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Foreword

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit MA-CL2, "Protective Coatings for M&E Equipment and Distribution Systems." The technical monitor was Joseph McCarty, CECW-ET.

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 Acting Technical Director of the Facility Acquisition and Revitalization business area is Dr. Paul A. Howdyshell. 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 exchanger systems are commonly employed in various Army facilities, including laundries, dining halls, and barracks. Directorate of Engineering and Housing engineers and maintenance personnel are frequently faced with recurrent fouling of heat exchanger tube bundles that reduces the thermal efficiency of these systems to the point where they fail to meet hot water demands.

Common maintenance practices that address this problem are costly and labor intensive, and involve hazardous chemical and waste handling. For example, water treatment can reduce or eliminate scaling and corrosion problems, but such treatment is expensive, requiring a significant capital investment (water treatment equipment and installation) and large ongoing expenses (testing and monitoring labor, chemicals, etc.). Another approach, one used previously at Fort Hood, TX, is to remove the heat exchanger periodically and clean off the scaling in an acid bath. This labor intensive process entails the disposal of the acid bath—a hazardous material. The need for a way to prevent scaling at a minimal cost led to efforts to develop a coating system that would prevent scaling and be virtually maintenance free, and to this long-term field study that examined the effects of applying a phenolic coating to the heat exchanger bundles in domestic water storage heaters (DWSHs).

Objectives

The objectives of this study were to: (1) evaluate the ability of a phenolic coating to relieve the fouling problems associated with DWSH heat exchangers, (2) evaluate the technical feasibility cost effectiveness of applying and using the coatings, and (3) make recommendations regarding the use of such coatings.

Approach

Field tests were conducted at Fort Hood to test coating technologies in DWSH heat exchangers. Initial field test result from 1987 and 1988 were reported in Hock et al. (1990). These initial tests indicated that an immersion-applied baked-on phenolic coating system significantly reduced scaling in DWSH applications. A longer-term field test was conducted at Fort Hood from May 1988 to May 1992 using a phenolic coating applied to two DWSH heat exchangers in Fort Hood's dining facilities.

Scope

This report projects annual cost savings for Fort Hood (a severe scaling site), and Fort Lewis, WA (a severe corrosion/erosion site). These results could be extended to other U.S. Army installations such as Fort Riley, KS; Fort Bragg, NC; and Fort Jackson, SC.

Mode of Technology Transfer

Corps of Engineers Guide Specifications 15400 (Plumbing, General) and 15404 (Plumbing, Hospital) have been changed to allow the use of the baked-on phenolic coating on potable water shell and tube heat exchangers. Specifications for this coating are found under section 2.10.4 of CEGS 15400 and section 2.13.3 of CEGS 15405. These two sections are presented in Appendix A. In addition, FEAP demonstration project FEAP-MB-K92 "Corrosion Resistant Coatings for Hot Water Heat Exchangers" produced an Ad Flyer and User Guide (*User Guide and Specifications for Baked Phenolic Coating Systems Applied to Domestic Hot Water Heat Exchangers*, ERDC/CERL SR-01-1) 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.

SI conversion factors				
1 Btu	=	100,000 therm	=	1055.56 Joule
1 Btu/(hr-sq ft-°F)	=	5.679 W/(m^2- C)		
1 Btu/(lb-°F)	=	4186.8 Joule/(Kg- C)		
1 gal (U.S.)	=	3.78 L		
1 gal (U.S.)/min	=	0.063 L/sec		
1 mil	=	0.0000245 m		
1 in.	=	25.4 mm	=	0.0254 m2
1 sq ft	=	0.0929 m^2		
1 lb	=	0.453 kg		
1 lbm (pound-mass)	=	0.453 kg (kg-mass)		
1 lb/sq in (psi)	=	6894.76 Pas		
1 lb/gal (U.S.)	=	0.112 kgm/L		
°F	=	(C × 1.8] + 32		

2 Background on Heat Exchangers

In general, a heat exchanger is a mechanical system that permits thermal contact between different thermal media while preventing physical contact. These systems are designed to provide controlled transfer of thermal energy from one medium to another. This chapter describes 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 employed in the Army is the DWSH (Figure 1). Such a system is composed of a cylindrical steel reservoir lined with concrete for corrosion protection. An opening at the bottom provides access to a U-tube bundle assembly.

Domestic water is the supply that is used for everyday human consumption. DWSH systems are found in dining halls, barracks, laundries, and other similar facilities. By maintaining a large reservoir, such a system can meet hot water needs during peak demand periods.

