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April 1994

Field Test Results of Corrosion-Resistant Coatings for Carbon-Steel Steam Condensate Return Lines

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by
Vincent F. Hock
Henry Cardenas
James R. Myers

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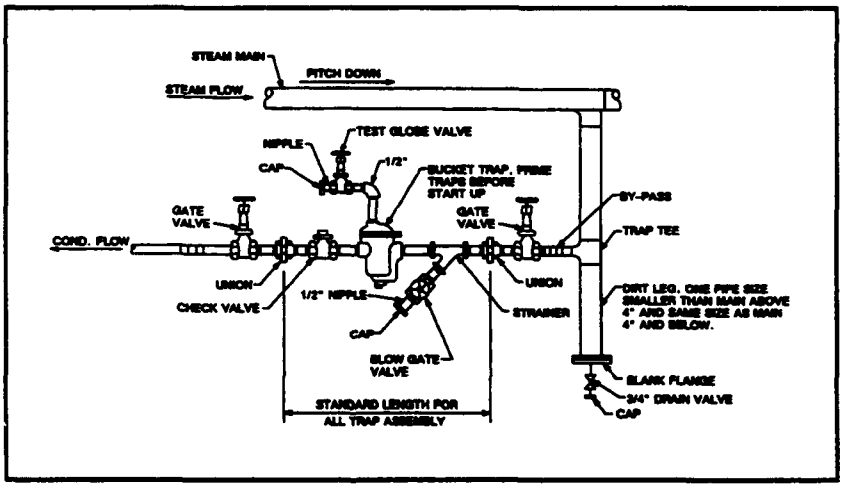

Steam heat is still used at many U.S. Army installations. Condensate return lines, which convey the liquid condensate that occurs throughout the system back to the boiler, form an integral part of steam distribution systems. Steam condensate return lines degrade through several site-specific mechanisms that result in corrosion and cause these systems to fail before reaching their expected design life.

This report presents the results of field tests done at an Army installation using corrosion-resistant phenolic coatings to mitigate these degradation processes. The coatings were found to be effective in mitigating condensate corrosion; preliminary results indicate that this coating may extend the expected service life of condensate return lines by at least 10 percent.

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Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit MM-CL3, "Protective Coatings for M&E Equipment and Distribution Systems." The technical monitor was Joseph McCarty, CEMP-ET.

The work was performed by the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Vincent Hock. Dr. James Myers is a corrosion consultant and the director of JRM Associates, Franklin, OH. The contributions of the following USACERL personnel are gratefully acknowledged: Vicki Van Blaricum, Michael Case, Kirk McGraw, and William Bahnfleth. The technical assistance provided by Malcolm McLeod, U.S. Army Center for Public Works (USACPW), and Edward Blake and Juel Knutson, Heresite Protective Coatings, Inc., was invaluable to the successful completion of this work. Dr. Paul Howdyshell is Chief, CECER-FM, and Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

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1 Introduction

Background

Many U.S. Army installations still use steam heat. The return lines that convey the liquid condensate from the steam distribution system to the boiler are integral to the system, and commonly develop corrosion-induced leakage that can cause premature system failure and drain-limited Operations and Maintenance (O&M) resources. Initial corrosion problems in condensate return lines usually start small, and losses from system leaks are simply replenished with makeup water systems. This practice can begin a vicious cycle. In time, the makeup water demand increases to the point where large volumes of potable water are introduced to the boiler water makeup treatment system, even further increasing the likelihood of corrosion-induced leaks.

Several available methods can successfully treat the kinds of corrosion that occur in condensate return lines. However, because return lines are often physically difficult to access, their treatment is limited to the use of a variety of chemical processes at relatively high capital, labor, and materials costs. To help provide corrosion protection at a lower cost, the U.S. Army Construction Engineering Research Laboratories (USACERL), together with Heresite Protective Coatings, Inc.,* has engaged in the development, laboratory testing, and field testing of several high-performance baked phenolic coating systems for use in immersion applications at high temperatures.** Field testing of phenolic coating in this application is needed to determine if this treatment is suitable for use on condensate return lines.

Objectives

The overall objectives of this study were to evaluate the ability of phenolic coatings to mitigate the corrosion problems associated with carbon-steel condensate return lines and heat exchangers. The objectives of this part of the study were to characterize corrosion problems associated with carbon-steel condensate return lines and investigate the ability of phenolic coatings to mitigate such corrosion.

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* Heresite Protective Coatings, Inc., 822 S. 14th St., PO Drawer 250, Manitowoc, WI 54221-0250, tel. 414/684-6646.

** V.F. Hock, V.L. Van Blaricum, C.H. Neff, J.R. Myers, G.M. Arguelles, and R.H. Knoll, *Development and Testing of an Anti-Scale/Corrosion Resistant Coating for Domestic Hot Water Heat Exchangers*, Technical Report (TR) M-91/05/ADA231716 (U.S. Army Construction Engineering Research Laboratory [USACERL], December 1990).

Approach

The types and principal causes of corrosion-induced leakage in condensate return lines were identified through a field investigation at three Army installations: (1) Fort Benjamin Harrison, IN, (2) Walter Reed Army Medical Center, Washington, DC, and (3) Fort Meade, MD. Field exposure tests were conducted at Fort Meade to test and evaluate candidate corrosion resistant coatings for application to carbon-steel condensate return lines. Results were tabulated and analyzed, and conclusions and recommendations were formulated.

Mode of Technology Transfer

It is recommended that the results of this study be incorporated into Corps of Engineers Guide Specifications 15562, *Heating and Utilities Systems, Central Steam* and 15569, *Water and Steam Heating; Oil, Gas or Both; up to 20 MBTUH*, to allow the use of the baked-on phenolic coating on heat distribution system condensate return lines.

2 Field Problems

Field investigations conducted as part of this study have outlined various forms of corrosion-induced leakage of condensate return lines and their causes. The following sections review the phenomenon and present actual case studies.

Background

Condensate return lines are an integral part of a steam distribution system that handle the liquid portion of the flow that condenses out of the gaseous state. The condensate water is received from a steam trap to be conveyed back to the boiler. The line is normally comprised of 1- to 2-in. diameter schedule 40 or 80 carbon-steel pipe.*

Condensate return lines can also be found in association with steam traps, the basic function of which is to separate mixtures of steam and condensate so that steam is fed back to the steam flow while water is released to the condensate return lines (Figure 1).

