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Demonstration of Anti-Scale Corrosion Resistant Coatings for Hot Water Heat Exchangers

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Foreword

This study was conducted for the Center for Public Works (USACPW), which has more recently been reorganized into the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under the Facilities Engineering Application Program (FEAP). The technical monitor was Malcolm McLeod, CEMP-RI.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL principal investigator was Vincent F. Hock. Martin J. Savoie is Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. The contributions of Dr. James Meyers, corrosion consultant and director of JRM Associates, Franklin, OH, and Vicki Van Blaricum, CERL, are gratefully acknowledged. The technical assistance provided by Malcolm McLeod, CECPW-FU-S; Leon Howard, Directorate of Engineering and Housing (DEH), Fort Hood, TX; Marvin Todd, Fort Bragg, NC; Bret Langlois, Fort Lewis, WA; and Ed Blake and Juel Knutson, Heresite-Saekaphen Inc., Manitowoc, WI, was invaluable to the successful completion of this work. The Acting Technical Director of the Facility Acquisition and Revitalization business area is Dr. Paul A. Howdysshell. The Acting Director of CERL is William D. Goran. The CERL technical editor was William J. Wolfe, Technical Resources.

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1 Introduction

Background

Domestic hot water heat exchangers are commonly used in various Army facilities such as the laundry, dining halls, and barracks. Recurrent fouling of heat exchanger tube bundles reduces the thermal efficiency of these systems to the point where they fail to meet hot water demands. Common maintenance practices for sustaining acceptable heat exchanger function are costly, labor intensive, and can involve hazardous chemical and waste handling issues. The use of phenolic coatings on heat exchangers has been found effective in providing maintenance-free extension of service life for these systems. Laboratory and short term field testing on the application of phenolic coating technology was conducted as reported by Hock et al. (1990). Long-term field demonstrations need to be evaluated.

Objective

The overall objective of this study was to evaluate the long-term ability of phenolic coatings to mitigate the fouling problems associated with domestic hot water heat exchangers. Specific objectives included:

- determining the capability of a phenolic coating system to enable delivery of hot water temperatures about 140 °F in both scaling and corrosive fouling waters
- determining the length of time that a phenolic coating system applied to heat exchanger tubes can provide maintenance-free service in a severely scaling water environment
- determining the simple payback for using phenolic coating technology on both scaling and corrosive waters.

Approach

Field exposure tests were conducted at Fort Hood, TX, Fort Lewis, WA, and Fort Bragg, NC to demonstrate this coating technology in field applications in domes-

tic hot water heat exchangers. The site conditions represented both corrosive and scaling environments and included both steam and high temperature hot water heating sources.

Mode of Technology Transfer

Corps of Engineers Guide Specifications (CEGS) 15400, Plumbing, General, Section 2.10.4 and CEGS 15404, Plumbing, Hospital, Section 2.13.3 have been changed to allow the use of the baked-on phenolic coating on potable water shell-and-tube heat exchangers.

This technology is also announced in a FEAP Ad Flyer and ERDC/CERL Special Report SR-01-1, *User Guide and Specifications for Baked Phenolic Coating Systems Applied to Domestic Hot Water Heat Exchangers*, describing the application, benefits, and availability of this technology.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

1 Btu	=	100,000 therm = 1055.56 Joule
1 Btu/(hr-sq ft.- °F)	=	5.67826 W/(sq meter- C)
1 Btu/(lb- °F)	=	4186.8 Joule/(kg- C)
1 gal (U.S.)	=	3.787412 l
1 gal (U.S.)/min	=	0.0630902 l/sec
1 mil	=	0.0000245 m
1 in.	=	25.4 mm = 0.0254 m
1 lb	=	0.453592 kg
1 lb/in ² (psi)	=	6894.76 Pas
1 lb/gal (U.S.)	=	0.1198264 kg/l

2 Background on Heat Exchangers

A heat exchanger is a mechanical system that permits thermal contact between different thermal mediums while preventing physical contact. These systems are designed to provide controlled transfer of thermal energy from one media or system to another. The following paragraphs describe hot water heat exchangers tested in this study; a more detailed discussion of heat exchangers is available in Hock et al. (1990).

A heat exchanger system commonly used in the Army is the domestic water storage heater (DWSH) (Figure 1). The system is composed of a cylindrical steel reservoir lined with concrete for corrosion protection. A water inlet at the bottom provides access to a U-tube bundle assembly. At Fort Hood, this assembly is 71.5 in. long and has 13 individual tubes of copper alloy with a surface area of 29.7 sq ft. By sustaining a large hot water reservoir, the system can provide sufficient hot water during the times of peak demand. Typical facilities that use these systems are dining halls, barracks, and laundries.

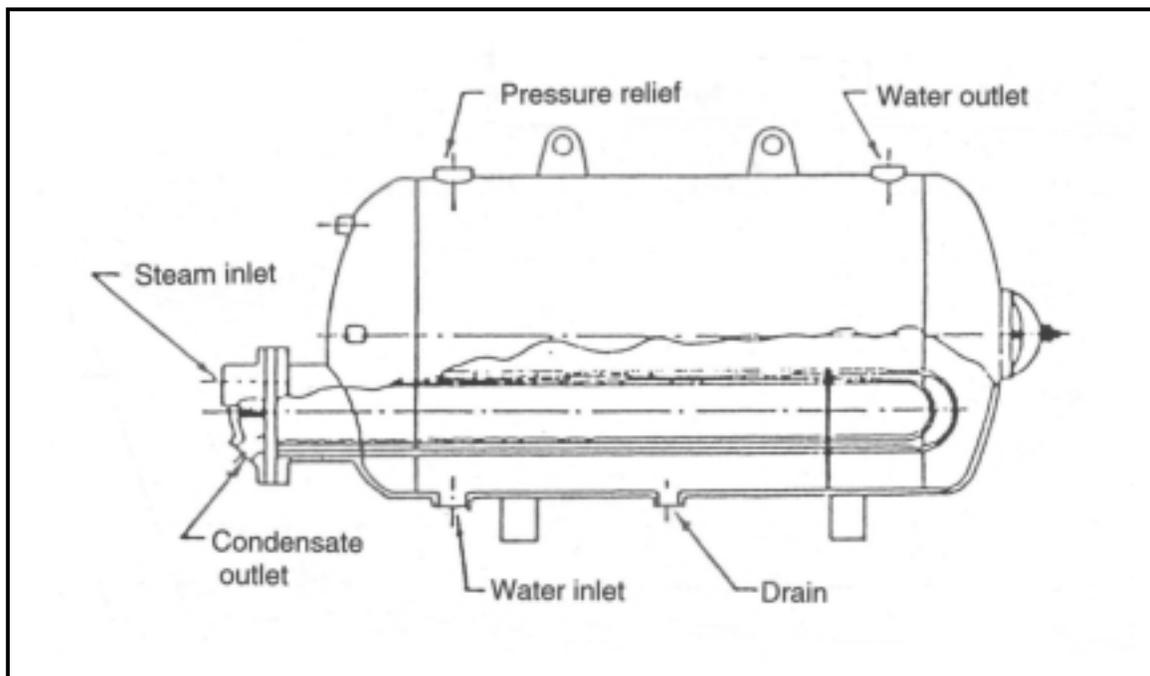


Figure 1. Domestic hot water storage heater.

Steam or hot water is circulated through the interior of the tube bundles. Heat is transferred from the steam through the copper pipe wall and into the domestic water medium. The domestic water enters the reservoir at one end beneath the U-tube assembly and exits at the top. This path provides the greatest amount of thermal exposure to maximize heat transfer. Under normal conditions at Fort Hood, the inlet waters at buildings (Bldg.) 29006 and 87017 enter the respective reservoirs at 60 to 70 °F and exit the top at 140 to 160 °F.

Figure 2 shows each of the physical elements of the heat exchanger that serve as barriers to heat flow. Visualize the flow of heat as starting on the inside (left) of the copper tube wall and traveling through various barriers to get to the outside of the tube wall and into the domestic water media. These various barriers are represented by the following variables:

- h_h = convective heat transfer coefficient on the hot side of the copper tube
- $R_{f,h}$ = fouling factor on the hot side of the copper tube
- t = thickness of the copper tube wall
- k = thermal conductivity of the solid barrier
- $R_{f,c}$ = fouling factor on the cold side of the copper tube
- h_c = convective heat transfer coefficient on the cold side of the solid barrier.

Using these factors, it is possible to construct an overall expression of resistance to heat flow in the heat exchanger. It is important to note that heat flow resistance contributed by a coating would take a form similar to that of the fouling-induced resistances $R_{f,h}$ and $R_{f,c}$.