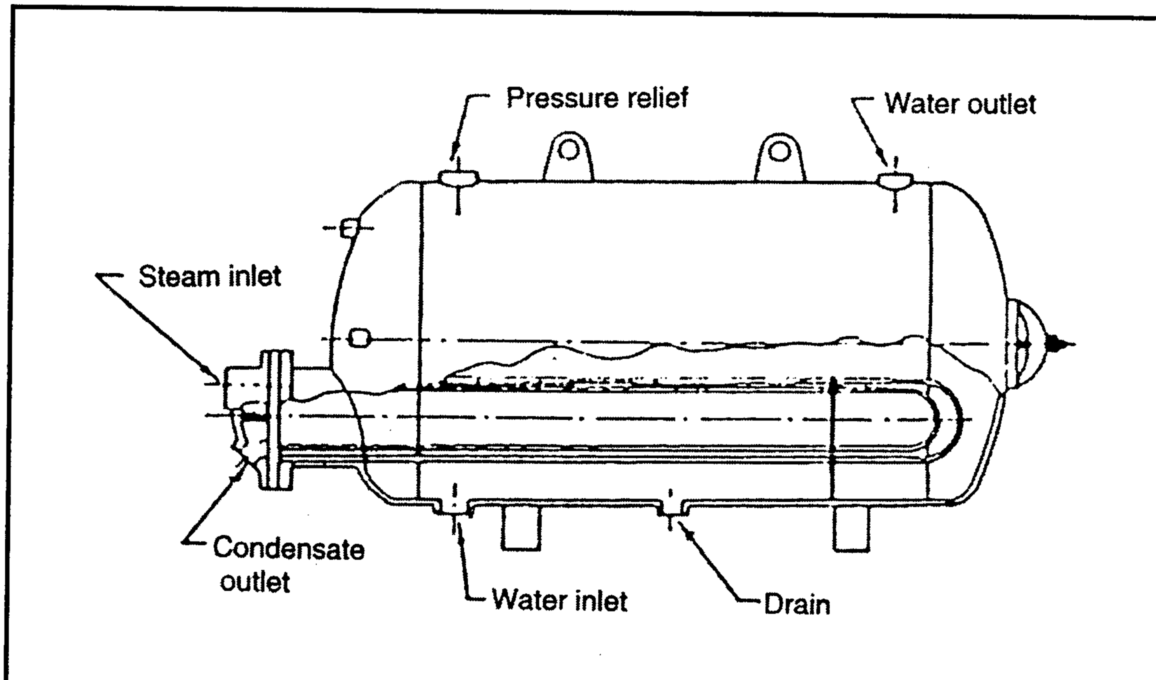

Figure 1. Domestic hot water storage heater.

Steam or hot water circulates through the interior of the tube bundles. Heat from the steam is transferred through the copper pipe wall 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 and maximizes heat transfer. Under normal conditions at Fort Hood, the incoming water at Buildings 29006 and 87017 enters the respective reservoirs at 60 to 70 °F and exits at 140 to 160 °F.

One may visualize heat flow across a tube bundle heat exchanger as starting on the inside of the copper tube and traveling through various barriers to get to the outside of the tube and into the domestic water media. Physical barriers include:

- inner fouling layer
- exchanger wall
- outer fouling layer.

The factors that affect heat flow and that will be used to construct an overall expression of the heat flow resistance in the heat exchanger include:

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 (Hock et al. 1990).

Note that heat flow resistance contributed by a coating will take a form similar to that of the fouling-induced resistances $R_{f,h}$ and $R_{f,c}$.

A model of 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 thus be expressed with the following formula:

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

In the field of heat transfer, the term U is used to express the overall heat transfer coefficient of the system. Thus, this parameter best indicates the performance of a given DWSH. Hock et al. (1990) offers a detailed discussion of the physical meanings of the terms in Equation 1 and presents an overall heat transfer coefficient that is related to various aspects of the system as follows:

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

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 term involving several system temperatures on the right side of the equation is an approximate mean value for the difference T_h - T_c, known as the logarithmic mean temperature difference, which is valid for heat exchanger systems in which T_h does not change, such as in steam-fed systems. Chapter 6 describes how Equation 2 was used to develop a field monitoring procedure for heat exchangers at Fort Hood.

3 Field Problems

Several field investigations involving fouling of domestic hot water heat exchangers have been conducted by CERL (Hock et al. 1990). This chapter discusses the heat exchanger fouling phenomenon and reviews the results of the ongoing field test at Fort Hood. Preliminary results of this field test were presented in Hock et al. (1990).

Scaling in Heat Exchangers

The scaling phenomenon is a deposition process that occurs in hard waters (Hock et al. 1990). This is frequently characterized by a hard, often whitish mass of encrusted matter composed of various minerals. While scale primarily consists of calcium carbonate, other minerals that also form deposits are magnesium carbonate, and calcium and magnesium silicates, sulfates, and hydroxides.

In general, as a given element of water approaches the hot tube bundle, the water temperature increases, the solubility of the mineral decreases, and the mineral is deposited onto the water side surface of the heat exchanger tube bundle. The formation of calcium carbonate ($CaCO_3$) deposits is governed by the following reaction:

$$Ca^2x2[HCO_3]^- \overset{T_c}{\rightarrow} CaCO_3 + CO_2(g) + H_2O(l)$$

where:

T_c = the critical calcium bicarbonate decomposition temperature.

In addition to this reaction, deposition of calcium carbonate is governed by several chemical and mechanical factors, including:

- pH
- calcium concentration
- alkalinity
- temperature
- total dissolved solids.

These five factors are included in the "Langelier index," which predicts the conditions that promote saturation of the solution with respect to calcium carbonate. A Langelier index of greater than zero 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, the following mechanical factors affect scale deposits:

- water velocity
- design
- operating conditions
- surface material.

This study focused on changing the nature of the surface material through application of a resin coating. Such a change in the surface material was expected to yield a major change in the scaling that occurred.

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

Scaling Problems at Fort Hood

In March 1986, Fort Hood personnel reported continuing problems with scaling on the surfaces of copper tube bundles inside of DWSHs (Hock et al. 1990). On 14 May 1986, CERL personnel visited the site to analyze the scaling problem.

Investigators examined the troubled DWSH located in a dining facility (Building 29006). The cement-lined tank had a capacity of 2115 gal. Typical daily hot water usage was 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 heavily scaled. The tube bundle assembly was made of a copper alloy, measured 71.5 in. long, and had a total surface area of 29.7 sq ft. Each of the 13 tubes is of 3/4 in. outside diameter. 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 is run through the inside of the tubes is generally adequate to generate the 140 °F service water temperature. However, the presence of the scale layer significantly diminished the overall heat transfer coefficient of the system. Maintenance records revealed it had been 4 months since this heat exchanger had been cleaned.

Another dining facility, Building 87017, was investigated on 14 and 15 October 1986. A heat exchanger assembly identical to that in Building 29006 was examined and found to exhibit similar calcium carbonate deposits of approximately 0.04 in. In this case, the heat exchanger had been in service for 10 months. It was noted that the hot water temperature was only 110 °F.