Condensate flows can be gravity driven, but are often augmented with pumps. Pressures existing in these lines may vary from design to design and are greatly influenced by differing maintenance practices. For example, a system designed for a given pressure may degenerate to the point where large quantities of makeup water

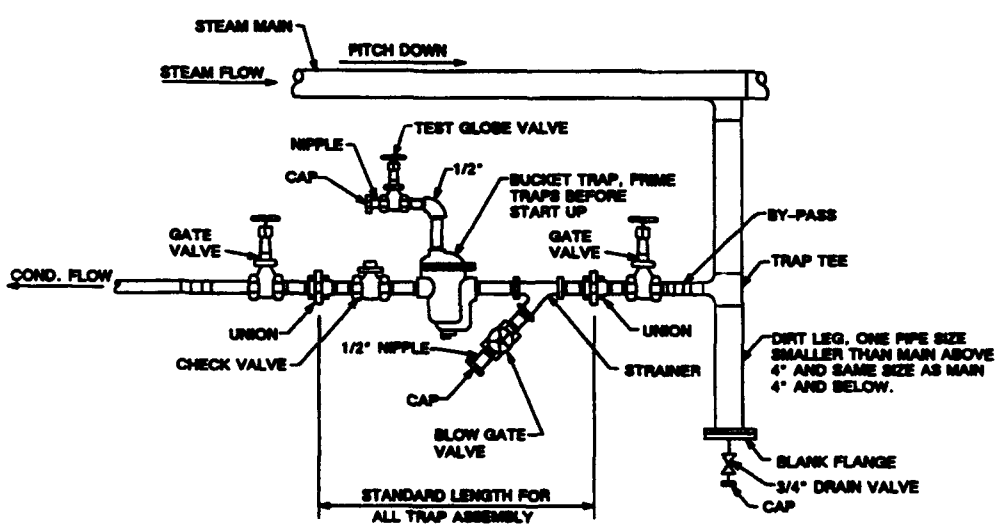

Figure 1. Steam system condensate return line.

* A metric conversion table is included on p 26.

are required to maintain steam service. Such systems commonly develop leaks so that observed pressures may drop to zero. Incidentally, a comparison of actual and intended condensate pressure does not necessarily offer an insight into system efficiency. It is plausible, however, to cite the percentage makeup water requirement as a parameter of system efficiency.

Corrosion in Condensate Return Lines

The fundamental causes of corrosion in carbon-steel condensate return lines are the dissolved gases CO_2 and O_2. The most prevalent of the two issues found in U.S. Government carbon-steel condensate return lines has been CO_2. When CO_2 goes into solution, it hydrolyses to form carbonic acid as follows:

$$CO_2 + H_2O \rightarrow C_2CO_3$$

At this point, the acid will attack iron as would any other acid. This attack occurs as CO_2 grooving or channeling and proceeds through the following reaction:

$$Fe + 2H_2CO_3 \rightarrow Fe(HCO_3)_2 + H_2$$

The rate of CO_2 attack is proportional to the amount of CO_2 present in the condensate water and the velocity of the flow. At pH values above 6.0, the concentration of CO_2 is approximately 2 parts per million (ppm) and the corrosion rate is relatively slow.

A particularly insidious aspect of this form of corrosion is that, once the process has initiated and under the right conditions, the carbon dioxide can be recycled. As the condensate travels downstream and passes areas of pressure drops or locations of reduced CO_2 content, the ferrous bicarbonates formed during the original attack will decompose:

$$Fe(HCO_3)_2 + 2H_2O \rightarrow Fe(OH)_2 + 2CO_2 + 2H_2O$$

Since pressure drops in the direction of flow are unavoidable, the recirculation of carbon dioxide may proceed readily. The CO_2 recycling dynamic contributes to the higher corrosion rates encountered near the downstream ends of long condensate return lines.

Where the condensate pH is less than 6.0 and CO_2 attack has initiated, the addition of oxygen facilitates the process by preventing the formation of a passive layer on the carbon-steel surfaces. The ferrous hydroxide [$Fe(OH)_2$] formed during the CO_2 recirculation reaction can then combine with O_2 as follows:

$$2Fe(OH)_2 + \frac{1}{2}O_2 + H_2O \rightarrow 2Fe(OH)_3 \rightarrow Fe_2O_3 \cdot 3H_2O$$

and

$$3Fe(OH)_2 + \frac{1}{2} O_2 + H_2O \rightarrow Fe(OH)_2 + 2Fe(OH)_3 \rightarrow Fe_3O_4 + 4H_2O$$

The final products of these two reactions are the reddish brown, hydrated hematite (Fe_2O_3) and the black, hydrated magnetite (Fe_3O_4) that are the commonly observed deposits found in condensate return lines, and that are known to cause flow restrictions.

Where O_2 is present in condensate with a pH greater than 6.0, the corrosion phenomena is entirely changed. In this case, the O_2 generally controls the corrosion process as an O_2-induced pitting of carbon-steel becomes the dominant activity. The corrosion pits occur randomly and typically contain hydrated magnetite covered by tubercles (mounds) with an outer layer of reddish brown hydrated hematite.

Corrosion Problems at Fort Benjamin Harrison

Condensate return line problems at the Fort Benjamin Harrison Medical Center stem from system-wide operation difficulties. On an average February day, the central boiler plant produces well over one million lb of steam at 100 pounds per square inch gage (psig). During the winter of 1987-1988, the system leaks were of sufficient intensity to induce a makeup water requirement of 80 percent, or about 110,000 gal per day.

The high makeup water requirements lead to inadvertent aggravation of the corrosion problems. Dealkalizers used at the heating plant were capable of processing only 60,000 to 70,000 gal per day. Large amounts of high alkalinity water containing up to 50 milligrams per liter (mg/L) of dissolved CO_2 were being fed into the steam system. Even though the boiler waters were being treated with neutralizing amines, the situation still promoted aggressive water chemistries with pH values of 4 reported in some locations.

Two basic concerns regarding the corrosion of the condensate return lines included: (1) CO_2-induced grooving and channeling, and (2) line plugging due to deposit of stream-carried corrosion products. It was reported during the winter of 1987-1988 at some locations that schedule 80 pipe was incurring thread-area perforations in as little as 9 months. Most of these rapid failures occurred at locations far from the heating plant where CO_2 levels were being recycled naturally so that the neutralizing additive was exhausted. Figure 2 shows a sample failed section of 1.0-in. diameter schedule 40 condensate return line removed on 4 May 1989 from a horizontal section in the Fort Benjamin Harrison Medical Center. Note that CO_2-induced corrosion occurred only along the bottom of the pipe. No CO_2-induced corrosion was detected, nor was the minimum wall thickness requirement violated at locations that were free of grooving/channeling.