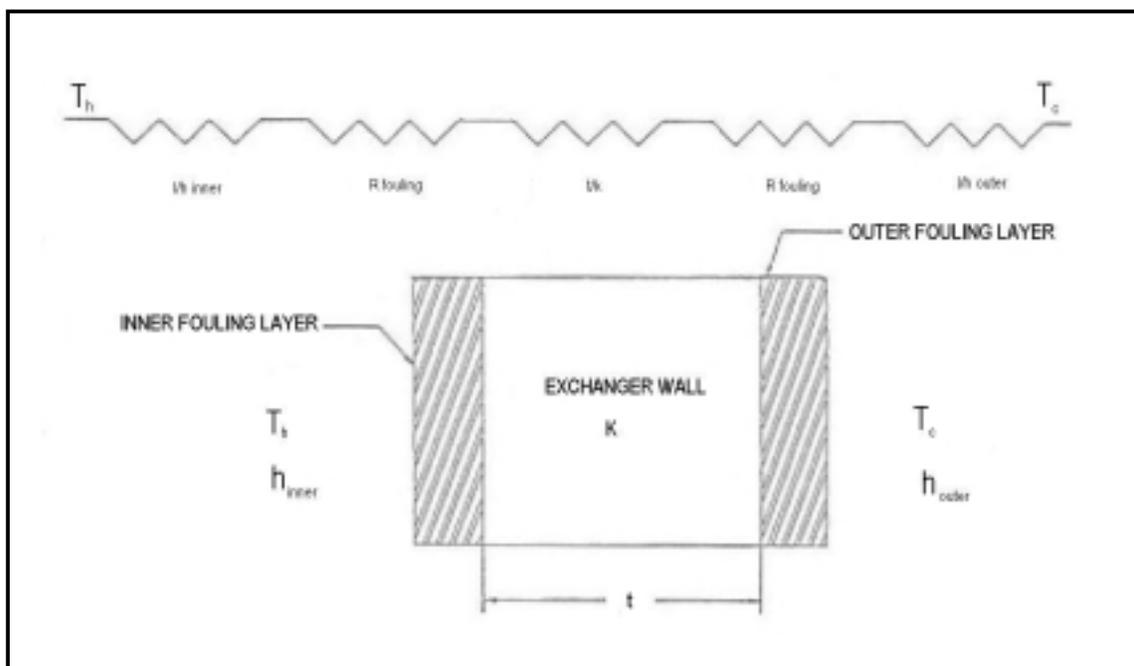


Figure 2. Thermal barriers on heat exchanger tube.

The concept of modeling the overall resistance of this expression is analogous to the concept of equivalent or overall resistance in electrical circuits. The overall resistance to heat flow can be given by:

$$\frac{1}{U} = \frac{1}{h_h} + R_{f,h} + \frac{t}{k} + R_{f,c} + \frac{1}{h_c} \quad [\text{Eq 1}]$$

In calculating heat transfer, the term U is referred to as the overall heat transfer coefficient of the system. It is this parameter that may best indicate the performance of a given DWSH. A detailed discussion of the terms in Equation 1 is given in Hock et al. (1990). This previous work also developed an overall heat transfer coefficient that is related to various aspects of the system:

$$\frac{Q}{A} = U * \left(\frac{T_h - T_c}{\ln \frac{T_s - T_c}{T_s - T_h}} \right) \quad [\text{Eq 2}]$$

where:

Q	=	Heat flow [BTU/hr]
A	=	Surface area [sq ft]
T _s	=	Steam temperature [°F]
T _c	=	Cold inlet water [°F]
T _h	=	Hot outlet water [°F]
U	=	Overall heat transfer coefficient [BTU/sq ft-hr-°F].

The fraction involving the various system temperatures on the right side of the equation is an approximate mean value for the difference $T_h - T_c$. This expression is referred to as the Logarithmic Mean Temperature Difference, and is valid for heat exchanger systems in which T_h does not change (such as in steam fed systems). Chapter 5 of this report, "Field Testing," describes how Eq 2 is used in the development of a field monitoring procedure for heat exchangers at Fort Hood, TX.

Background on Heat Exchanger Fouling

Note that the term "fouling" is often used broadly to refer to corrosion and scaling issues. While both corrosion and scaling can each have a deleterious impact on the heat transfer coefficient of a heat exchanger, this study focused on mitigation of scaling in heat exchangers.

The scaling phenomena is a deposition process that occurs in waters that are referred to as hard waters. This occurrence is often characterized by a hard, often

whitish mass of encrusted matter that is composed of various minerals. While scale primarily consists of calcium carbonate, deposits can form from calcium, magnesium, carbonate, silicate, sulfate.

As water approaches the hot tube bundle, its temperature increases, the solubility of any minerals in the water decreases, and minerals are deposited onto the water side surface of the heat exchanger tube bundle. The following reaction governs formation of calcium carbonate (CaCO_3) deposits.



where T_c is the critical calcium bicarbonate decomposition temperature.

Calcium carbonate deposition is also governed by pH, calcium concentration, alkalinity, temperature, and total dissolved solids.

These five factors are included in an expression referred to as the Langelier index, which predicts the conditions that promote saturation of the solution with respect to calcium carbonate. A positive Langelier index indicates a water solution that will tend to form scale. A negative Langelier index indicates a water solution that may tend to be corrosive.

In addition to the chemical factors already mentioned, there are several mechanical factors affect the tendency for scale to deposit, including water velocity, design, operating conditions, and surface material. The work conducted herein focused on changing the nature of the surface material through application of a resin coating.

Corrosion in Heat Exchangers

Myers (1974) defines corrosion as the deterioration of a material, usually a metal or alloy, because of a reaction with its environment. In nature, metals customarily exist in the form of brittle oxides. This is the natural state of lowest energy in which most metals exist and in which the metal is in equilibrium with its environment. Industry has little use for metals in their oxidized, brittle, nonconductive natural form. Most metals must undergo an extraction and purification process before they can be used in industry. The process of extraction and purification can be defined as transforming the metal into a form with higher energy potential. Because metals in their more useful states exist in a higher potential

energy form, they will always tend to revert to their lower energy equilibrium state by the corrosion process.

Corrosion of metals is an electrochemical process. The corrosion reaction involves four components: an anode (more negative electrode), a cathode (more positive electrode), an electrolyte (corrosive or aqueous environment), and a metallic circuit connecting the anode and the cathode. Dissolution of metal (as ions) occurs at the anode. The metal at the anode oxidizes (loses electrons), and the corrosion current enters the electrolyte at this point. Electrons lost at the anode flow through the metallic circuit to the cathode, where reactions involving the gain of electrons (reduction) take place. The same concepts apply to galvanic (dissimilar metal) corrosion as to corrosion involving only one material. When one material is involved, microscopic anodes and cathodes develop on its surface, and the same type of oxidation and reduction reactions takes place.

Corrosion is a common problem in domestic hot water storage heaters. Since many of the heat exchanger shells are cement lined, corrosion usually takes place in the tube bundle. The four components of a corrosion cell are present in a domestic water storage heater. The surface of the heat exchanger tube bundle contains many microscopic anodes and cathodes. As described above, dissolution of metal will occur at the anodes. The metallic path is provided by the tube bundle metal itself. Water serves as the electrolyte. Despite water's corrosivity, it is valuable in heat exchange applications because it has a high heat capacity and is abundant and inexpensive.

Heat exchanger tube bundles commonly undergo a form of corrosion known as erosion corrosion. Most metals depend on a protective surface film for corrosion resistance. When the protective film has poor adherence, accelerated corrosion can occur. Myers (1974) describes erosion corrosion as a repetitive formation (a corrosion process) and destruction (a mechanical erosion process) of these surface films. Erosion corrosion is aggravated by high water velocities and temperatures, and by certain constituents in the water. It is characterized by the appearance of waves, valleys, and deep grooves on the metal surface. An absence of residual corrosion products and a clean metal appearance also are characteristic of erosion corrosion.

Since corrosion in potable water heat exchangers involves a degradation of the tube bundle material, it will eventually result in leaks. This is a potential health hazard, because a leak allows treated, nonpotable water to be mixed with potable water that may be used for cooking or drinking. In addition, repair, replacement, and the effects of shutdown time are costly.

3 Field Problems

CERL has conducted several field investigations involving fouling of domestic hot water heat exchangers (Hock et al. 1990). This phenomenon is introduced in the following sections. In addition, an actual case study is reviewed.

Scaling Problems at Fort Hood, TX

In March 1986, Fort Hood, TX, personnel reported continuing problems with scale forming on the surfaces of copper tube bundles in domestic hot water heaters. During a May 1986 site visit, investigators examined a water storage heater located in a dining facility (Building 29006). The cement-lined tank has a capacity of 2115 gal. Typical daily hot water use is 11,000 gal. Recurrent difficulties were reported in sustaining the dining hall hot water supply above the required 140 °F. When the heat exchanger tube bundles were removed they appeared as shown in Figure 3.