The assembly was acid cleaned in a large vat filled with hydrochloric acid until the scale was dissolved. Three months after reinstallation of the assembly, a new scale deposit of 0.015 in. was observed. CERL representatives collected water samples while at Fort Hood. Table 1 summarizes the chemical analysis of those samples. Note that scale deposits developed in the Fort Hood DWSHs even though the local water has a negative Langelier index. This is because calcium carbonate solubility decreases as water temperature rises; when the Fort Hood water contacts the hot tube bundles, the Langelier index rises sharply and scale is deposited. Maintenance records indicated that the heat exchangers needed to be removed and acid cleaned every 60 to 90 days to sustain required performance levels (Hock et al. 1990). 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.

4 Scaling Mitigation Methods

There are several ways to mitigate scaling problems. For heat exchangers, the options range from periodic rehabilitation to ongoing chemical treatment:

- acid cleaning
- chemical feed treatment
- ion exchange treatment
- carbon dioxide treatment
- anti-scale/corrosion resistant coatings (Hock et al. 1990).

Acid cleaning is commonly used at installations with severe scaling problems. The process is simply an after-the-fact rehabilitation using an HCl acid bath. A given treatment can require up to an entire day during which the facility must go without hot water. Also, handling and disposal of the acid requires special precautions. This practice is a labor intensive drain on operations and maintenance (O&M) resources and must be repeated as often as every 60 to 90 days.

Lime softening is the most common type of chemical treatment for scale mitigation in potable water systems. Calcium, magnesium, and bicarbonate ions are precipitated from the water before entry into the distribution system. The precipitate is removed through filtration or sedimentation. Finally, CO_2 is added to bring the pH down to a scaling resistant level.

Ion exchange methods resemble a filtration process. In this case, however, the water is passed though an ion-impregnated resin bed. While passing through the bed, nonscale-forming ions are substituted for calcium and magnesium. This is a costly process that requires periodic replenishing of the resin bed.

Carbon dioxide treatment is a carefully monitored process that can provide both rehabilitation and maintenance of equipment exposed to naturally scaling water. The pH of the water is simply monitored to determine the frequency and amount of CO_2 additions required to dissolve existing scale deposits. The pH is interactively controlled to minimize both corrosion and scaling. The use of an anti-scale/corrosion resistant coating provides a protective barrier that reduces the nucleation and growth of scale-forming species and prevents the attack of aggressive species. Industrial applications have existed for many years. Now, with the development of high-performance baked phenolics, this method is available for potable water systems.

5 Development and Application of the Phenolic Coating System

CERL worked with Heresite-Saekephen, Inc.,* to develop, laboratory test, and field test several high performance baked phenolic coating systems for high temperature immersion applications (Hock et al. 1990). This chapter describes the coating system that was factory applied and field tested at Fort Hood, TX.

The selected coating, as applied to DWSH heat exchangers at Fort Hood, consists of three parts:

1. A wash primer
2. A pigmented base coating
3. A clear glossy top coating.

Before applying the coating, surface preparation involves a white metal abrasive blast cleaning in compliance with Steel Structures Painting Council regulation SSPC-SP-5. The coating is then applied in the following steps:

1. The bundle is dipped in wash primer to apply the first coat (and the only wash primer coat).
2. The bundle is baked to 135 °C.
3. The bundle is dipped in pigmented baking phenolic. (Spray coating was found to be unsuitable due to poor control of the coating thickness.)
4. The volatiles are permitted to flash.
5. The bundle is heated in 40 °C increments on 30 minute intervals until the coating reaches 160 °C.
6. Steps 3 through 5 are repeated until the total coating is 0.004 to 0.006 in. (4 to 6 mils) thick. This typically requires four coats. (The tube bundle is allowed to cool to room temperature between coats.)

* Now known as Heresite Protective Coatings, Inc., 822 South 14th St., Manitowoc, WI 54220, tel 414/684-6646.

7. The bundle is dipped in clear coat.
8. The bundle is heated in 40 °C increments on 30 minute intervals until the coating reaches 160 °C.
9. The coating surface is polished with a 400-A grit emery cloth.
10. Steps 7 though 9 are repeated once.
11. The final clear coat layer is sprayed on.
12. The bundle is heated in 40 °C increments at 30-minute intervals until the coating reaches 220 °C.
13. This temperature is maintained for another 2 to 4 hours until the final cure color appears. CEGS section 15400, "Plumbing, General Purpose," and section 15405, "Plumbing, Hospital," contain more information regarding the use of phenolic coatings. These CEGS sections appear in Appendix A.

6 Field Testing

The phenolic coating system described in Chapter 5 was tested on copper tube bundles at Fort Hood to measure its effectiveness against scaling over a period of several years. The heat exchangers in the DWSHs in two dining facilities, Building 29006 and Building 87017, were selected for the tests because of severe and ongoing scaling problems. This chapter documents this testing process.

Field Test Approach for Heat Exchanger Coating Tests

Earlier it was mentioned that evaluation of the performance of a heat exchanger may be characterized by the overall heat transfer coefficient (U). It was also mentioned that scale on a tube surface would cause a reduction in U and hinder the heat transfer. To evaluate whether the phenolic coating can suppress scale formation, the evaluators determined that the parameter U must be monitored.

To monitor the parameter U, one must measure the quantities Q, A, T_s, T_c, and T_h (see Equation 2, p 9). While it is generally inconvenient to measure Q (heat flow), it is known that:

$$Q = F \cdot C_p \cdot [T_h - T_c] \qquad \text{[Eq 3]}$$

where:

F	=	mass flow rate of cold inlet water [lbm/s, pound-mass/second]
Cp	=	heat capacity of water [Btu/lbm·°F]
Th	=	hot outlet water temperature [°F]
Tc	=	cold inlet water temperature [°F].

Substituting Equation 4 into Equation 2, then evaluating the new equation for U, yields:

$$U = \frac{F \cdot C_p \cdot \ln\left[\frac{T_s - T_C}{T_s - T_h}\right]}{A} \qquad \text{[Eq 4]}$$

where:

T_s = steam service temperature.