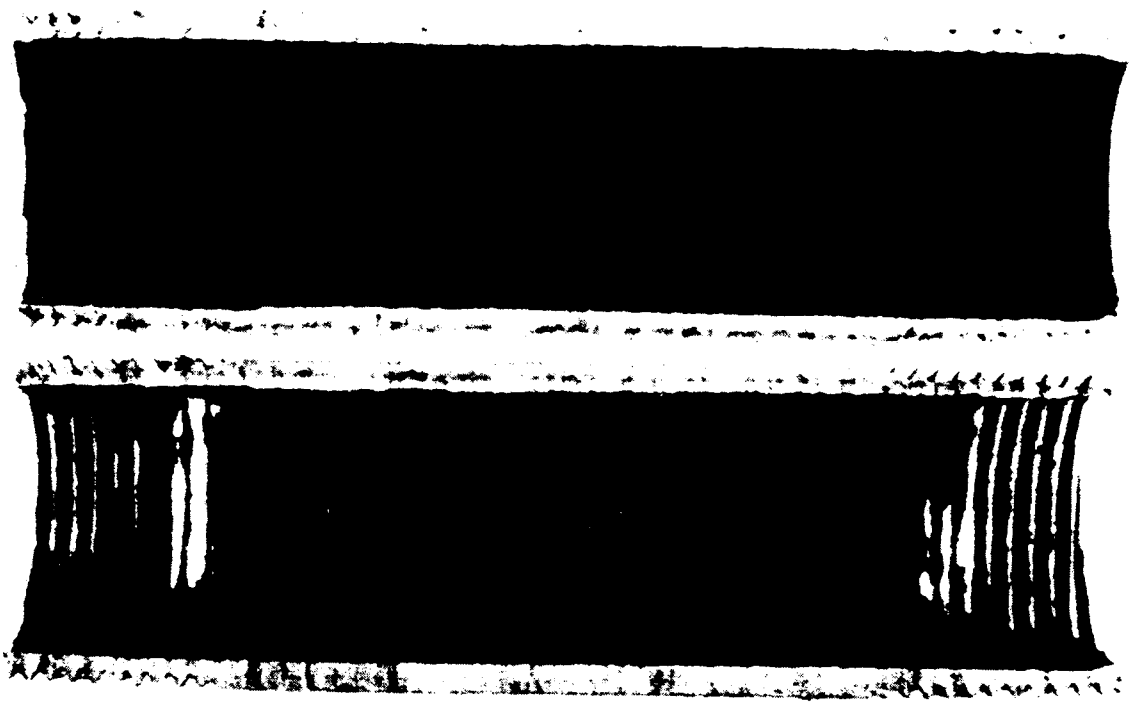

Figure 2. Failed condensate return line specimen, Fort Benjamin Harrison Medical Center.

The issue of line plugging develops downstream of the grooving/channeling. Figure 3 shows a severely restricted cross section of carbon-steel pipe taken from a vertical run of condensate return line in the medical center located just above a condensate-receiver tank. Note that no significant corrosion occurred on the pipe wall. The specimen satisfied the wall thickness requirement for a 1.25-in. nominal diameter schedule 40 carbon-steel pipe.

Corrosion Problems at Walter Reed Army Medical Center

Steam generation at the central heating plant at the Walter Reed Army Medical Center produces 320,000 pounds per hour (lb/hr) at a pressure of 110 psig. On an average February day, the plant uses up to 30 percent makeup water due to system leakage occuring in carbon-steel condensate return lines within buildings.

The makeup water is taken from the Potomac River, sodium-zeolite softened, and degasified. Various additions to the water include: sodium sulfite, phosphates, dispersants, and caustic. No amine neutralizers are permitted due to restrictions set

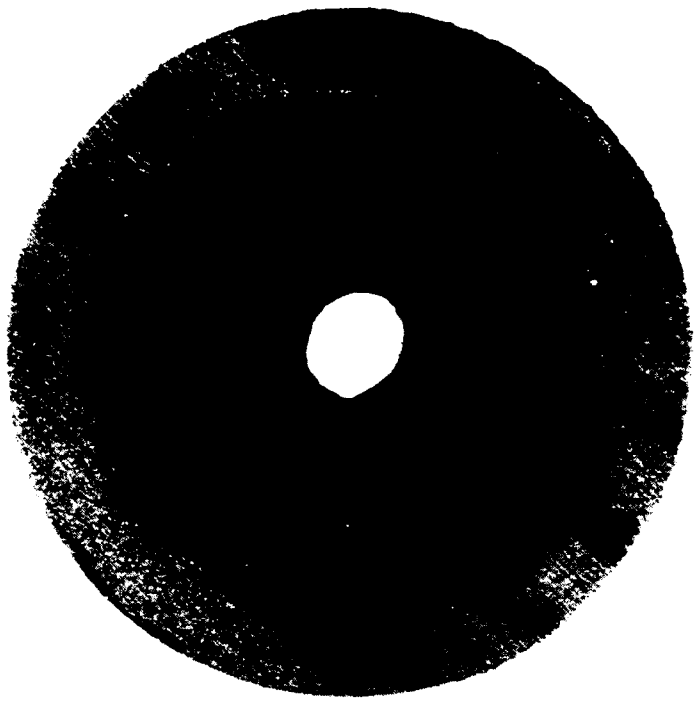

Figure 3. Cross-section of deposit restricted condensate return line, Fort Benjamin Harrison Medical Center.

by the local medical personnel. Dealkalization is only partially executed due to mechanical system limitations.

Water is dealkalized at a rate of 20 gal per minute (gpm). A major building addition has developed a serious bypass flow. Nondealkalized water enters the makeup stream at a rate of 35 gpm. Under these circumstances, the condensate water typically exhibits pH values less than 6. The resulting corrosion rates are relatively high. Small diameter, schedule 40, carbon-steel condensate return lines often incur thread area leaks within 2 years of installation. Figure 4 shows samples of failed condensate return line specimens taken from the Medical Center on 26 May 1989. The specimens taken from a horizontal section contain thread area leaks induced by CO_2 grooving or channeling following 2 years of service. Corrosion occurred along the bottoms of the pipes. No O_2-induced corrosion was observed. Also, the pipe wall areas not affected by grooving or channeling retained sufficient thickness to meet the requirements for schedule 40 carbon-steel pipe.

