line	5,300 psi 376 kg/sq.cm.
Penetration*	ASTM G-17 -40°F to 240°F (-40°C to 116°C)	0
Tensile Strength	ASTM D-2370	10,000 psi 710 kg/sq.cm.
Elongation	ASTM D-2370	7.1%
Compressive Strength	ASTM D-695	13,700 psi 973 kg/sq.cm.
Thermal Shock	310°F to -100°F(154°C to -73°C)4 in.x4 in.(10.2 cm x10.2 cm) coated panel	10 cycles no effect
Volume Resistivity	ASTM D-257	1.27x10^{17}ohm cm
Salt Fog	ASTM B-117 1,000 hours	No blistering, no discoloration, no loss of adhesion
Salt Crock*	90 day, 5 volt, 5% NACL	Disbondment diameter 50 mm average
	90 day,1.5 volt,3%,ASTM G-8 salt solution	Disbondment diameter 51 mm average
	90 day,6 volt,3%,ASTM G-8 salt solution	Disbondment diameter 46 mm average
	180 day,1.5 volt,3%,ASTM G-8 salt solution sand crock 230°F(110°C) panel temperature,22 mil (0.560 mm) coating thickness	Disbondment diameter 39 mm average
Hot Water Resistance*	190°F(88°C)immersion 2,200 hours	Surface roughness and small surface blisters, coat softer, good adhesion

Property	Test Description	Results
Hot Water Resistance	160°F (71°C) immersion 2,200 hours	Slight color change, very slight softening, excellent adhesion
	140° (60°C) immersion 2,200 hours	Very slight color change, excellent adhesion
Bendability*	Pipe coupon mandrel bend at 73°F (23°C)	15 pipe diameters average
	Pipe coupon mandrel bend at 0°F (-18°C)	15 pipe diameters average

*Tests conducted on two 3/8 inch (60 mm) OD production coated pipe.

COAL TAR

The coal tar enamel coating used in this study is Bitumastic 70-B Standard Enamel as manufactured by Koppers Company. It is described by the manufacturer as a fully plasticized enamel covering a wide temperature range. It is applied to a pipe whose surface is prepared by blasting to meet NACE Standard TM-01-70, Visual Standards, between NACE NO. 3 and NACE No. 2. After a primary coat of 70-B primer, the enamel is hot-applied to produce a coating thickness of 3/32" minimum.

The manufacturer's literature lists the characteristics given in Table A-3.

TABLE A-3. CHARACTERISTICS OF BITUMASTIC ENAMELS

Characteristic	BITUMASTIC 70-B STD Enamel
Softening Point (^{o}F) ASTM C36 (R & B)	220-235
ASH (%) By weight by ignition	25-35
Specific Gravity at 77^{o}F ASTM D71	1.40-1.60
Penetration (ASTM D5)	
at 77^{o}F	4-9
at 115^{o}F	12-25
SAG (1/16-in.max.) AWWA C203-62	24 hours at 160^{o}F
Crack (none) AWWA C203-62	6 hours at -10^{o}F
Normal Application Temperature (^{o}F)	450-490
Temperature Exposure Range (^{o}F)	-10 to 160

PLASTIC TAPE

The plastic tape coating used in this study is a cold-applied, self-adhesive pipe wrap known as Servi-Wrap P-400 as manufactured by W. R. Grace & Company. It is described by the manufacturer as a "tough, pliable, corrosion resistant pipe wrap" that "provides a dual seal of a cross laminate, high density polyethylene film combined with a thick, factory controlled layer of adhesive-consistency, bituminous rubber compound." It was applied to a clean and dry pipe surface in accordance with the manufacturer's recommendations.

The manufacturers literature lists the physical properties given in Table A-4.

TABLE A-4. TYPICAL PHYSICAL PROPERTIES OF PLASTIC TAPE

Property	Value	Test Method
Color	Dark Grey-Black	
Thickness	Compound 40 Mils Film 4 Mils Total 44 Mils	
Tensile Strength	5125 psi	ASTM D-882-56T
Elongation at Break	205%	ASTM D-882-56T
Impact Resistance (1)		
Single Layer	13 Kg Cm	ASTM G-14
Double Layer	39	
Puncture Resistance (2)	57 lb	ASTM E-154
Adhesion to Steel - Initial	6 lb	DIN 30670 Modified
30 Min	8 lb/in.	
Adhesion to Self - Initial	3 lb/in.	
30 Min	4 lb/in.	
Permeance-Perms. (3)	0.1 Max.	ASTM E-96 Method B
Pliability (4)	Pass	ASTM C-711
Exposure to Fungi In Soil - 16 Weeks	Unaffected	
Alkali & Acid Resistance	Excellent	
Dielectric Breakdown	9700 Volts	ASTM D-149

Property	Value	Test Method
Resistance to Cathodic Disbondment	Excellent	ASTM G-8
Conformability	Excellent	
Operating Temperature Range	-25°F.to 150°F.	
Application Temperature Range	40°F.to 120°F.	