Equation 4 reveals that the performance of the phenolic coating applied to a heat exchanger tube bundle can be evaluated by monitoring the four parameters T_s, T_c, T_h, and F. (C_p and A are constants.)

Field Test Procedure

To facilitate data collection, monitoring systems were installed in Buildings 29006 and 87017. The systems were set up to take readings for each of the four variable parameters required to calculate the overall heat transfer coefficient (U) for the two heat exchangers. Each data collection system included the following components:

- one portable four channel data logger with playback
- three Type J thermocouples
- one paddlewheel flowmeter.

Figure 2 shows the placement of the three thermocouples and the flow sensor on a DWSH. The data logger and playback systems can store up to 30 days of data. Data was downloaded to a personal computer once per month for analysis.

Fort Hood Field Test Results

Field measurements for flow rate, steam temperature, cold inlet water temperature, and hot outlet water temperature are presented in Figures 3 through 12. Monthly averages are plotted over the 48 month period of May 1988 to May 1992. Figures 3 through 12 are based strictly on averaged monthly data. Due to the complexity of the data analysis, no attempt was made to analyze the data in increments fine enough to pick up changes due to time of day, etc. For example, no attempt was made to analyze the effect of the phenolic coating on nighttime or daytime DWSH performance.

Figures 3 and 4 show the average monthly flow rates (F) over this period. Flow rates for Building 29006 ranged from zero, when the building was shut down, to a recorded maximum of 12 gal/min. As exhibited in the plot, the flow rates fluctuated greatly with building use over the period. While Building 87017 incurred no recorded shutdowns, it also underwent significant fluctuations in use.

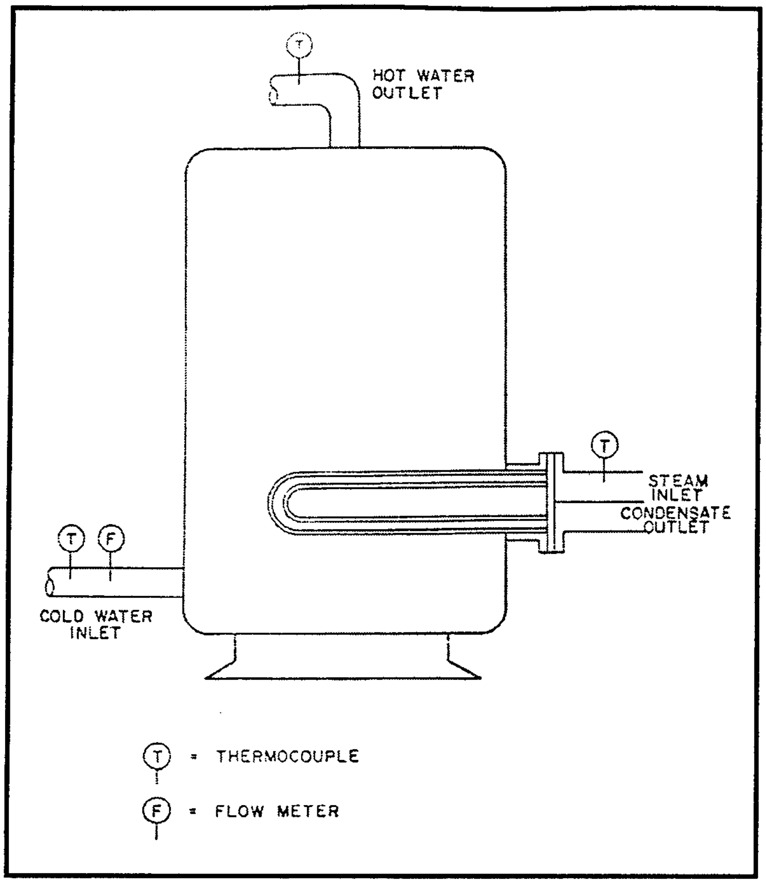

Figure 2. Placement of sensors on heat exchanger at Fort Hood.

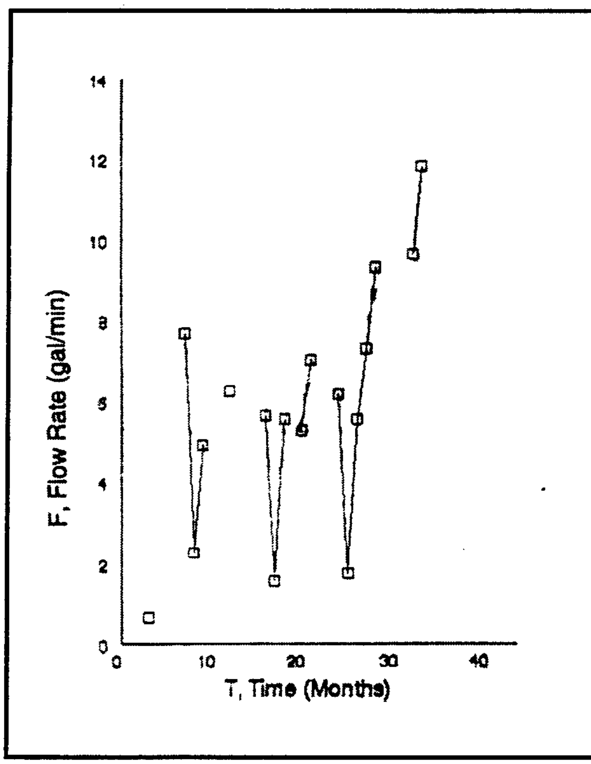

Figure 3. Flow rates (F) for phenolic-coated heat exchanger system in Bldg 29006.