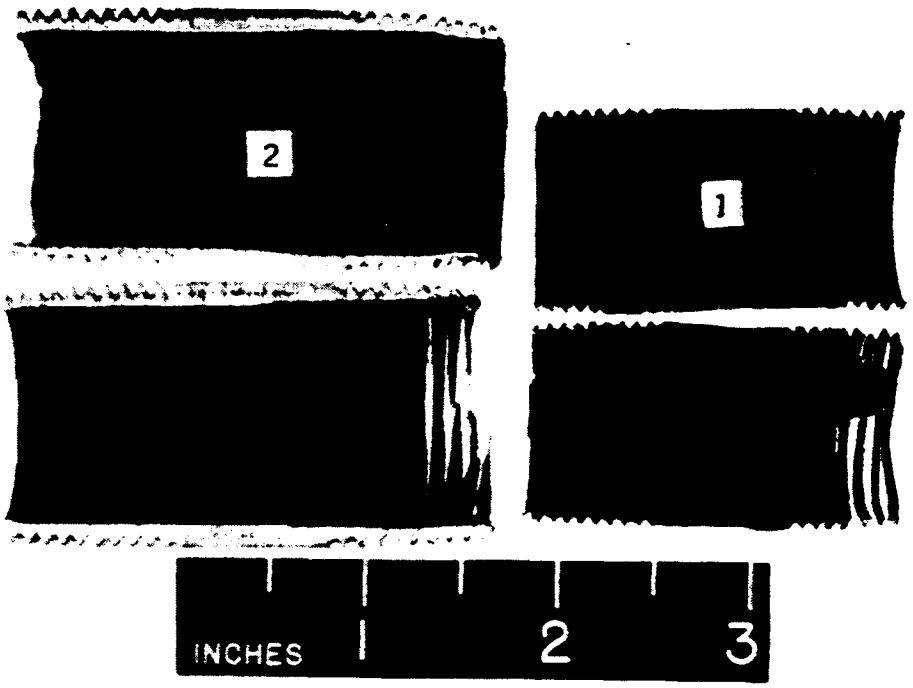

Figure 4. Failed condensate return line pipe, Reed Army Medical Center, Washington, DC.

Corrosion Problems at Kimbrough Army Hospital, Fort Meade

Heating plant No. 3 at Kimbrough Army Hospital generates steam at approximately 12,000 lb/hr at a pressure of 90 psig. On a typical December day in 1989, the operation required 29 percent makeup water, mostly attributed to the corrosion-induced leakage associated with the condensate return lines.

Water used to generate the steam is taken from the little Patuxent River and a well supply. Before feeding it into the boiler, the water is sodium-zeolite softened and deaerated. Additions to the boiler water include sodium sulfite, phosphate, tannin, and caustic soda. Amine neutralizers were not included among the additives due to a perceived carcinogen hazard.

With pH values generally less than 6, the condensate was understandably aggressive to carbon-steel. Figure 5 shows a carbon-steel pipe specimen taken from a horizontal position in the Kimbrough Army Hospital located just 500 ft from the boiler plant.

The 2.0-in. diameter schedule 40 specimen failed 3 years following installation due to CO_2 grooving or channeling. Examination of the specimen revealed no indication of O_2-induced corrosion, and that grooving or channeling occurred in the lower portion of the pipe.

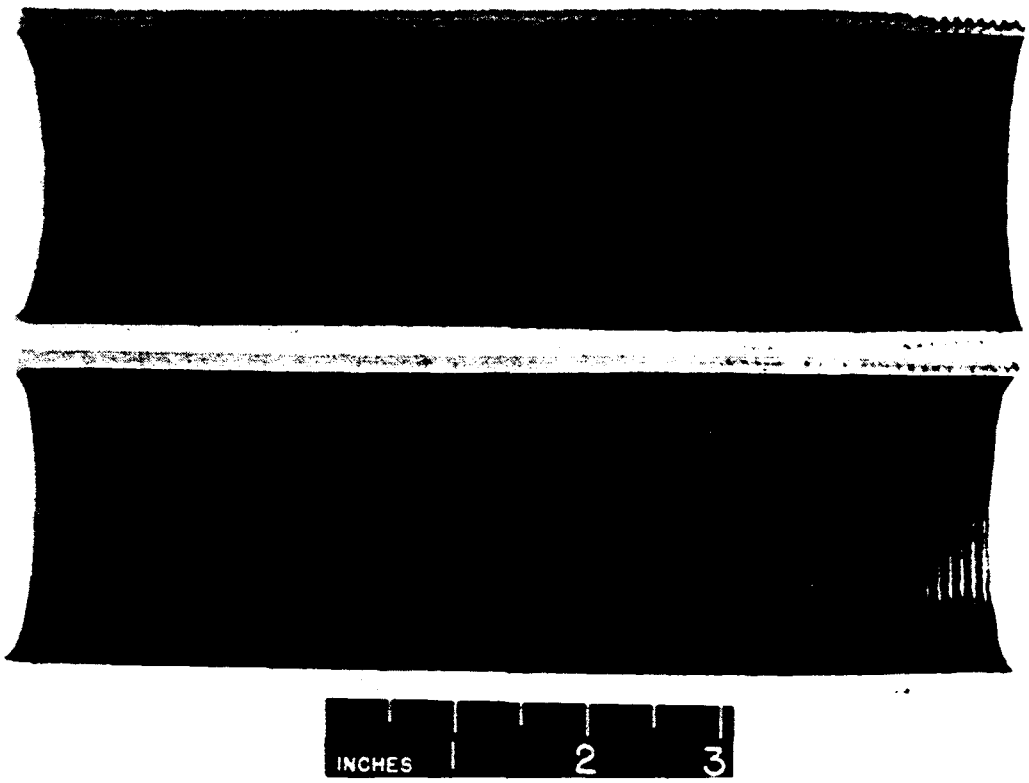

Figure 5. Failed condensate return line specimen, Kimbrough Army Hospital, Fort Meade, MD.

3 Mitigation Methods for Corrosion in Condensate Return Lines

Corrosion Control in Condensate Return Lines

Of the several available methods for mitigating corrosion problems, the treatment of condensate return lines is limited to a variety of chemical treatments due to the inaccessibility of these systems. Controlling condensate return line corrosion fundamentally hinges on minimizing the O_2 and CO_2 present. The processes always involve some level monitoring of, and formulating a response to, system chemistry. The following sections detail existing methods for controlling condensate return line corrosion.