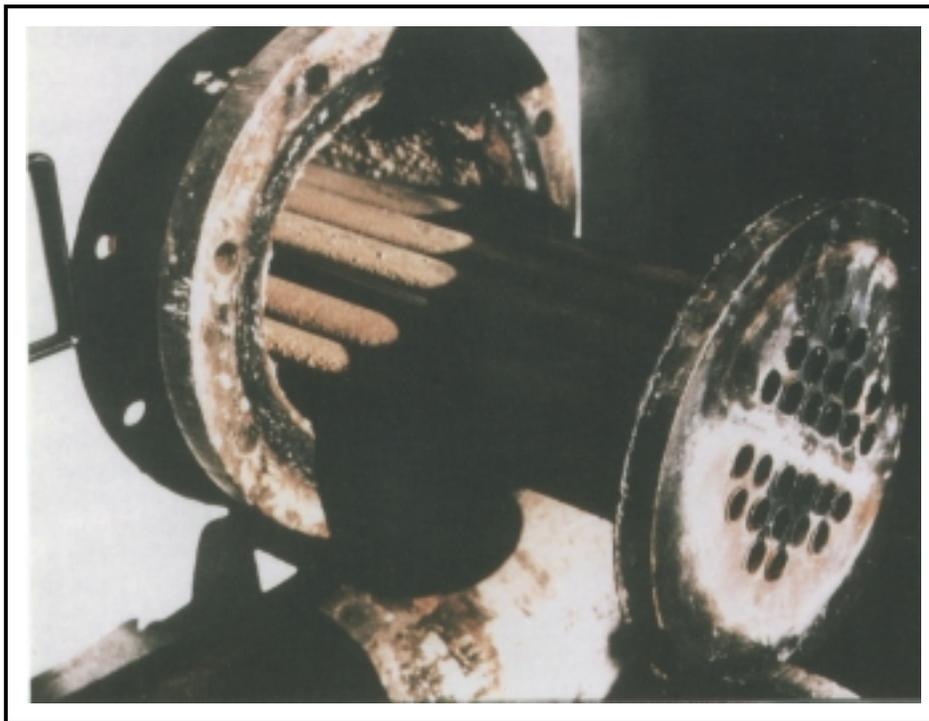


Figure 3. Scaled heat exchanger tube bundle, Fort Hood, TX.

The tube bundle assembly is made of copper and measures 71.5 in. long with a total surface area of 29.7 sq ft. Each of the 13 tubes has an outside diameter of 3/4 in. A 0.07-in. deposit, comprised primarily of calcium carbonate, coated the exterior or water side surfaces of the tubes. The 12 psi steam supply that runs through the tubes is generally adequate for generating the 140 °F service water temperature. However, the presence of the scale layer significantly diminishes the overall heat transfer coefficient of the system. Examination of maintenance records revealed that this heat exchanger had gone 4 months since the last cleaning.

Another dining facility at Fort Hood, Building 87017, was investigated on 14 to 15 October 1986. A heat exchanger assembly identical to the previous case was examined and found to exhibit similar calcium carbonate deposits of approximately 0.04 in. The heat exchanger had been in service for 10 months. The hot water temperature was only 110 °F. The tube assembly was acid cleaned in a large vat filled with hydrochloric acid until the scale was dissolved. At 3 months following reinstallation of the assembly, researchers observed a new scale deposit of 0.015 in.

Table 1 lists the results of water chemistry tests at Fort Hood. It is interesting to note that even in the case of water with a negative Langelier index as shown at the bottom of Table 1, that the tube bundles still developed scale deposits. The reason for this occurrence is the fact that calcium carbonate solubility decreases as the water temperature increases. Thus when the local Fort Hood water comes in contact with the hot tube bundles, the Langelier index rises sharply and scale is deposited onto the heat exchanger.

Maintenance records indicate that to sustain required performance levels, the heat exchangers needed to be pulled and acid cleaned every 60 to 90 days. Chapter 4 summarizes several of the methods available for mitigating fouling problems.

Table 1. Fort Hood water chemistry data.

Constituent/Property [*]	South Fort Cold Water	South Fort Hot Water	North Fort Cold Water
Temperature, °C	17	34	20
Dissolved carbon dioxide (CO ₂)	<5	<5	10
Dissolved oxygen (O ₂)	9	7	1.5
pH	7.1	7.2	7.7
Sulfide	0	0	0
Resistivity, ohm-cm	3200		510
Chloride, as Cl	49		427
Sulfate, as SO ₄	29		316
Alkalinity, as CaCO ₃	116	141	369
Total dissolved solids	127	1230	
Hardness, as CaCO ₃	146		62
Calcium, as Ca	44		12
Magnesium, as Mg	7.6		7.2
Zinc, as Zn	0.02		0.11
Iron, as Fe	0.18		0.44
Copper, as Cu	<0.01		<0.01
Manganese, as Mn	0.01		0.01
Sodium, as Na	22		420
Silica, as SiO ₂	27		27
Langelier index	-0.7	-0.23	-0.3
[*] All units are milligrams per liter (mg/L) unless otherwise noted.			

Scaling Problems Observed at Fort Bragg, NC

A corrosion site survey was conducted in September 1986 at Fort Bragg, NC to gather data on the corrosivity of the soil and water. Complete water chemistry data is shown in Table 2. The water at Fort Bragg is obtained from a river supply. The distribution water at Fort Bragg has a Langelier index of -2.3 for cold water and -1.7 for hot water. The water is nearly saturated with dissolved oxygen and has an unusually low alkalinity. Thus, the water is not expected to deposit scale but is expected to be somewhat corrosive. However, corrosion has not been a problem in copper potable water systems at Fort Bragg.

A second site visit was made in June 1987 to examine domestic water heat exchangers. The two hot water storage tanks in Building D-3348, a multistory barracks, were drained and the tube bundles were removed for examination (Figure 4). The vertical cylinder tanks each have a capacity of 830 gal. The U-tube bundles are made of brass, with a 6-in. diameter and a 45-in. length.

Table 2. Fort Bragg water chemistry data.

Constituent/Property*	Cold Water	Hot Water
Temperature, °C	22	42
Dissolved carbon dioxide (CO ₂)	<5	<5
Dissolved oxygen (O ₂)	7	7
pH	7.4	7.2
Sulfide	0	0
Resistivity, ohm-cm	11000	
Chloride, as Cl	14	
Sulfate, as SO ₄	13	
Alkalinity, as CaCO ₃	5	
Total dissolved solids	77	
Hardness, as CaCO ₃	36	
Calcium, as Ca	12	
Magnesium, as Mg	0.78	
Zinc, as Zn	0.07	
Iron, as Fe	0.09	
Copper, as Cu	<0.01	
Manganese, as Mn	0.03	
Sodium, as Na	2.2	
Silica, as SiO ₂	8	
Langelier index	-2.3	-1.7
*All units are milligrams per liter (mg/l) unless otherwise noted.		



Figure 4. Removal of tube bundle, Bldg D-2248, Fort Bragg, NC.

The heating medium is high temperature hot water at 375 to 385 °F, which flows through the tube bundle and heats the domestic water in the tank to approximately 130 °F. The tube bundles had been in service for approximately 17 yr, and their waterside surfaces were covered with a brownish-colored scale deposit with thicknesses up to 0.14 in. Subsequent energy dispersive spectroscopy and microchemical analysis revealed that the deposit was comprised of calcium carbonate, hydrated hematite ("red rust"), and products containing phosphorus. The source of the hematite was most likely the corrosion of ferrous-based materials upstream from the heaters. This is understandable since the water at Fort Bragg is relatively corrosive. The deposit immediately adjacent to the bundle surface also contained aluminum, zinc, and copper. It is possible that the sources of the phosphorus and aluminum were chemicals used to treat the river water supply.

Although the rate of scale deposition is not as rapid as in the dining halls at Fort Hood, it still represented a significant maintenance problem and a loss in heat transfer efficiency, which resulted in the inability to provide adequate amounts of hot water at times of high demand.

Corrosion Problems at Fort Lewis

A corrosion site survey was conducted in April 1986 at Fort Lewis, Washington, to gather data on the corrosivity of its soil and water. Table 3 lists complete water chemistry data. There are two distribution waters at Fort Lewis: one comes from a seven-well system; the other comes from Sequallitchew Springs. Waterside corrosion is a serious concern in the potable water piping systems. The water chemistry data collected show that both distribution waters would be expected to be corrosive, since the waters both have low alkalinities and high amounts of dissolved oxygen and carbon dioxide.

The Langelier indexes for the well system and the Sequallitchew Springs system are, respectively, -2.5 and -2.4. As mentioned in section 3, waters with positive Langelier indexes have the tendency to deposit calcium carbonate scale, while waters with negative Langelier indexes have the tendency to be corrosive. Thus, neither water has the tendency to deposit calcium carbonate scale and both should be relatively corrosive.

A second site survey was conducted in June 1987 to observe problems in potable water heat exchangers. The findings were as expected; corrosion is a major problem in the domestic water storage heaters. Heat exchangers at Fort Lewis are fed by steam and high temperature hot water.

Table 3. Fort Lewis water chemistry data.

Constituent/Property	Distribution Water From Well System	Distribution Water from Sequallitchew Spring
Temperature, °C	12	12
Dissolved carbon dioxide (CO ₂)	19	16
Dissolved oxygen (O ₂)	7	5.5
pH	6.4	6.7
Sulfide	0	0
Resistivity, ohm-cm	8050	9300
Chloride, as Cl	5	4
Sulfate, as SO ₄	11	9
Alkalinity, as CaCO ₃	42	42
Total dissolved solids	58	44
Hardness, as CaCO ₃	50	46
Calcium, as Ca	13	10
Magnesium, as Mg	4.5	4
Zinc, as Zn	<0.01	<0.01
Iron, as Fe	0.05	0.01
Copper, as Cu	<0.01	<0.01
Manganese, as Mn	<0.01	<0.01
Sodium, as Na	5.8	6.1
Silica, as SiO ₂	10	17
Langelier index	-2.5	-2.4
*All units are milligrams per liter (mg/l) unless otherwise noted.		