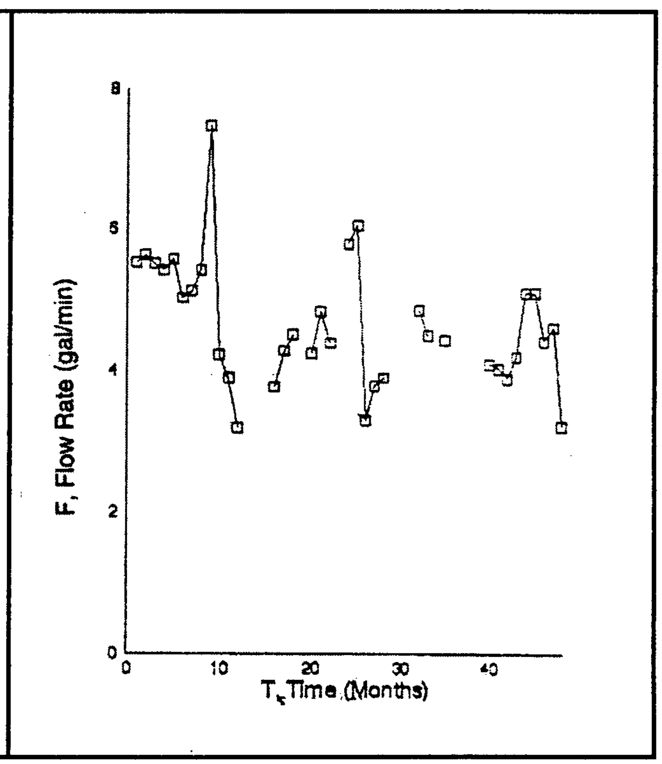

Figure 4. Flow rates (F) for phenolic-coated heat exchanger system in Bldg 87017.

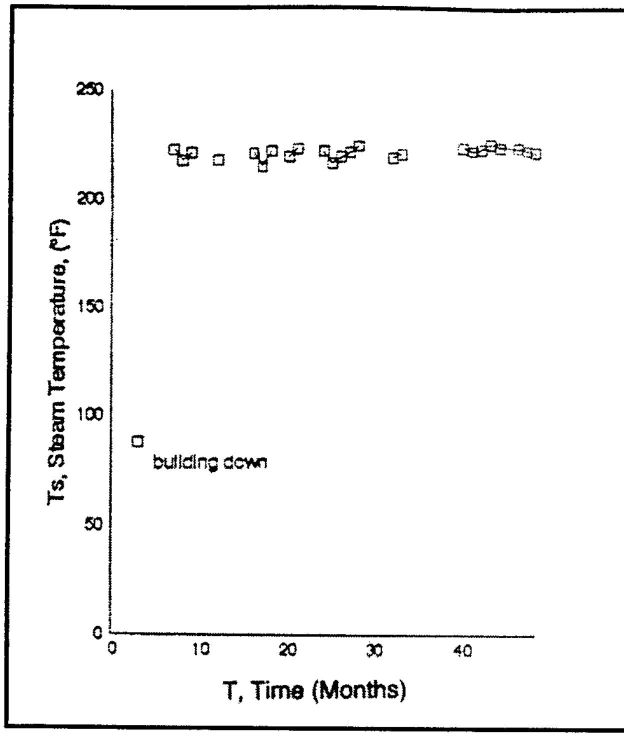

Figure 5. Steam service temperatures (T_s) for phenolic-coated heat exchanger system in Bldg 29006.

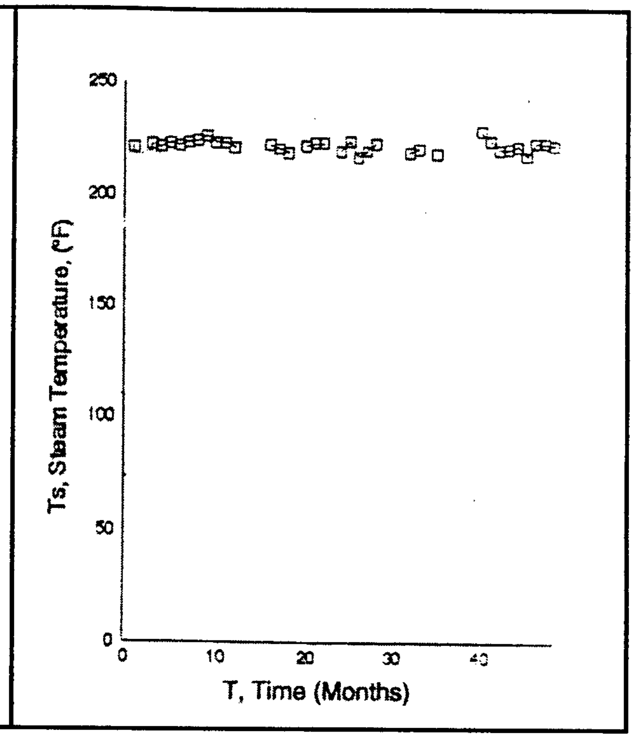

Figure 6. Steam service temperatures (T_s) for phenolic-coated heat exchanger system in Bldg 87017.

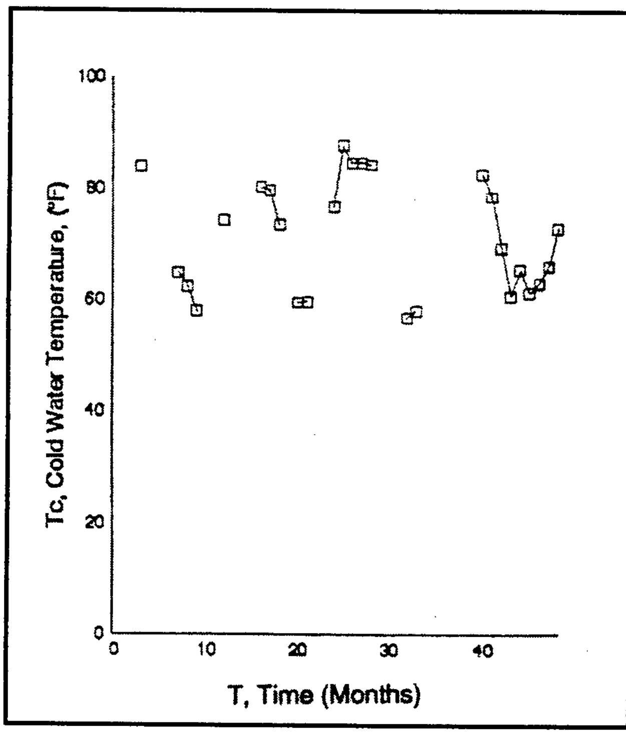

Figure 7. Cold inlet water temperatures (T_c) for phenolic-coated heat exchanger system in Bldg 29006.