Oxygen Control

The first line of defense against O_2-induced corrosion involves elimination of ingress of air. A common location where such breaches are often left unattended, is at deaeration heaters. Well maintained deaeration heaters can be expected to keep O_2 levels down to 0.01 ppm. Proper function of deaeration heaters is not possible unless there is an adequate supply of steam at sufficient temperatures made available to unit heaters. Proper operation of the deaereator ensures that these requirements are met. In addition, care must be taken to ensure that vents are free from obstructions.

Other locations of air entrance include valves, pumps, steam straps, and receiver vents. An ongoing preventive maintenance program should emphasize these considerations as well as the identification and repair of condensate and heat exchanger leaks. Such practice would preclude the need to treat significant quantities of O_2-rich makeup waters.

The elimination of dissolved O_2 in the boiler is accomplished by incorporating a simple additive–catalyzed sodium sulfite to the boiler water. This effectively removes aggressive oxygen. The sulfite works through the reaction:

$$Na_2SO_3 + \frac{1}{2} O_2 \rightarrow Na_2SO_4$$

To ensure that oxygen levels are sufficiently suppressed, it is recommended that the residual sodium sulfite content (measured as sulfite, SO_3^-) be maintained between 20 and 40 ppm. Note that addition of sodium sulfite promotes a higher level of total dissolved solids, which increases the boiler blowdown rate.

Carbon Dioxide Control

Bicarbonates and carbonates are the primary sources of CO_2 in condensate return water. Next in line is the stream of CO_2 that enters with improperly deaerated makeup water. In the case of the system carbonates, CO_2 is evolved as various carbonate species undergo heat-induced decomposition. For example, this phenomenon occurs in the following reactions:

$$2NaCO_3 - \Delta \rightarrow Na_2CO_3 + H_2O + CO_2$$

followed by

$$Na_2CO_3 + H_2O - \Delta \rightarrow 2NaOH + CO_2$$

Other species that can thermally decompose include calcium and magnesium carbonates. Specifically, CO_2 control seeks to minimize the amounts of HCO_3^- (bicarbonate) and $CO_3^=$ (carbonate) present in the condensate water. Elimination of these species is typically carried out through some form of external treatment process, including:

1. Demineralization
2. Hot lime softening
3. Split-stream, sodium hydrogen, ion exchange
4. Chloride-cycle ion exchange
5. Hydroxide-cycle ion exchange
6. Hydrogen-cycle ion exchange followed by degasification and caustic neutralization
7. Corrosion resistant coatings.

The chloride cycle ion exchange is an often-used technique at U.S. Military facilities. This method exhibits a low initial investment as well as low operating costs. A given system is capable of reducing the methyl orange alkalinity to approximately 10 percent of that of the incoming water. However, this process increases levels of chloride and dissolved solids, raising the boiler blowdown rate.

Alternatively, it is possible to neutralize the presence of carbonic acid in the system through an internal CO_2 control process. In this process, neutralizing amines are added to the boiler water. These species can volatilize with the steam as well as dissolve in the condensate water to neutralize carbonic acid. For this reason, it is important to ensure that dosages are tailored to match intended hydroxide liberation to the known pH of the system. The typical target pH is in the range of 8.0 to 8.3. Special attention is required in selecting and formulating amine additions to the boiler water. Several amine species are used for internal treatment, including: (1) Ammonia,* (2) Morpholine, (3) Cyclohexylamine, and (4) Diethylaminoethanol.

* Note that ammonia is often avoided as it can adversely affect copper and copper alloys.

Two significant limitations exist with respect to amine addition. In systems that require large makeup water flows, the method can prove too costly. Also, for systems that incur O_2-induced pitting, the addition of amines is ineffective. An alternative to neutralizing amines is to add a filming amine. A filming amine is a polar organic species that attaches to the pipe wall with the hydrophilic end of the molecule, and forms a barrier with the hydrophobic end. This barrier effectively blocks CO_2 and O_2 access to the pipe wall.

These molecules are typically 10 to 18 atom saturated carbon chains. However, the preferred filming amine is $CH_3(CH_2)_{17}NH_2$. The usual system dosage is 1 to 3 ppm. Films are best sustained within the pH range of 5.5 to 8.5. Since these species are surfactants, they tend to penetrate rust and produce significant levels of suspended rust particles. For older systems it is advisable to approach the final dosage over a period of weeks to limit the amount of suspended rust that evolves at any one time. Care must also be taken to avoid large fluctuations in pH, contamination of the water, or overdosage of filming amine. These occurrences can lead to instability and break down of the film, the development of mineral obstructions, and system clogging.

The use of corrosion-resistant coatings permits a cost effective option that is free of the labor intensity, training requirements, chemical pitfalls, and the relatively high cost of the previously mentioned approaches.

Phenolic Coating System

While it is possible to eliminate or protect against corrosion processes through proper water treatment, the capital costs, testing and monitoring labor, and continuing chemical costs required for these approaches supported the incentive to develop a coating system that is virtually maintenance free. Together with Heresite Protective Coatings, Inc., USACERL has engaged in the development, laboratory testing, and field testing of several high-performance baked phenolic coating systems for use in immersion applications at high temperatures. It was this factory-applied coating system that was field tested at Fort Meade.

The coating system applied to condensate return lines at Fort Meade consists of essentially two parts: (1) wash primer and (2) pigmented base coating. Before the coating application, surface preparation involves a white metal abrasive blast in compliance with Steel Structures Painting Council Regulation SSPC-SP-5. The first coating application is a dip application of the wash primer. The pipe is then baked at 135 °C. Next the pigmented baking phenolic is incrementally dip-applied. After each coat, the volatiles are permitted to flash. The system is gradually heated via increments of 40 °C every 30 minutes until the coating reaches 160 °F. Successive coats are added until a final thickness of 0.004 to 0.006 in. (4 to 6 mils) is obtained. This thickness is typically achieved with four coats. For the final cure, the temperature is raised 40 °C every 30 minutes until 220 °F is reached. This temperature is maintained for another 2 to 4 hours until the final cure color is detected. At this point, the pipe is ready for installation.

4 Field Testing

The phenolic coating system was tested for its ability to prevent corrosion on condensate return lines at Fort Meade, MD. The following sections document results of the continued testing of coated condensate return lines at Fort Meade.