According to Fort Lewis personnel, erosion corrosion as described above commonly occurs immediately in front of the tube sheet or at the U-bend in the tube bundle. In a new tube bundle, the tubes extend about 1/8 in. beyond the tube sheet. Some of the ends of the tubes are flared. At Fort Lewis, this part of the tube erodes away by the water, eventually causing a leak in the vicinity of the tube sheet. The leaks are usually repaired with brass plugs and the bundle is returned to service, but eventually the leaking becomes so severe that the bundle must be replaced. According to Fort Lewis personnel, the average life of a heat exchanger tube bundle at Fort Lewis is 3 to 5 yr.

During the June 1987 site survey, two of the hot water storage tanks were drained and the tube bundles were pulled out for observation. One of the exchangers was located in Building 3281, a dining hall. The heating fluid is high temperature (220 to 240 °F) hot water. The incoming cold water is heated to approximately 150 to 170 °F. It was observed that a loosely adherent, reddish brown deposit was present on the tube bundle, mostly near the tube sheet (evident in Figure 5). Erosion of the ends of the tubes in the bundle was observed (Figure 6).



Figure 5. Fouled tube bundle, Fort Lewis, WA.

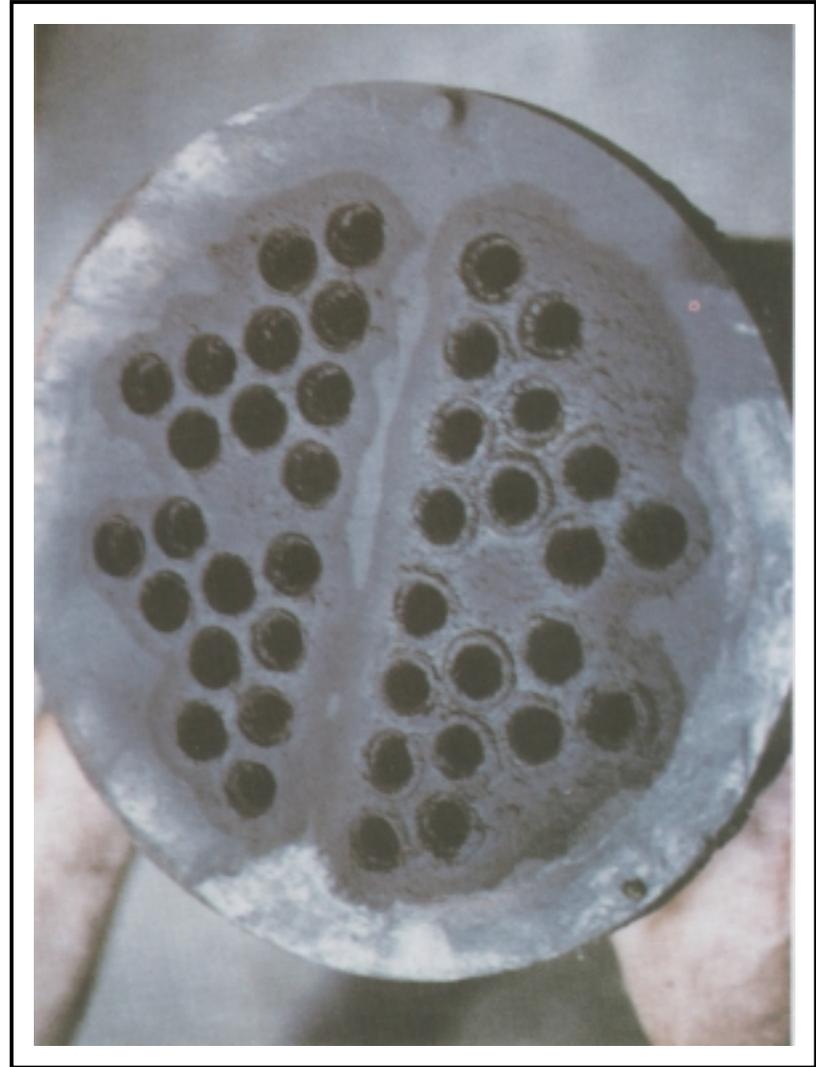


Figure 6. Erosion of tube bundle, Fort Lewis, WA.

The second exchanger was located in Building 3418, a multistory barracks. The heating fluid is steam, and the cold water is heated to approximately 140 °F. A similar deposit was observed on the surface of the tube bundle. In addition, the ends of the tubes at the tube sheet were badly eroded. Subsequent energy dispersive spectroscopy and microchemical analysis on the reddish brown deposits revealed they were comprised primarily of iron, silica, and magnesium, indicating that corrosion products and serpentine were responsible for most of the deposit. Calcium carbonate scale was not found. It is probable that the corrosion products resulted from corrosion at a location upstream of the heat exchanger, were dissolved in the water, and were then deposited in the heat exchanger.

4 Field Testing

Application of the Phenolic Coating System

Although it is possible to eliminate or protect against fouling through proper water treatment, the capital costs, testing/monitoring labor, and continuing chemical costs required for this approach supported the incentive to develop a coating system that is virtually maintenance free. Together with Heresite-Saekaphen Inc., Manitowac, WI, CERL 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 temperature. The following sections describe the overall coating system that was factory applied and field tested. The coating applied to DWSH heat exchangers at Fort Hood and Fort Lewis consists of essentially three layers:

1. Wash primer
2. Pigmented base coating
3. A clear glossy top coat.

In the case of Fort Lewis, coating is also applied to the interior of the tubes and to the tube sheet to provide erosion corrosion protection. For more information regarding the use of phenolic coatings, see the Corps of Engineers Guide Specification section 15400, "Plumbing, General Purpose," and section 15405, "Plumbing, Hospital.

The phenolic coating system was tested on copper heat exchanger tube bundles at Fort Hood and Fort Bragg to prevent scaling, and at Fort Lewis to prevent water side corrosion fouling and interior tube erosion corrosion. Hock (1990) gives the initial installation and field test results of a coated heat exchanger at Fort Hood. The following sections document the continued testing of coated heat exchangers at Fort Hood, and similar testing of coated heat exchangers at Fort Bragg and Fort Lewis.

Heat Exchanger Coating Tests

Two test sites were selected at Fort Hood, TX based on existing problems with scaling. Dining facilities Bldg. 29006 and 87017 were selected for long-term evaluation of phenolic coating performance in a calcium carbonate scaling environment. Two heat exchanger sites were selected at Fort Bragg in Bldg. Delta-2007 to demonstrate a coated and uncoated case in a calcium carbonate scaling environment. Two other heat exchanger sites were selected for testing at Fort Lewis, WA. These two sites were selected to represent a corrosive water environment. The following sections describe the approaches and procedures engaged to execute this work.

Field Test Approach

Because the performance of a heat exchanger may be characterized by the overall heat transfer coefficient (U), the presence of corrosion or scale on a tube surface would cause a reduction in U and hinder the delivery of heat. Over time, the amount of tube fouling renders the heat exchanger unable to deliver hot water at the required temperature despite maintaining a constant full flow of steam or high temperature hot water. Under these circumstances the evaluation of the heat exchanger performance can be conducted by installing a thermocouple at the hot water outlet (as shown in Figure 7) and monitoring the hot water exit (T_h) values. In this case, data was collected continuously on a data logger and downloaded to disk once a month for analysis.

Fort Hood Field Test Results

Figures 8 and 9 show field measurements for the hot outlet water temperatures. The data is plotted as monthly averages occurring over a 48-month period starting in May 1988 and ending in May 1992. The average monthly hot water temperature was maintained between 137 and 170 F for Buildings 29006 and 87017 over a 48-month period. Neither of these figures appears to reveal any trend of degradation. However, note that the heat exchanger was removed from Building 29006 on 28 April 1992 to rehabilitate the coating that had failed due to spalling after 4.5 yr of an estimated 5-yr service life.