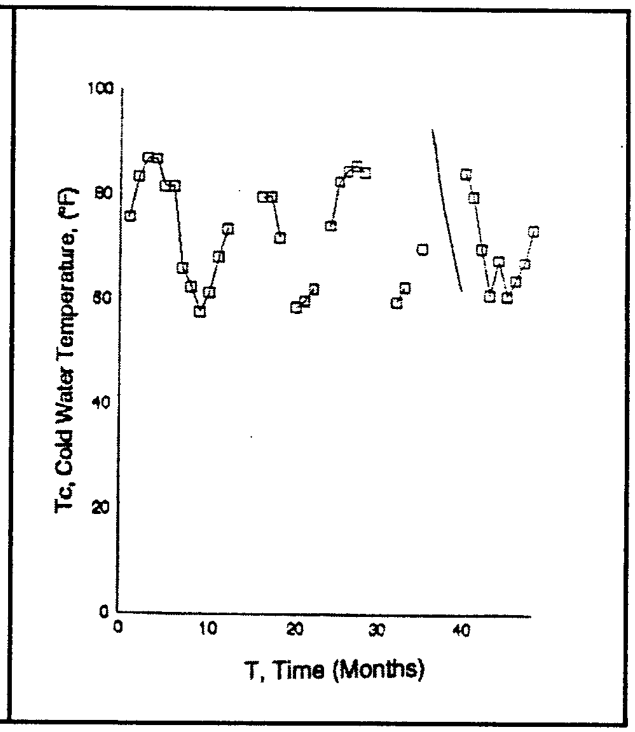

Figure 8. Cold inlet water temperatures (T_c) for phenolic-coated heat exchanger system in Bldg 87017.

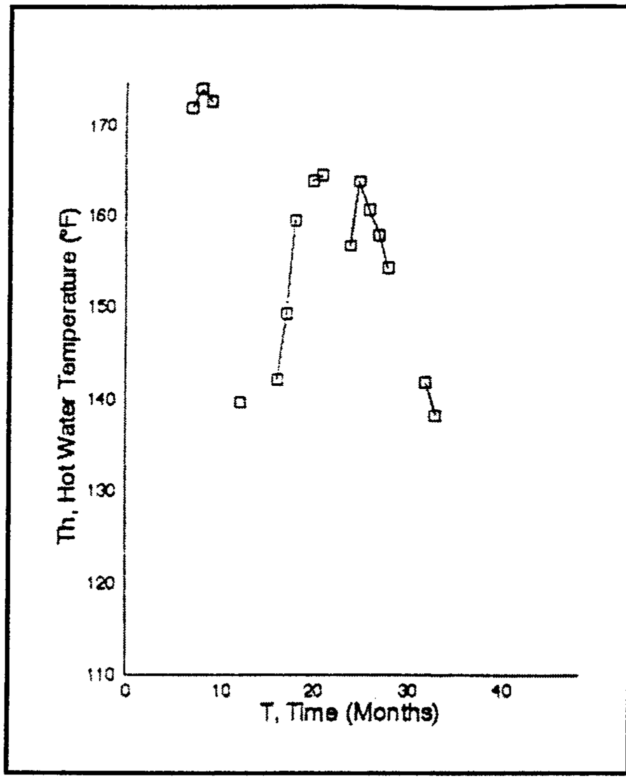

Figure 9. Hot outlet water temperatures (T_h) for phenolic-coated heat exchanger system in Bldg 29006.

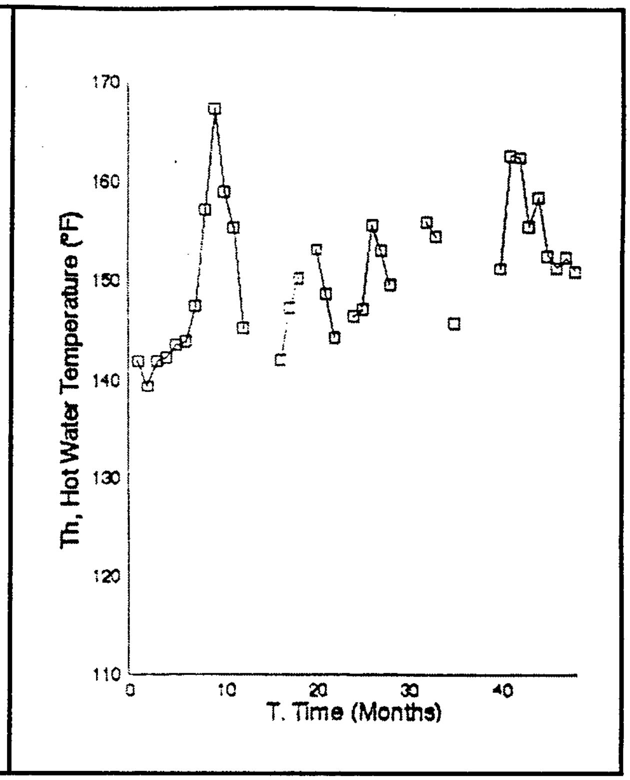

Figure 10. Hot outlet water temperatures (T_h) for phenolic-coated heat exchanger system in Bldg 87017.