Condensate Return Line Coating Tests at Fort Meade

Field tests were initiated at three sites. Two of the sites (buildings 2482 and 2490) were supplied by the Kimbrough Boiler Plant. The third site (building 9827) was supplied by the Department of Defense Central Heating/Boiler Plant. Neither of the plants employed dealkalization or amine neutralization.

Field Test Approach

The fundamental approach was to expose a condensate corrosion test pipe (supplied by the U.S. Army Engineering and Housing Support Center [USAEHSC], Fort Belvoir, VA) to actual service conditions to determine the condensate corrosion rate. Concurrently, exposure tests using uncoated and coated test pipes were designed to give a direct durability comparison. Chemical analysis of condensate water samples at each site was also obtained.

Field Test Procedure

The types and numbers of test pipes installed at each of the three test sites were:

1. One, schedule 40 carbon steel, uncoated condensate corrosion rate tester
2. Three, 6-in. long schedule 40 carbon steel, coated
3. One, 12-in. long schedule 40 carbon steel, coated.

Five in-line test pipes were installed at each building. Figures 6, 7, and 8 show the test pipe installations at buildings 2490, 2482, and 9827 respectively. Test pipe A was removed and analyzed from each site after 90 days.

The first of the B test pipes were removed and analyzed after 170 days, and the second B test pipes were removed after 450 days. As of this date, the third B test pipes and the C test pipes are still under test.

Figure 6. In-line condensate test pipes, Bldg 2490, Fort Meade, MD.

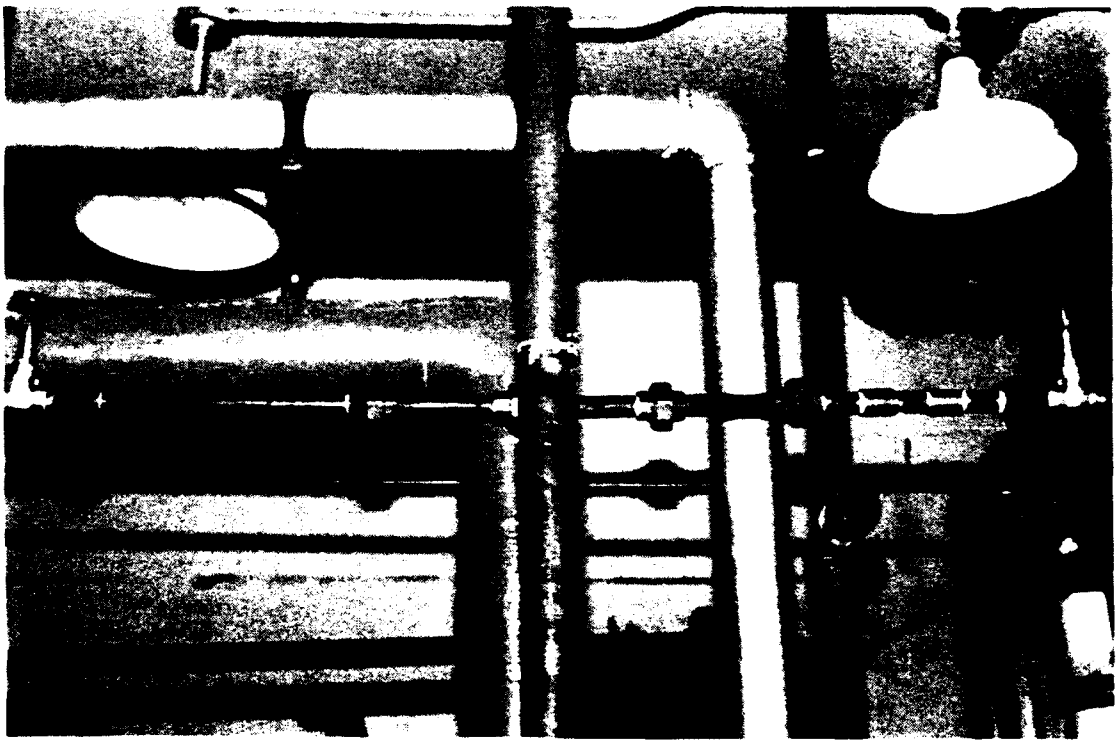

Figure 7. In-line condensate test pipes, Bldg 2482, Fort Meade, MD.

Figure 8. In-line condensate test pipes, Bldg 9827, Fort Meade, MD.

Field Test Results

Table 1 summarizes the two chemical analyses conducted on Fort Meade condensate water samples. In all cases, the hardness ranged from zero to 2 mg/L. The August and November samples of buildings 2490 and 2482 showed pH values that varied between 5.8 and 6.4 in the acidic region. For building 9827, the pH changed greatly from 6.0 initially to 8.9. The water changed not only from acidic to basic but also from light brown to clear in appearance. Other changes in the condensate at building 9827 were observed as both the total dissolved solids and the conductivity increased tenfold between collection of the first and second samples. Also, the total alkalinity recorded in this building increased from 10 to 40 mg/L. Recorded values for total alkalinity, conductivity, and total dissolved solids in buildings 2490 and 2382 varied slightly in the two samples between 5 and 10 mg/L. The appearance of the condensate in these two buildings was clear in both cases. No clear patterns were observed in the values of dissolved carbon dioxide content in the six samples. Building 2482 was reported to maintain the same CO2 content in each case, at 8 mg/L. This value dropped from 20 mg/L to 0 mg/L in building 9827, and from 25 mg/L to 13 mg/L in building 2490.

Table 2 summarizes condensate corrosion test pipe A exposure results. Yearly corrosion rates were determined based on the standard 90-day exposure time. Building 2482 condensate was seen to be the least corrosive of the three cases with a corrosion rate of 2 mils per year (mpy). A higher rate of corrosion occurred at building 9827, at 17 mpy. Values ranging from 17 to 22 mpy indicate that the condensate

Table 1. Chemical compositions of condensate at Fort Meade, MD.

Properties	Building 2490	Building 9827	Building 2482
(Sample Collected 22 August 1990)			
pH	5.8	6.0	6.4
Appearance	Clear	Lt. Brown	Clear
Hardness, as $CaCO_3$*	2	2	2
Carbon Dioxide	25	20	8
Total Alkalinity, as $CaCO_3$	8	10	10
Conductivity, μmho/cm	9	20	9
Total Dissolved Solids	5	12	5
(Sample Collected 19 November 1990)			
pH	6.2	8.9	6.4
Appearance	Clear	Clear**	Clear**
Hardness, as $CaCO_3$	2	2	0
Carbon Dioxide	13	0	8
Total Alkalinity, as $CaCO_3$	10	40	10
Conductivity, μmho/cm	6	200	10
Total Dissolved Solids	4	120	6

* Values reported in mg/l unless otherwise noted; Data obtained by personnel at USAEHSC.
** With sediment.