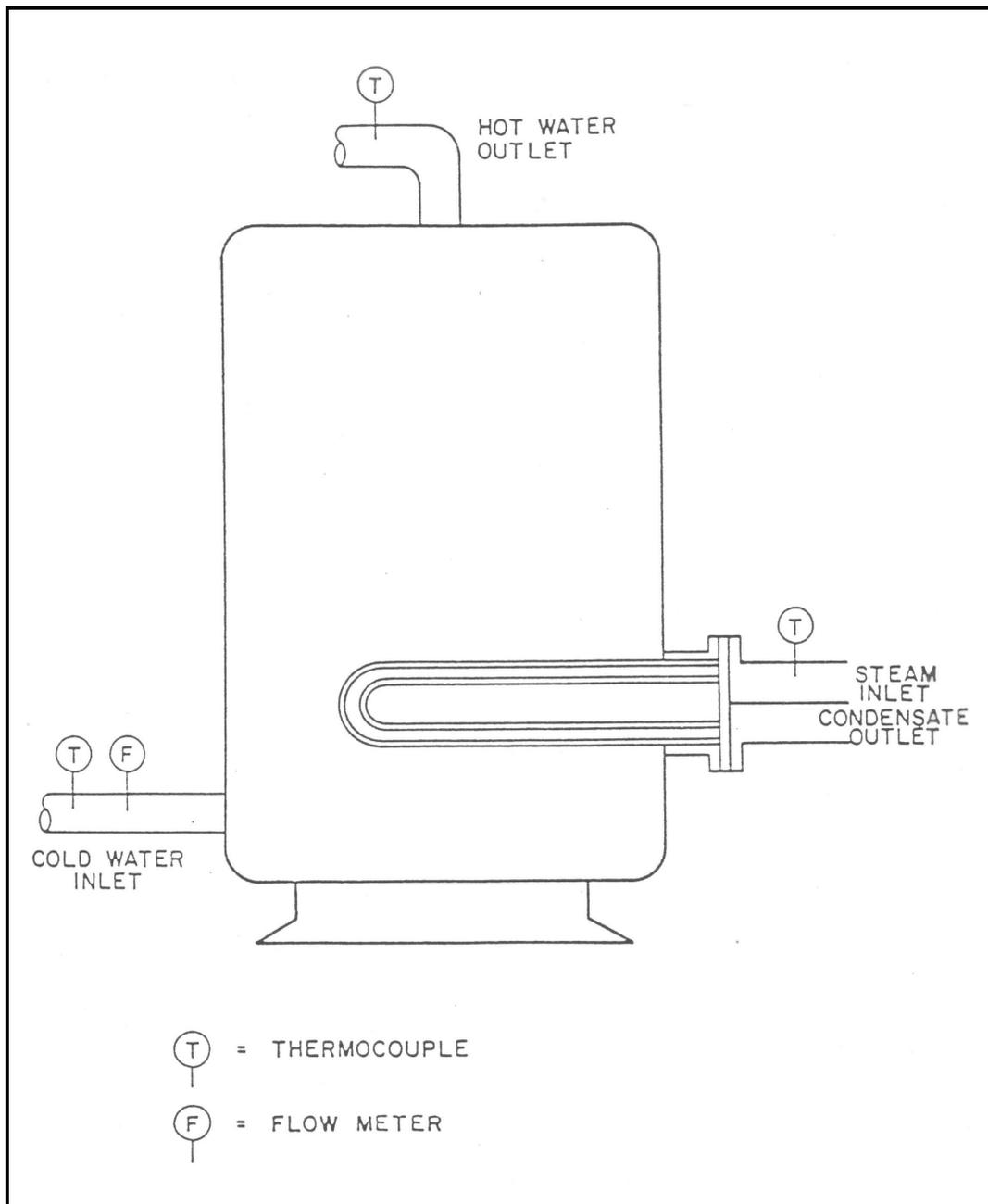


Figure 7. Placement of sensors on heat exchangers.

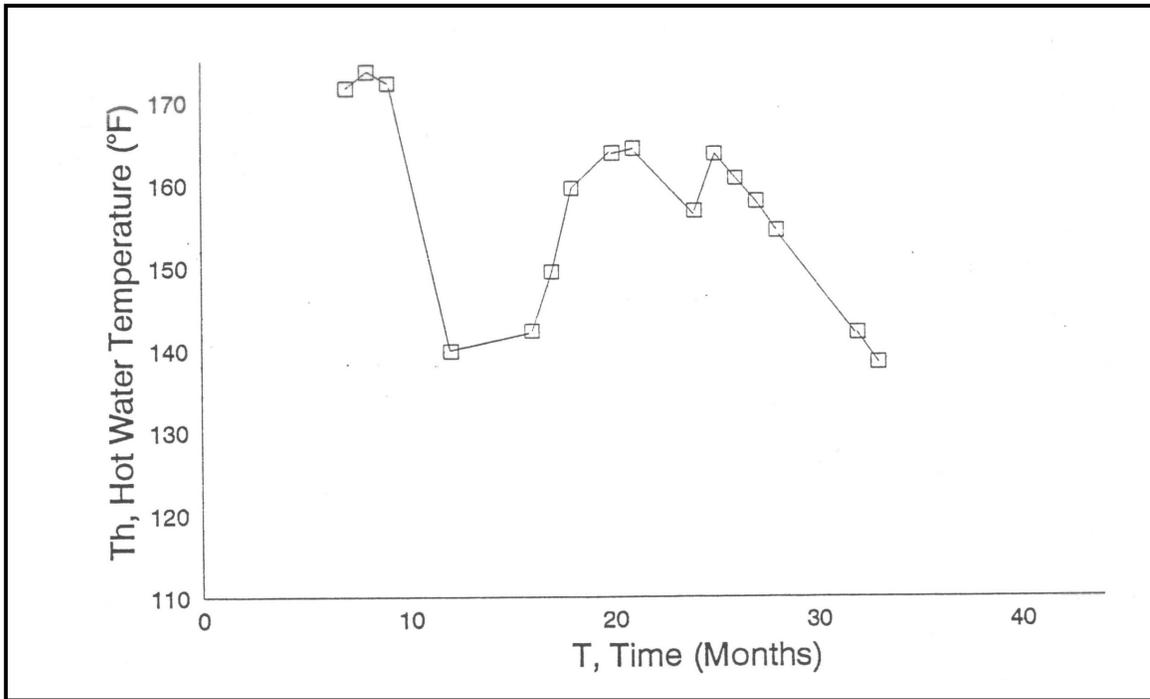


Figure 8. Hot outlet water temperatures for phenolic-coated heat exchanger, Bldg 29006, Fort Hood, TX.

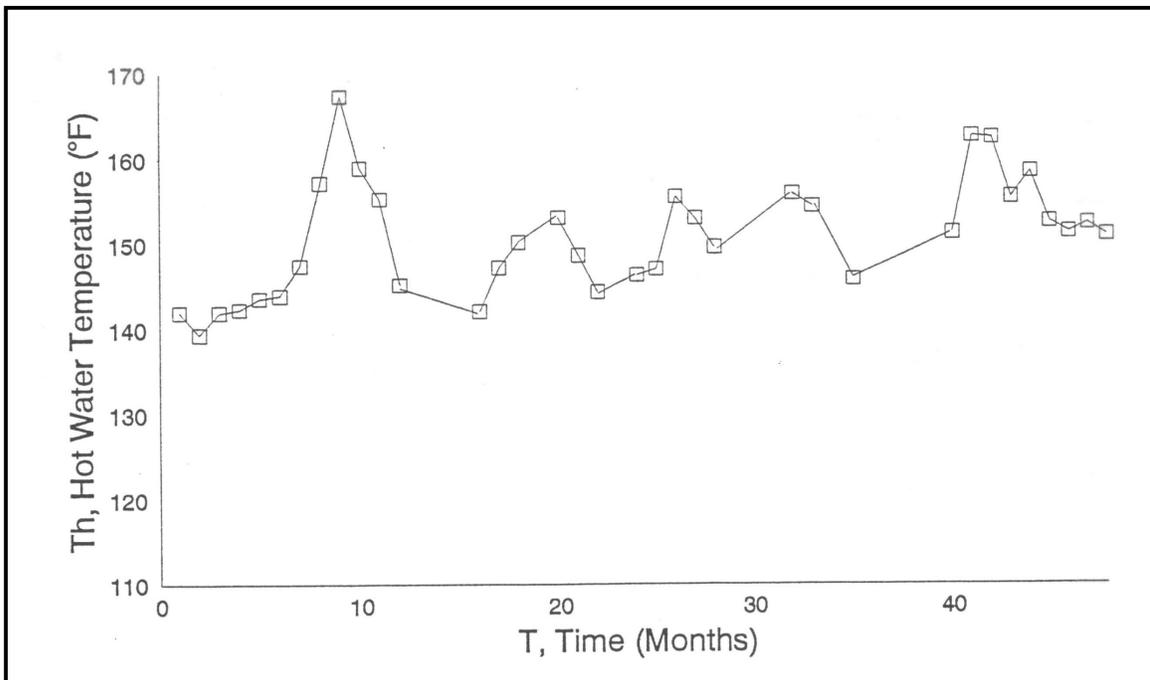


Figure 9. Hot outlet water temperatures for phenolic-coated heat exchanger, Bldg 87017, Fort Hood, TX.

Fort Bragg Field Test Results

Two heat exchangers in barracks Building Delta-2007 at Fort Bragg, NC were selected for monitoring. These two systems were instrumented (as shown in Figure 1, p 9) in September 1988. At this time, one of the heat exchangers was coated. The other system, which had been in service since 1965, was instrumented to provide a baseline comparison of coated and uncoated heat exchanger performance. As of June 1993, the coated heat exchanger has delivered 140 °F as required.

Fort Lewis Field Test Results

Figures 10 and 11 show field measurements for hot outlet water temperatures at Buildings 3654 and 3657. The data is plotted as monthly averages occurring over a 10-month period starting in December of 1990 and ending in October of 1991. Hot water outlet temperature values shown in Figures 10 and 11 were observed to remain within the range of 64 to 81 °C (147 to 178 °F). The warmest values in each case occurred during the month of September.