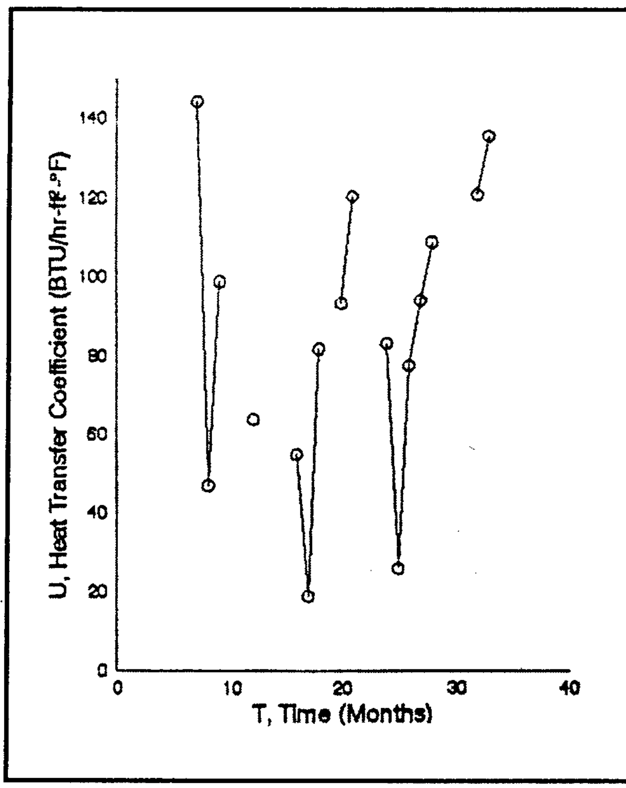

Figure 11. Heat transfer coefficients (U) for phenolic-coated heat exchanger system in Bldg 29006.

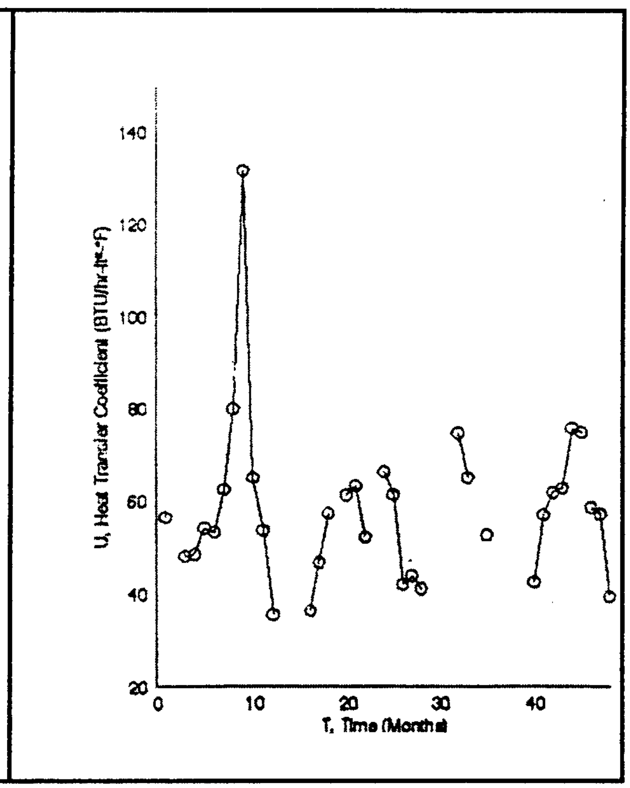

Figure 12. Heat transfer coefficients (U) for phenolic-coated heat exchanger system in Bldg 87017.

Steam service temperatures (T_s) are presented in Figures 5 and 6. The low initial value for Building 29006 again represents a period when the facility was not in use. Apart from this departure, the steam service temperatures measured over this study showed little variation; they were generally recorded in the region of 220 to 225 °F.

The cold inlet water temperatures (T_c) are recorded in Figures 7 and 8. Oscillations were found to follow the seasons somewhat sinusoidally in the range from approximately 55 to 90 °F. This pattern is more apparent for Building 87017 (Figure 8), where more data points were collected, than for Building 29006 (Figure 7).

Large fluctuations also characterized the hot water outlet temperatures (T_h) (Figures 9 and 10). On two occasions in Building 29006 and once in Building 87017, the water temperature dipped slightly below the 140 °F mark. Average hot water temperatures above 170 °F were recorded for 3 months during the winter of 1988-89 in Building 6. The average hot water temperature approached 170 °F in Building 87017 once during the same winter.

Figures 11 and 12 present the overall heat transfer coefficients (U) for the coated heat exchanger systems. These values were calculated using the average monthly values of flow rate (F) and steam (T_s), cold water (T_c), and hot water (T_h) temperatures presented in Figures 3 through 10. Neither Figure 11 nor Figure 12 reveals any degradation. However, note that the heat exchanger was removed from Building 29006 on 28 April 1992 to rehabilitate the coating that had incurred spallation failure after 4.5 years of an estimated 5-year service life.

7 Life-Cycle Cost Analysis

The simple payback for the coating system at the Fort Hood demonstration site is approximately 2 months. The cost of coating one tube bundle is about $800, including removing and reinstalling the tube bundle. Application of the phenolic coating yields an annual cost avoidance estimated at $5050 per heat exchanger under the severe scaling conditions at Fort Hood. Table 2 lists projected annual cost savings for the entire installations at Fort Hood,* Fort Lewis (a severe corrosion/erosion site), and Fort Benjamin Harrison (a moderate corrosion/erosion site) (Hock et al. 1990). These results could be extended to other Army installations such as Fort Riley, KS, Fort Bragg, NC, and Fort Jackson, SC.

Appendix B to this report gives a more detailed cost analysis of heat exchanger fouling at Fort Hood is presented.

Table 2. 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
Fort Harrison	53	$19,569	$42,400	2.1

* Note that the calculated payback period for Fort Hood's dining halls is much shorter than for the installation as a whole, which results from the higher maintenance requirements of the dining hall heat exchangers.