Table 2. Corrosion rates of carbon-steel pipe exposed to condensate at Fort Meade, MD.

Condensate Corrosion Rate Test Pipe	Location	Corrosion Rate, mpy[2]
A-1	Bldg 2490	17-22
A-2	Bldg 9827	17
A-3	Bldg 2482	2

* Based on 90-day exposure tests conducted by personnel at USAEHSC.
** mpy = mils per year.

of building 2490 was found to promote the most corrosive conditions of the three locations.

Table 3 summarizes the field test results of phenolic coated pipes tested in buildings 2490, 2482, and 9827. In all cases, the coating surfaces were found to be covered with thin layers of loosely adherent black and/or reddish-brown condensate deposits. Energy dispersive spectroscopic analysis revealed these deposits to be primarily composed of hydrated magnetite (Fe_3O_4) and hydrated hematite (Fe_2O_3).

It was found that all the iron oxide deposits could be easily removed by wiping with a wet sponge. Beneath the deposits the coating was found intact in each case. All specimens, whether exposed for 170 or 450 days, appeared to incur at least partial discoloration, which varied over the surfaces (Figures 9 to 14). In Figures 11 and 13, highlighted arrows identify isolated regions where the coating had blistered. These sites were found to contain hydrated magnetite beneath the blisters, yet no major corrosion induced pits were observed. Stereomicroscopic examination and cursory scribe testing revealed that the condensate had caused some softening of the coating.

Table 3. Performance of phenolic coating in condensate return lines at Fort Meade, MD.

Coated Specimen	Location (Bldg#)	Exposure (Days)	Appearance	Figure
B-1	2482	173	Partial discoloration	9
B-2	9827	172	Partial discoloration	10
B-3	2490	175	Partial discoloration, slight blistering	11
B-4	2482	455	Partial discoloration	12
B-5	9827	454	Partial discoloration, slight blistering	13
B-6	2490	457	Partial discoloration	14

Figure 9. Cleaned pipe B-1, following 173 days of exposure.

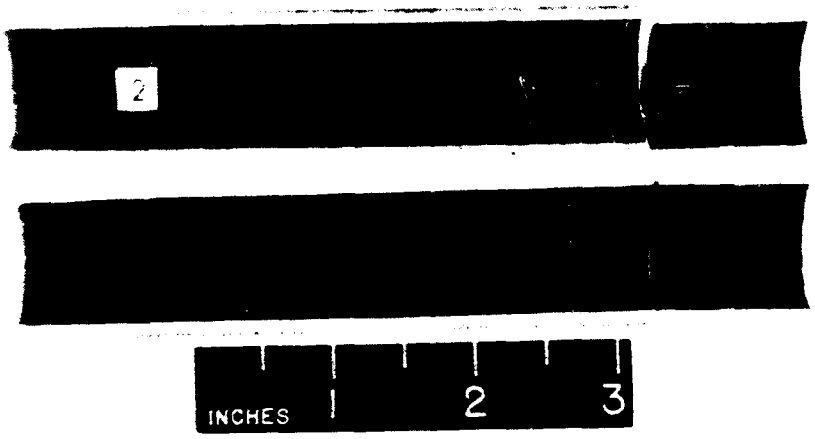

Figure 10. Cleaned pipe B-2, following 172 days of exposure.

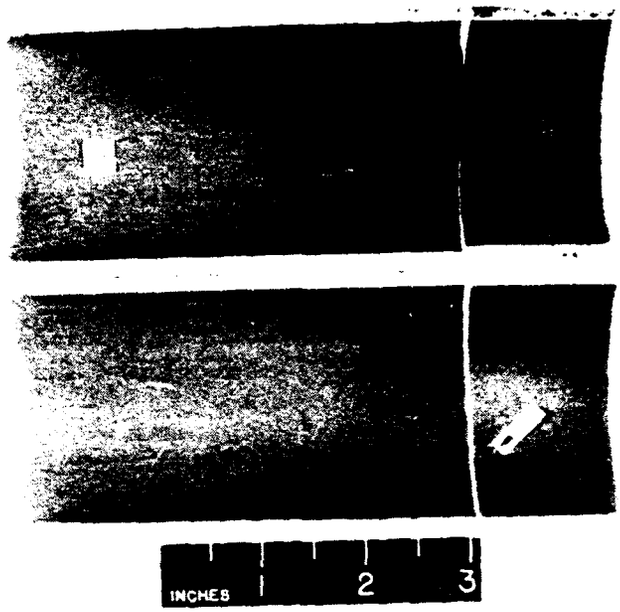

Figure 11. Cleaned pipe B-3, following 175 days of exposure.

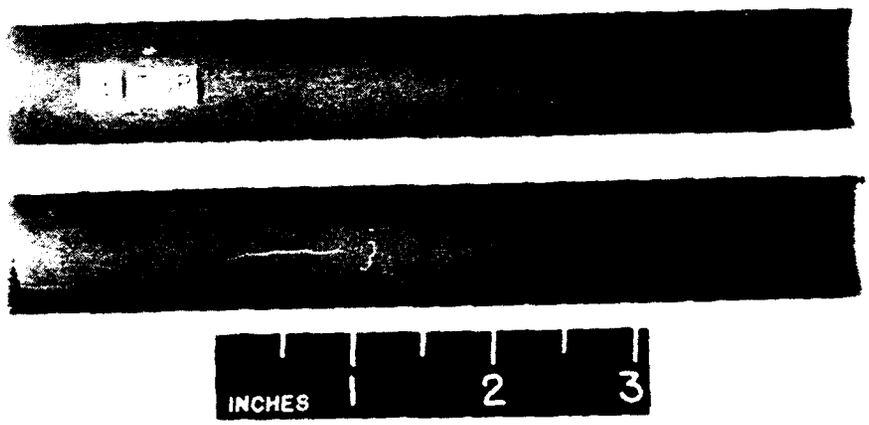

Figure 12. Cleaned pipe B-4, following 455 days of exposure.