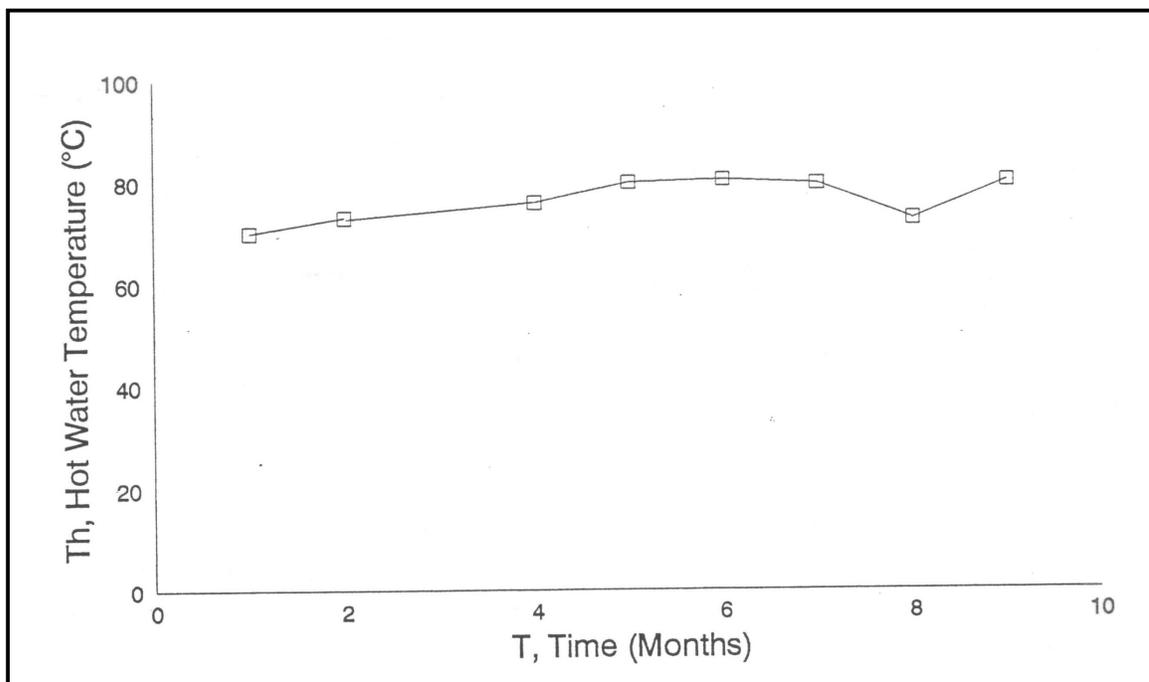


Figure 10. Hot outlet water temperatures for phenolic-coated heat exchanger, Bldg 3654, Fort Lewis, WA.

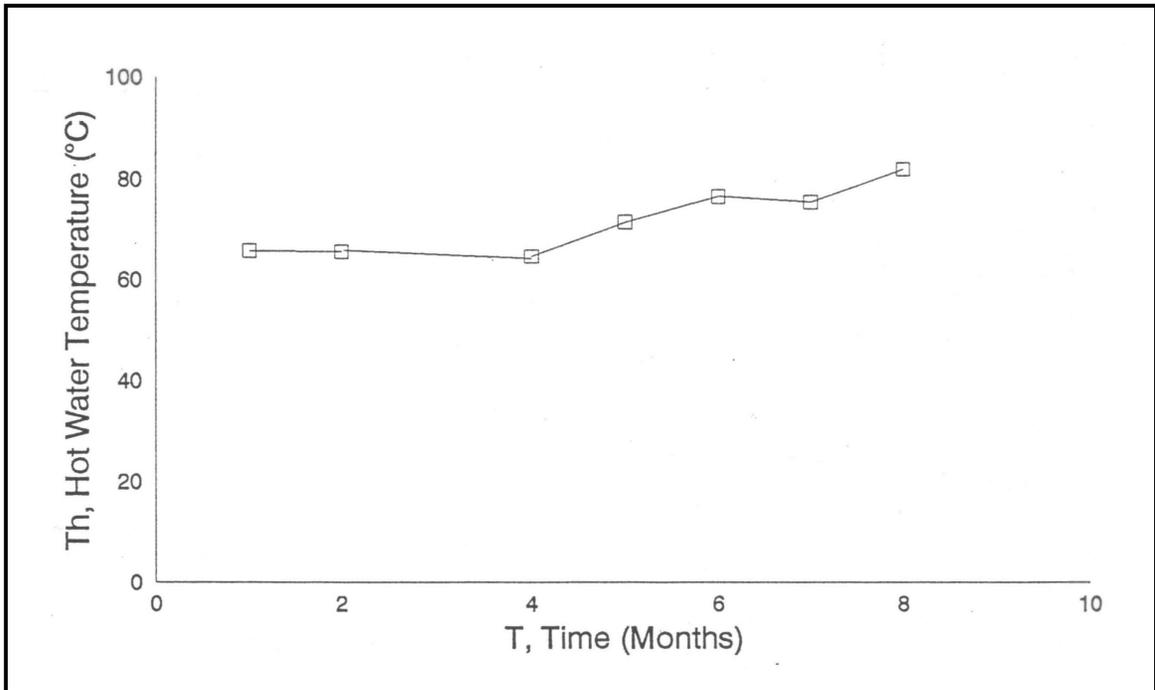


Figure 11. Hot outlet water temperatures for phenolic-coated heat exchanger, Bldg 3657, Fort Lewis, WA.

5 Life Cycle Cost Analysis

The simple payback for the coating system at the Fort Hood demonstration site is approximately 2 months. The cost of the coating (including removing and re-installing the tube bundle) for one tube bundle is about \$800, and the annual cost avoidance is estimated at \$5050 per exchanger under the severe scaling conditions at Fort Hood. In Table 4, annual cost savings for entire installations have been projected for Fort Hood and Fort Lewis (a severe corrosion/erosion site). These results could be extended to other Army installations such as Fort Bragg, NC. A more detailed cost analysis on for heat exchanger fouling at Fort Hood and Fort Lewis are presented in Appendixes B and C, respectively.

Cost of Heat Exchanger Fouling at Fort Hood, TX

Heat Exchanger Inventory

This inventory includes potable hot water storage heaters only. Of 117 exchangers, all use steam as the heat transfer medium with the exception of three electric heaters. The dining hall heaters are broken out separately because they experience much more severe scaling problems than the others. Cost calculations are performed separately for these units: Large dining hall exchangers (2); all other steam-fed exchangers (112); electric heaters (3).

Dining Hall Heat Exchangers

Average Annual Number of Repair Actions. According to DEH personnel, the two dining hall heat exchangers are removed and cleaned approximately six times per year. Thus, for the two dining hall heat exchangers, there are a total of 12 repair actions per year.

Table 4. Coating investment payback.

Site	No. of Exchangers	Annual Cost of Problem	Cost of Coating All Exchangers	Simple Payback (yr)
Fort Hood	115	\$56,923	\$92,000	1.6
Fort Lewis	97	60,624	77,600	1.3

Average Annual Number of Complete Replacements. According to DEH personnel, one new tube bundle is purchased per year for the dining halls.

Calculation

The cost of dining hall heat exchanger fouling at Fort Hood was calculated as:

1. Direct costs (dining halls)
 - a. From IFS: Labor rate = \$17.06/hr
 - b. From DEH personnel: Average repair action takes 11 hr (2 workers); new tube bundle costs \$1700; capacity of tanks = 2115 gal

$$\text{Direct labor cost} = \$17.06 * 2 \text{ workers} * 11 \text{ hr} * 12 \text{ repairs} = \$4504$$

$$\text{Direct materials cost} = 1 \text{ replacement} * \$1700 = \$1700$$

2. Associated losses (dining halls)

$$\text{Tank draindown: } \$12.80 \text{ per } 1000 \text{ gal} * 2.115 * 12 \text{ actions} = \$325$$

$$\text{Acid disposal: } \$12.00 \text{ per action} * 12 \text{ actions} = \$144$$

3. Operations and maintenance: covered under labor
4. Downtime (dining halls): Downtime costs in the dining halls include the cost of paper plates and plastic utensils. Cold food items must also be purchased, but this does not involve costs above what would normally be spent on food. Paper plate/ utensil cost is approximately \$300 per repair action.

$$\text{Downtime costs} = \$300 * 12 \text{ actions} = \$3600$$

5. Total cost for dining halls:

Labor	\$ 4,504
Materials	1,700
Associated losses	325
Operations/maintenance	0
Downtime	<u>3,600</u>
Total	\$10,129

All Other Steam-Fed Exchangers

Average Annual Number of Repair Actions. According to tabulations of data supplied by DEH personnel, the remaining 112 heat exchangers are removed

and cleaned an average of once every 2.25 yr. Thus, there is a total of 52 repair actions per year.

Average Annual Number of Complete Replacements. According to DEH personnel, 5 new tube bundles are purchased per year for the remainder of Fort Hood.

Calculation

The cost of steam-fed heat exchanger fouling (other than dining hall exchangers) was calculated as:

1. Direct costs (all other steam-fed exchangers)

From IFS: Labor rate = \$17.06/hr.