8 Discussion

The results in Chapter 6 provide convincing evidence that the baked phenolic coating system substantially reduces scaling problems on DWSH heat exchangers. This chapter contains a detailed interpretation of these findings.

As presented in Chapter 6, the average flow rates were 2 and 5 gal/min (Figures 3 and 4). As expected, the steam service temperatures exhibited the least fluctuation (Figures 5 and 6). The flow rates and the steam service temperatures were somewhat lower than those reported during the initial test in 1988 (Hock et al. 1990).

The cold inlet water temperatures were as expected. There was no distinction to make here between sustained usage and monthly averages. Four cycles appeared in the curve; these sinusoidal oscillations agreed well with the seasonal temperature changes during the 4 years.

As anticipated, the pattern of the hot water outlet temperatures (Figures 9 and 10) was governed by the pattern of the overall heat transfer coefficients (Figures 11 and 12). In turn, the heat transfer coefficient pattern was governed by the flow rates (Figures 3 and 4). Since the flow rates (Figures 5 and 6) were by far the most erratic aspect of the heat exchanger systems, it follows that these patterns dominated the pattern of values of the heat transfer coefficients (Figures 11 and 12).

In a physical sense, one may observe that the convective component of the overall heat transfer coefficient is the only component that could change on a continual basis. Any changes in flow caused changes in this term and therefore drove the entire pattern of the overall heat transfer coefficient. As shown in Equation 1 (p), only the flow rate pattern remains intact during computation of the overall heat transfer coefficient; any patterns associated with the three measured temperatures are disrupted by calculation of the logarithmic mean temperature difference. It is also anticipated that the pattern of the heat transfer coefficients would exhibit a negative slope under the progressive influence of growing scale deposits. In other words, the primary influences on the trend of the heat transfer coefficient and the dependent hot water temperatures are the trend in flow rates and the development of scale deposits.

However, there is no indication of a negative sloping trend in the hot water outlet patterns (Figures 9 and 10). In addition, the average hot water temperature was consistently maintained at or above 137 °F. These observations indicate that scale has not formed on the coated tube bundles in either building.

These findings mean that heat exchanger tube bundles that previously required a once-per-90-days cycle of acid cleaning may simply be given a one-time fix (a phenolic coating system) that has provided over 4 years of satisfactory performance. While one of the heat exchangers (in Building 29006) did incur spallation after 4.5 years, the treated tube bundles are estimated to have a 5-year life cycle.

9 Conclusions and Recommendations

After evaluating the ability of a phenolic coating to relieve the fouling problems associated with DWSH heat exchangers, and evaluating the technical feasibility and cost effectiveness of applying and using the coatings, this study concludes that:

1. The phenolic-based composite coating system applied to potable water heat exchangers at Fort Hood successfully maintained the temperature of the hot water at or above 140 °F for 4.5 years.
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 for 4.5 years.
3. The simple payback for the phenolic-based composite coated heat exchangers treated at the Fort Hood dining halls is approximately 2 months.

Based on these results, it is recommended that:

1. Phenolic-based composite coatings should be considered as an alternative to chemical treatment in potable water heat exchangers as specified in CEGS 15400 in installations where scaling reduces the coefficient of heat transfer of an unscaled copper tube bundle by at least 50 percent and the life cycle cost analysis as shown in Appendix B 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 (Appendix A) section 2.10.4 should be followed.

References

Corps of Engineers Guide Specifications 15400 (Plumbing, General), Section 2.10.4, "Phenolic Resin Coatings."

Corps of Engineers Guide Specifications 15405 (Plumbing Hospital) Section 2.13.3, "Phenolic Resin Coating."

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., and 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).

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/gallon minimum and 7.4 lbs/gallon 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/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.

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

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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 be 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 be 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, Texas

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 workers * 11 hr * 12 repairs = $4504

(5) Direct materials cost = 1 replacement * $1700 = $1700

2. Associated losses (dining halls)

a. Tank draindown: $12.80 per 1000 gal * 2.115 * 12 actions = $325

b. Acid disposal: $12.00 per action * 12 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. Therefore:

Downtime costs = $300 * 12 actions = $3600

5. Total cost for dining halls:

Labor	$ 4,504
Materials	1,700
Associated losses	325
Operations/maintenance	0
Downtime	3,600
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:
      (1) 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
   c. Direct labor cost = $17.06 * 2 workers * 6 hr * 52 repairs = $10,645
   d. Direct materials cost = 5 replacements * $1700 = $8500
2. Associated losses (all other steam-fed exchangers)
   a. Tank draindown: $12.80 per 1000 gal * 1.155 * 52 actions = $769
   b. Acid disposal: $12.00 per action * 52 actions = $624
3. Operations and maintenance (all other steam-fed exchangers)
   a. From DEH personnel: 3 hr per replacement to order, specify, and inspect exchangers
   b. 5 replacements * $17.06/hr * 3 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:

0.5 hr * 125 soldiers * $8/hr * 52 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	26,000
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 follows:

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

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14. ABSTRACT

U.S. Army Directorate of Engineering and Housing engineers and maintenance personnel are frequently faced with recurrent fouling of heat exchanger tube bundles that reduces the thermal efficiency of these systems to the point where they fail to meet hot water demands of various Army facilities. Common maintenance practices that address this problem are costly, labor intensive, and involve hazardous chemical and waste handling.

This long-term field study examined the effects of applying a phenolic coating to the heat exchanger bundles in domestic water storage heaters (DWSHs) to prevent scaling and creating a virtually maintenance-free system. It was found that: (1) the phenolic-based composite coating system applied to potable water heat exchangers at Fort Hood maintained the temperature of the hot water at or above 140 °F for 4.5 years; (2) the coated heat exchangers eliminated the need for 90-day acid cleaning cycles; and (3) the simple payback for a phenolic-based composite coated heat exchanger at Fort Hood was approximately 2 months.

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