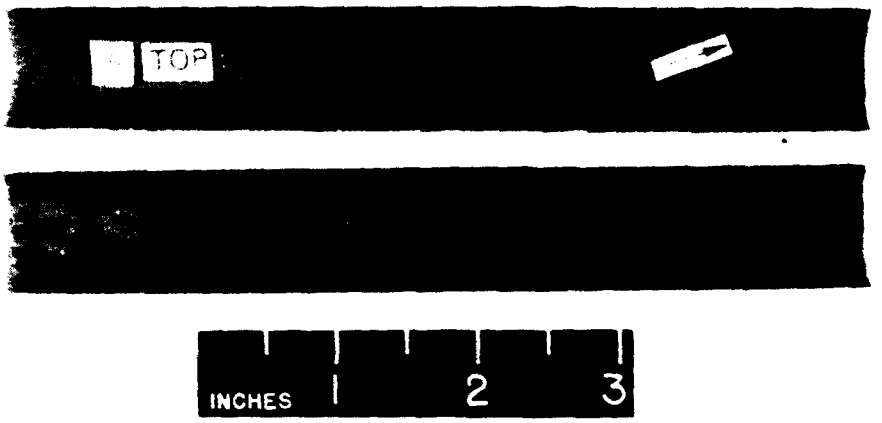

Figure 13. Cleaned pipe B-5, following 454 days of exposure.

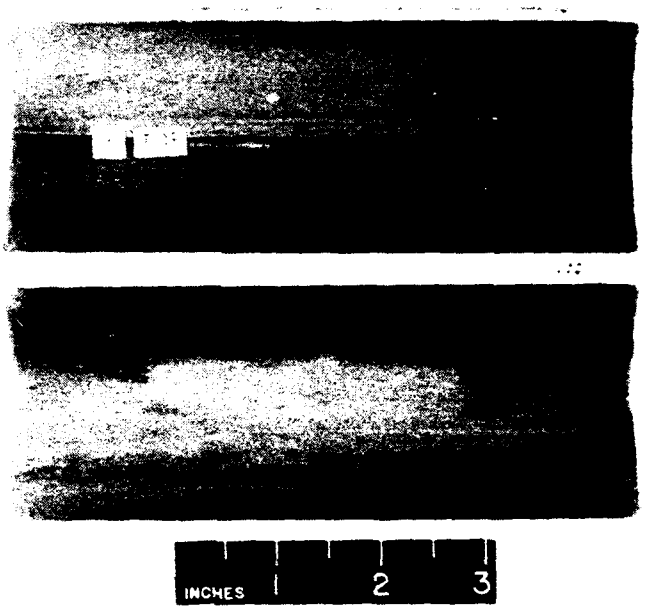

Figure 14. Cleaned pipe B-6, following 457 days of exposure.

5 Discussion of Fort Meade Results

The results recorded in Chapter 5 evidence a favorable performance of the baked phenolic coating system. The chemical analysis summarized in Table 1 helped reveal a major factor that leads to condensate return line corrosion. Many of the parameters considered in the table exhibited considerable variation from the date of the first to the second sampling. In one case, the level of CO_2 was found to be 25 mg/L. This amount of CO_2 in the condensate would be expected to develop carbonic acid and render the environment very aggressive to carbon steel. Suspicion of corrosive capability of the CO_2 level in the condensate was confirmed by the findings of the corrosion rate field test summarized in Table 2. Building 2490 showed the highest average CO_2 levels at 13 mg/L, and also showed the highest corrosion rates with values that ranged from 17 to 22 mpy. Building 2482 showed the lowest CO_2 content at 8 mg/L, and similarly yielded the lowest corrosion rate at 2 mpy. The presence of high CO_2 levels in the condensate return lines promoted significant corrosion rates in carbon steel exposed for 90 days. In comparison, the phenolic coated specimens bore exposure times ranging from 172 to 455 days with relatively little corrosion at isolated points, and with no observed pitting of the substrate. Phenolic coating protection of carbon steel pipe reduced the condensate return line corrosion from approximately 20 mpy down to zero.

Thin layers of condensate deposits initially masked the true performance of the phenolic coatings. The black and reddish brown deposits were easily removed by wiping with a wet sponge. This observation supported the belief that this material originated from elsewhere in the system. EDS analysis confirmed that this material was composed primarily of iron oxides in the form of hydrated magnetite (Fe_3O_4) and hydrated hematite (Fe_2O_3). Thus, the black and reddish brown, hydrated, iron oxide deposits originated from the corrosion of carbon-steel pipes and fittings upstream from the test locations.

Removing the condensate deposits permitted evaluation of the performance of the phenolic coatings. An immediately obvious impact of the environment was the variable discoloration observed on all six specimens (Figures 9 to 14). Environment-induced softening was also detected through limited scribe testing as well as stereomicroscopic examination. Localized occurrences of blistering occurred on specimens B-3 and B-5, indicating limited water permeation of the resin. Furthermore, since small amounts of hydrated magnetite were found, it may be possible that CO_2 breached the barrier. However, the lack of observed pitting may indicate that even the permeation of the barrier does not necessarily halt all protective benefit. The phenolic coating has thus far exhibited the capacity to lengthen the anticipated 10-year service life of a carbon-steel condensate return line by more than 10 percent.

6 Conclusions and Recommendations

This study concludes that:

1. Phenolic coated condensate return line pipes installed at Fort Meade, MD have not shown any significant signs of corrosion-induced pitting attack after 477 days of exposure as compared to a corrosion rate of 17 mpy (bldg 9827) for uncoated steel specimens as determined from 90-day condensate corrosion test pipe exposure tests.

2. It is estimated that the anticipated 10-year service life of a uncoated carbon steel condensate return line could be extended by the application of a phenolic-based coating system.

It is recommended that:

1. The field test of phenolic coated condensate return lines at Fort Meade, MD be continued for at least 2 additional years.

2. A life cycle cost analysis be performed on coated versus chemically-treated condensate return lines to determine actual payback.

Metric Conversion Table

1 mil	=	0.0000245 m
1 in.	=	25.4 mm = 0.0254 m
1 gal (U.S.)	=	3.78 L
1 gal (U.S.)/min	=	0.063 L/sec
1 ft	=	0.305 m
1 Btu	=	100,000 therm = 1055.56 Joule
1 lb	=	0.453 kg
1 lb/in^2 (psi)	=	6894.76 Pa
1 lb/gal (U.S.)	=	0.1198 kg/L
1 Btu/(hr-sq.ft.-°F)	=	5.678 W/(m^2-°C)
1 Btu/(lb-°F)	=	4186.8 Joule/Kg-°C)

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