From DEH personnel: Average repair action takes 6 hr; (2 workers); new tube bundle costs \$1700; average tank capacity = 1155 gal

Direct labor cost = $\$17.06 * 2 \text{ workers} * 6 \text{ hr} * 52 \text{ repairs} = \$10,645$

Direct materials cost = $5 \text{ replacements} * \$1700 = \$8500$

2. Associated losses (all other steam-fed exchangers)

Tank draindown: $\$12.80 \text{ per } 1000 \text{ gal} * 1.155 * 52 \text{ actions} = \769

Acid disposal: $\$12.00 \text{ per action} * 52 \text{ actions} = \624

3. Operations and maintenance (all other steam-fed exchangers): From DEH personnel:

3 hr per replacement to order/specify/inspect exchangers

$5 \text{ replacements} * \$17.06/\text{hr} * 3 \text{ hr} = \256

4. Downtime (all other steam-fed exchangers): Similar assumptions will be made here as for Fort Lewis:

- a. Since average repair takes about 6 hr (according to DEH personnel), assume that soldiers in that building will be inconvenienced for 1 day. "Inconvenienced" means that they will have to find alternate facilities at which to bathe and/or do laundry.
- b. barracks houses 125 soldiers.
- c. The troop loses 1/2 hr per repair to go to alternate facilities.

- d. $1/2 \text{ hr} * 125 \text{ soldiers} * \$8/\text{hr} * 52 \text{ repairs} = \$26,000$
5. Total cost for all other exchangers:
- | | |
|------------------------|---------------|
| Labor | \$10,645 |
| Materials | 8,500 |
| Tank Draindown | 769 |
| Acid Disposal | 624 |
| Operations/Maintenance | 256 |
| Downtime | <u>26,000</u> |
| Total | \$46,794 |
6. Fort Hood total: $\$46,794 + 10,129 = \$56,923$

Cost of Heat Exchanger Fouling at Fort Lewis, WA

Fort Lewis has four kinds of hot water facilities (Table 5).

Average Annual Number of Repair Actions

According to IFS, the average number of repair actions per year is 32. According to DEH personnel, there are 48 repair actions per year related to potable water heat exchangers. Averaging these, we will estimate: Average annual number of repair actions = 40

Average Annual Number of Complete Replacements

According to DEH personnel, 20 percent of repair actions on potable water heat exchangers involve replacement of the tube bundle. Thus: Average annual number of replacements = 8

Calculation

The cost of heat exchanger fouling at Fort Lewis was calculated as:

1. Direct costs: labor & materials
 - a. Limitation: In the IFS database, the heat exchangers used for potable water and for building heat were not identified separately. Therefore, labor cost estimates from IFS include both.
 - b. From IFS: Base direct labor rate: \$15.25 per hour (including overhead and material burden); hours spent on heat exchanger repairs: 1069
 - c. From DEH Personnel: New tube bundle costs: \$1400

- d. Total annual direct labor cost = $\$15.25 * 1069 \text{ hr} = \$16,302$
- e. Direct materials cost = $8 \text{ replacements} * \$1400 = \$11,200$
2. Associated losses:
Tank draindown: $\$12.80 \text{ per action} * 40 \text{ actions} = \580
3. Operations and maintenance:
- From DEH Personnel: 1 hr per job to order, inspect, and specify exchangers
 - $40 \text{ jobs} * 1 \text{ hr} * \$15.25/\text{hr} = \$610$
4. Downtime: the downtime calculation depends on the following assumptions:
- Since average repair takes about 6 hr (according to DEH personnel), assume that soldiers in that building will be inconvenienced for 1 day. "Inconvenienced" means that they will have to find alternate facilities at which to bathe and/or do laundry.
 - A barracks houses 200 soldiers.
 - The troop loses $\frac{1}{2}$ hr per repair to go to alternate facilities, i.e.,
 $\frac{1}{2} \text{ hr} * \$8.00/\text{hr} * 40 \text{ jobs} * 200 \text{ soldiers} = \$32,000$
5. Total cost:
- | | |
|------------------------|-----------------|
| Labor | \$16,302 |
| Materials | 11,200 |
| Associated losses | 512 |
| Operations/maintenance | 610 |
| Downtime | <u>32,000</u> |
| Total | \$60,624 |

6 Discussion

Completely absent from the hot water outlet patterns (as shown in Figures 8 to 11) of either site is any indication of a negative sloping trend among the hot water delivery values. Additionally, the average hot water temperature was maintained at 140 °F at Fort Hood, and above 147 °F at Fort Lewis. Similarly, the personnel at Fort Bragg have experienced no difficulty in maintaining the 140 °F required hot water temperature. These observations indicate that the scale has not formed on the coated tube bundles at Fort Hood and Fort Bragg and the corrosion fouling did not form on the tube bundles at Fort Lewis. For Fort Hood Building 87017 in particular, this finding means that a 90-day cycle of acid cleaning may be replaced by a one-time fix that has provided over 4 yr of satisfactory performance.

7 Conclusions and Recommendations

This study concludes that:

1. Based on the data presented in Chapter 6, the phenolic based composite coating system applied to potable water heat exchangers at Fort Hood, TX, Fort Bragg, NC, and Fort Lewis, WA, maintained the hot water delivery temperatures at or above 140 °F in both scaling and corrosive fouling waters.
2. The coated heat exchangers eliminated the need for 90-day acid cleaning cycles to remove the scale buildup on uncoated tubes at Fort Hood, TX for 4.5 yr.
3. The simple payback for using phenolic based coating technology on heat exchangers at Fort Hood, TX and Fort Lewis, WA is less than 2 yr.

It is recommended that:

1. Phenolic based composite coatings be considered for use as an alternative to chemical treatment in potable water heat exchangers as specified in CEGS 15400 Plumbing, General Purpose, for cases where scaling or corrosion reduces significantly reduces the hot water delivery temperatures and the life cycle cost analysis (as shown in Appendix B and C) justifies the use of coatings over a chemical treatment system.
2. If the phenolic based composite coating system is selected, the specifications outlined in CEGS 15400 section 2.10.4 Phenolic Resin Coating should be followed (Appendix A).

References

Hock, Vincent F., *User Guide and Specifications for Baked Phenolic Coating Systems Applied to Domestic Hot Water Heat Exchangers*, Special Report (SR) ERDC/CERL SR-01-1 (U.S. Army Construction Engineering Research Laboratory [CERL], January 2001).

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

Myers, J.R., *Fundamentals and Forms of Corrosion* (Air Force Institute of Technology, 1974).

Appendix A: Excerpts From Relevant Guide Specifications

Corps of Engineers Guide Specification Section 15400 (Plumbing, General)

2.10.4 Phenolic Resin Coatings

The phenolic resin coil coating system shall be a product specifically intended for use on steel, copper, copper alloy, and stainless steel water heating coils. All coating components shall be capable of withstanding dry heat temperatures up to 300 degrees F. All coating material shall meet the requirements of CFR 21 Part 175. The coating system shall consist of the following three components:

2.10.4.1 Wash Primer

The wash primer shall be composed of a combination of polyvinyl butyryl and a heat hardening phenolic resin. The weight per gallon shall be between 7.0 lbs/gal minimum and 7.4 lbs/gal maximum.

2.10.4.2 Pigmented Base Coat

The pigmented baking phenolic base coat shall consist of heat hardening phenolic resins, suitable pigments of the earth type, and softening agents. It shall not contain drying oils or cellulose material. The weight per gallon shall be between 10.3 lbs/gal minimum and 10.7 lbs/gal maximum. The non-volatile solids content shall be between 60 percent minimum and 64 percent maximum by weight.

2.10.4.3 Clear Top Coat

The clear non-pigmented baking phenolic top coat shall have a weight per gallon of between 8.65 lbs/gallon minimum and 8.95 lbs/gallon maximum. The non-volatile solids content shall be between 48 percent minimum and 52 percent maximum by weight.

Corps of Engineers Guide Specification Section 15405 Plumbing, Hospital

2.13.3 Phenolic Resin Coating

 NOTE: If interior erosion of the tubes at or near the tube sheet is expected to be a severe problem, change the wording of this paragraph and its subparagraphs to require the coating to be applied to the first 5 to 8 inches inside the tubes by brushing.

The phenolic resin coating shall be applied at either the coil or coating manufacturer's factory. The coil shall be chemically cleaned to remove any scale if present and to etch the metal surface. The exposed exterior surface of the coil shall be abrasively cleaned to white metal blast in accordance with SSPC SP 5. The coating shall be a product specifically intended for use on the material the water heating coils are made of, i.e., steel, copper, copper alloy, or stainless steel. All coating components shall be capable of withstanding temperatures up to 300 degrees F dry bulb; and meet the requirements of CFR 21 Part 175. [The entire exterior surface] [and] [the first 5 to 8 inches inside the tubes] of each coil shall be coated with the three component phenolic resin coating system. The system shall consist of the following, the wash primer, the pigmented base coat, and the clear top coat. Immediate and final cure times and temperatures shall be as recommended by the coating manufacturer.