Notes:
(1) Film Break
(2) Stretched by Blunt Object
(3) Grains/Sq Ft /Hr /In Hg
(4) 180° Bend Over 1/4 inch Mandrel @ -35°F.

ASPHALT COATING

The asphalt coating used in this study, identified by the trade mark Somastic, is manufactured and applied by H. C. Price Company. The manufacturer describes this coating as a dense mixture of asphalt-mastic. Typical general proportions of material in the mastic mix are as follows:

Asphalt	10% to 12% by weight
Aggregate: Sand and Lime Filler	88% to 90% by weight
Fiber	0.10% to 0.15% by weight

"The materials are blended and mixed in a specially built asphalt-mastic heating plant designed to maintain absolute control on proportions and temperatures of the mix. Pug mills are used to deliver a continuous flow of mastic from the machine, sufficient mixing time being alloted to secure a final homogeneous coating weighing approximately 135 pounds per cubic foot."

The pipe surface is prepared by preheating to drive off moisture, then cleaned and steel shot blasted. A hot primer is applied and the asphalt-mastic mixture is extruded over the circumference of the primed pipe in a continuous process to form a uniformly thick, seamless coating. The coating thickness on the specimens used in this study was 3/8" nominal and 5/16" minimum.

The specifications derived from the manufacturer's literature are:

1. PRIMER - .35 Gallon per 100 square foot Minimum Somastic Primer produced from manufactured asphalt, natural asphalt and appropriate petroleum thinner.

2. ASPHALT (10% to 12% by Weight)

Operating Temperature, °F	120--	150--	190--
Softening Point (Ring and Ball), °F	150-175	175-200	210-220
Penetration at 77° 100 g, 5 sec	21-26	15-17	7-11
Flash Point (Cleveland Open Cup), °F	450	450	450
Loss on Heating at 325°F, 5 hours,%	0.5	0.5	0.5
Ductility at 77°F,cm	3.5	3.5	1.0
Percent Soluble in CCl_4	99.0	99.0	99.0

3. AGGREGATE (88% to 90% by Weight)
   Clean non-micaceous and graded to maximum density.
   (a) Sand
   100% Passing 6 Mesh U.S. Standard Screen
   (b) Mineral Filler
   Crushed Stone or Equivalent minimum 75% by weight passes 200 Mesh U. S. Standard Screen; 100% passes 50 Mesh U. S. Standard Screen.

4. FIBER (0.10% to .15% by Weight of Total Mastic Materials)
   The individual filaments shall be predominately one-fourth to one inch in length and have a nominal diameter of 0.0001 to 0.001 inch as determined by Owens-Corning Fiberglass Test Method No. TF-515K for nominal filament diameter.

APPENDIX B

HOUSTON TAP WATER ANALYSIS RESULTS

The chemical and semiquantitative spectrographic analyses are given in Tables B-1 and B-2, respectively.

TABLE B-1. CHEMICAL ANALYSIS

Chloride, mg/l	40.
Sulfate, mg/l	2.0
Nitrate Nitrogen, mg/l	0.14
Dissolved Oxygen, mg/l	7.0
Total Solids, mg/l	305.
Total Fixed Solids, mg/l	256.
pH	7.0
Specific Conductance, mho/cm	430.0
Alkalinity, mg/l	172.0

TABLE B-2. SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS

Elements	Approximate No. of mg/l
Calcium	167.
Magnesium	6.
Sodium	4.
Iron	0.5
Silicon	0.7
Aluminum	0.1
Boron	0.2
Copper	0.1

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INITAL DISTRIBUTION

HQ AFSC/DEEE	1
HQ ATC/DEMM	1
HQ SAC/DEEM	1
HQ PACAF/DEEE	1
HQ MAC/DE	1
HQ TAC/DE	1
HQ AAC/DEEE	1
HQ AFLC/DEMG	1
HQ USAFE/DEMO	1
AFIT/DET	1
HQ AUL/LSE 71-249	1
AFIT/Tech Library	1
USAFA/DFCEM	1
DTIC/DDA	12
HQ AFRES/DEMM	1
FAA/RD430	1
ANGSC/DEM	1
CERF	1
CERL	1
USAWES	1
HQ AFESC/TST	1
HQ AFESC/DEMM	1
HQ AFESC/RDCF	5
AFATL/DLODR	1
AFATL/DLODL	1

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