2.13.3.1 Coating Coil Interiors

One coat of the wash primer component shall be applied by brushing or flooding. Several coats of the pigmented base component shall be applied by brushing, immersion, or flooding. Several coats of the clear top (non-pigmented) component shall be applied by brushing, immersion, or flooding, with exception of the final coat which may be applied by spraying.

2.13.3.2 Coating Coil Exteriors

One coat of the wash primer component shall be applied by flooding. Several coats of the pigmented base component shall be applied by immersion or flooding. Several coats of the clear top (non-pigmented) component shall be applied by immersion or flooding, with exception of the final coat which may be applied by spraying.

2.13.3.3 Coating Components

- a. Wash Primer. The wash primer component shall be composed of a combination of a polyvinyl butyryl and heat hardening phenolic resin. The weight per gallon shall be between 7.0 lbs/gallon minimum and 7.4 lbs/gallon maximum.
- b. Pigmented Base. The pigmented base component shall be applied to dry film thickness of 0.004 to 0.006 inch. The pigmented base shall consist of heat hardening phenolic resins, suitable pigments of the earth type, and softening agents. It shall not contain drying oils or cellulose material. The weight per gallon shall be between 10.3 lbs/gallon minimum and 10.7 lbs/gallon maximum. The non-volatile solids content shall be between 60 percent minimum and 64 percent maximum by weight.
- c. Clear Top. The clear top (non-pigmented) component shall be applied until the dry film thickness of the total coating system is between 0.005 and 0.007 inch. The clear non-pigmented top coat shall have a weight per gallon of between 8.65 lbs/gallon minimum and 8.95 lbs/gallon maximum. The non-volatile solids content shall be between 48 percent minimum and 52 percent maximum by weight.

For background information on the development of the baked phenolic coating, refer to CERL Technical Report M-91/05, "Development and Testing of an Anti-Scale/Corrosion Resistant Coating for Domestic Hot Water Heat Exchangers.

Appendix B: Cost of Heat Exchanger Fouling at Fort Hood, TX

Heat Exchanger Inventory

This inventory includes potable water storage heaters only. Of 117 exchangers, all use steam as the heat transfer medium with the exception of three electric heaters. The dining hall heaters are discussed separately because they experience much more severe scaling problems than the others. Cost calculations are performed separately for these units: large dining hall exchangers (2); all other steam-fed exchangers (112); and electric heaters (3).

Dining Hall Heat Exchangers

Average Annual Number of Repair Actions

According to Directorate of Engineering and Housing (DEH) personnel, the two dining hall heat exchangers are removed and cleaned four to six times per year. Thus, for the two dining hall heat exchangers there are typically eight to twelve repair actions per year.

Average Annual Number of Complete Replacements

According to DEH personnel, one new tube bundle is purchased per year for the dining halls.

Calculation

The cost of dining hall heat exchanger fouling at Fort Hood was calculated as follows:

1. Direct costs (dining halls)
 - a. From the Integrated Facilities System (IFS): Labor rate = \$17.06/hr.

- b. From DEH personnel:
- (1) Average repair action takes 11 hr (2 workers)
 - (2) New tube bundle costs \$1700
 - (3) Capacity of tanks = 2115 gal
 - (4) Direct labor cost = $\$17.06 * 2 \text{ workers} * 11 \text{ hr} * 12 \text{ repairs} = \4504
 - (5) Direct materials cost = $1 \text{ replacement} * \$1700 = \$1700$
2. Associated losses (dining halls)
- a. Tank draindown: $\$12.80 \text{ per } 1000 \text{ gal} * 2.115 * 12 \text{ actions} = \325
 - b. Acid disposal: $\$12.00 \text{ per action} * 12 \text{ actions} = \144
3. Operations and maintenance: covered under labor
4. Downtime (dining halls): Downtime costs in the dining halls include the cost of paper plates and plastic utensils. Cold food items must also be purchased, but this does not involve costs above what would normally be spent on food. Paper plate/ utensil cost is approximately \$300 per repair action.

Downtime costs = $\$300 * 12 \text{ actions} = \3600

5. Total cost for dining halls:

Labor	\$ 4,504
Materials	1,700
Associated losses	325
Operations/maintenance	0
Downtime	<u>3,600</u>
Total	\$10,129

All Other Steam-Fed Exchangers

Average Annual Number of Repair Actions

According to DEH data, the remaining 112 heat exchangers are removed and cleaned an average of once every 2.25 yr. Thus, there are typically 52 repair actions per year.

Average Annual Number of Complete Replacements

According to DEH personnel, five new tube bundles are purchased per year for the remainder of Fort Hood.

Calculation

The cost of steam-fed heat exchanger fouling (other than dining hall exchangers) was calculated as follows:

1. Direct costs (all other steam-fed exchangers)
 - a. From IFS: Labor rate = \$17.06/hr
 - b. From DEH personnel:
 - (1) Average repair action takes 6 hr for 2 workers (total of 12 hr)
 - (2) New tube bundle costs \$1700
 - (3) Average tank capacity = 1155 gal
 - (4) Direct labor cost = $\$17.06 * 2 \text{ workers} * 6 \text{ hr} * 52 \text{ repairs} = \$10,645$
 - (5) Direct materials cost = $5 \text{ replacements} * \$1700 = \$8500$
2. Associated losses (all other steam-fed exchangers)
 - a. Tank draindown: $\$12.80 \text{ per } 1000 \text{ gal} * 1.155 * 52 \text{ actions} = \769
 - b. Acid disposal: $\$12.00 \text{ per action} * 52 \text{ actions} = \624
3. Operations and maintenance (all other steam-fed exchangers) From DEH personnel:
 - a. 3 hr per replacement to order, specify, and inspect exchangers
 - b. $5 \text{ replacements} * \$17.06/\text{hr} * 3 \text{ hr} = \256
4. Downtime (all other steam-fed exchangers) (Similar assumptions are made here as for Fort Lewis.)
 - a. Since average repair takes about 6 hr (according to DEH personnel), assume that soldiers in that building will be inconvenienced for 1 day. ("Inconvenienced" means that they will have to find alternate facilities at which to bathe and/or do laundry.)
 - b. A barracks houses 125 soldiers.
 - c. The troop loses 0.5 hr per repair to go to alternate facilities
 - d. $0.5 \text{ hr} * 125 \text{ soldiers} * \$8/\text{hr} * 52 \text{ repairs} = \$26,000$

5. Total cost for all other exchangers:

Labor	\$10,645
Materials	8,500
Tank Draindown	769
Acid Disposal	624
Operations/Maintenance	256
Downtime	<u>26,000</u>
Total	\$46,794

Total Costs of Heat Exchanger Fouling at Fort Hood

Based on the preceding calculations, the total cost of heat exchanger fouling at Fort Hood can be summarized as:

Dining facility heat exchangers (2)	\$10,129
All other steam-fed heat exchangers (112)	<u>46,794</u>
Total expense	\$56,923

Appendix C: Cost of Heat Exchanger Fouling at Fort Lewis, WA

Heat Exchanger Inventory

Fort Lewis has four kinds of hot water facilities (Table C1).

Table C1. Fort Lewis heat exchanger inventory.

Type	Number
Steam-fed potable HW	39
Steam-fed facility heat	51
HTHW-fed potable HW	58
HTHW-fed facility heat	15

Average Annual Number of Complete Replacement

According to DEH personnel, 20 percent of repair action on potable water heat exchangers involve replacement of the tube bundle. Thus, the average annual number of replacements is eight.

Calculation

The cost of heat exchanger fouling at Fort Lewis was calculated as:

1. Direct costs (dining halls)
 - a. Limitation: In the IFS data base, the heat exchangers used for potable water and for building heat were not identified separately. Therefore, labor cost estimates from IFS include both.
 - b. From IFS: Base direct labor rate: \$15.25 per hour (including overhead and material burden); hours spent on heat exchanger repairs: 1069

- c. From DEH personnel: New tube bundle costs \$1400
- (1) Total annual direct labor cost = $\$15.25 * 1069 \text{ hr} = \$16,302$
- (2) Direct materials cost = $8 \text{ replacements} * \$1400 = \$11,200$
2. Associated losses (dining halls)
- Tank draindown: $\$12.80 \text{ per action} * 40 \text{ actions} = \580
3. Operations and maintenance: From DH personnel: 1 hr per job to order, inspect, and specify exchangers:
- $40 \text{ jobs} * 1 \text{ hr} * \$15.25/\text{hr} = \$610$
4. Downtime: the downtime calculation depends on the following assumptions:
- a. Since an average repair takes about 6 hr (according to DEH personnel), assume that soldiers in the building will be inconvenienced for 1 day. ("Inconvenienced" means that they will have to find alternative facilities at which to bathe and/or do laundry.
- b. A barracks houses 200 soldiers
- c. The troop loses $\frac{1}{2}$ hr per repair to go to alternative facilities:
- $\frac{1}{2} \text{ hr} * \$8.00/\text{hr} * 40 \text{ jobs} * 200 \text{ soldiers} = \$32,000$

Total cost for dining halls:

Labor	\$ 16,302
Materials	11,200
Associated losses	512
Operations/maintenance	610
Downtime	<u>32,000</u>
Total	\$60,624

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