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Development and Testing of an Anti-Scale/Corrosion Resistant Coating for Domestic Hot Water Heat Exchangers

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This report presents the results of an investigation into the use of baked-on phenolic coatings to prevent scale deposit and corrosion in potable water heat exchangers. The report documents corrosion and scaling problems observed in potable water heat exchangers at Army installations and compares various methods for mitigating these problems, focusing on laboratory and field testing of a baked-on phenolic coating system. A cost analysis showing the feasibility of the coating in various environments is presented. The coating proved to be effective in mitigating scaling and corrosion problems in potable water heat exchangers and in maintaining hot water temperatures at or above 140 °F (59.4 °C). The coating also proved to be highly cost effective in both corrosive and scaling environments by decreasing maintenance and repair and downtime costs.

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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 4A162731AT41, "Military Facilities Engineering Technology"; Work Unit CO-048, "Metallic Surface Treatment Technology for Corrosion Resistant Components." The HQUSACE technical monitor is Mr. Joe McCarty, CEMP-EE.

Mr. Chester Neff is a researcher at the Illinois State Water Survey. Dr. James Myers is a corrosion consultant and the director of JRM Associates, Franklin, OH. The contributions of Thomas Baik, John Shales, and Timothy O'Neill, USACERL, and Mike Case, Kirk McGraw and Bill Bahnfleth, USACERL Energy Division, are gratefully acknowledged. The technical assistance provided by Mr. William Timmerman, Headquarters, U.S. Army Forces Command (HQFORSCOM), Mr. Malcolm McLeod, U.S. Army Engineering and Housing Support Center (USAEHSC), Mr. Leon Howard, Directorate of Engineering and Housing (DEH), Fort Hood, TX, and Mr. Ed Blake and Mr. Juel Knutson, Heresite-Saekaphen, was invaluable to the successful completion of this work.

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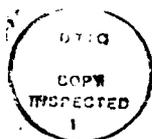
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1 INTRODUCTION

Background

Shell-and-tube heat exchangers are employed throughout the Army to supply domestic hot water for large buildings such as hospitals, dining facilities, barracks and offices. An optimal heat exchanger transfers heat from the source to the target material with minimal loss to the surrounding environment. The actual amount of heat transferred varies with the heat exchanger design, the specific applications desired, the physical limits as dictated by thermal efficiency, and finally, with fouling (corrosion buildup or scaling), which compounds over time to reduce thermal efficiency. When the heat exchangers fail to operate efficiently, heating capacity degrades, and maintenance and operating costs of the unit increase. Such maintenance costs are cyclic, depending on the rate of fouling. In the case of the Army's existing domestic hot water heat exchangers, the design, the application, and the physical limits dictated by thermal efficiency are fixed. However, corrective action can be taken to minimize the loss of efficiency and maintenance problems due to fouling.

Objectives

The objectives of this study were: (1) to determine the nature and assess the significance of the Army's heat exchanger fouling problem, and (2) to evaluate the ability of phenolic coatings to solve the fouling problem.

Approach

Field studies were conducted to determine the extent and nature of the fouling problem at several Army installations. A baked-on phenolic coating system was developed for use on potable water heat exchangers and was evaluated in the laboratory. The coating was then field tested at Fort Hood, Texas, where severe fouling problems existed. A cost analysis was performed to determine the feasibility of widespread application of the coating.

Mode of Technology Transfer

It is recommended that Corps of Engineers Guide Specifications 15400 (Plumbing, General) and 15401 (Plumbing, Hospital), be changed to allow the use of the baked-on phenolic coatings investigated in this study on potable hot water heat exchangers.

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2 HEAT EXCHANGERS: AN OVERVIEW

What is a Heat Exchanger?

Controlled heat exchange is a vital part of many industrial and scientific processes. The heat exchanger is one of the industrial developments that makes controlled heat transfer possible. A heat exchanger is a device that brings fluids of different temperatures into thermal communication across a barrier (such as a metal tube wall), transferring thermal energy from a hot fluid to a cold fluid, the objective being either to heat a given fluid, like the saturated steam entering a superheater in a steam power plant, or to cool a given fluid, like the cooling water passing through a radiator of an automobile. The properties of the barrier between the two fluids affect the efficiency and capacity of the heat exchanger. Over the years, heat exchangers have expanded in diversity to meet the growing demands of industry, technology, and science. Such demands on heat exchangers are highly specific: many industrial processes require the exchange of heat in measurable and consistent amounts. Heat exchangers must be durable and efficient. They are designed to accommodate specific fluid pressure, fluid heat capacity and temperature, coefficients of thermal expansion and thermal conductivity of the tube material, and fluid velocity and its relation to the rate of heat transfer. An efficient optimal heat exchanger will maximize heat transfer rates, while minimizing pressure drops, initial cost, and thermal losses to the surrounding environment. The amount of heat actually transferred varies with the design of the heat exchanger, the specific applications desired, the physical limits as dictated by thermal efficiency, and fouling.

Heat Exchanger Configurations

Heat exchangers are customarily categorized by their structural design configurations: how the pieces fit together and how they perform in the way they are fitted. The purpose of design is to meet specifications for a given application. Heat exchangers usually involve matter in the fluid state as the prime carrier of thermal energy. Therefore, in a "fluid medium" heat exchanger, there is a flowing hot (higher temperature) fluid, and a cold (lower temperature) fluid. Heat exchangers may be classified by the relative directions of fluid flow in the heat exchanger components into three basic types: parallel flow, counter (or countercurrent) flow, and crossflow (Figure 1).

The simplest counterflow and parallel flow configurations involve two concentric tubes with one fluid flowing in the central tube and the other flowing in the outer portion, called the annulus or shell. Such a heat exchanger, with one tube inside another, is called the shell and tube design. In the parallel flow configuration, both fluids move in the same direction. In the counterflow configuration, the fluids move in opposite directions. In the crossflow exchanger, which is commonly used to heat gas or air, the directions of flow are perpendicular to each other.

Heat exchangers are seldom crossflow, parallel flow, or counterflow *exclusively*. Most heat exchangers incorporate combinations of the three flow types and are often designed to be as compact, efficient, and durable as possible. A good example is the incorporation of the U-tube, which results in a compact design, reduces thermal stresses, and facilitates maintenance (Figure 2). U-tubes are used in almost all of the domestic hot water storage heaters that are the subject of this report.

Heat Exchanger Materials

The most commonly chosen heat exchanger material is metal. Metals have many physical properties that make them good materials for heat exchange: high thermal conductivity, high temperature resistance, high strength and load-bearing capacities, malleability, and ductility. The first metals used for

(a) Parallel flow   (b) Counterflow   (c) Crossflow
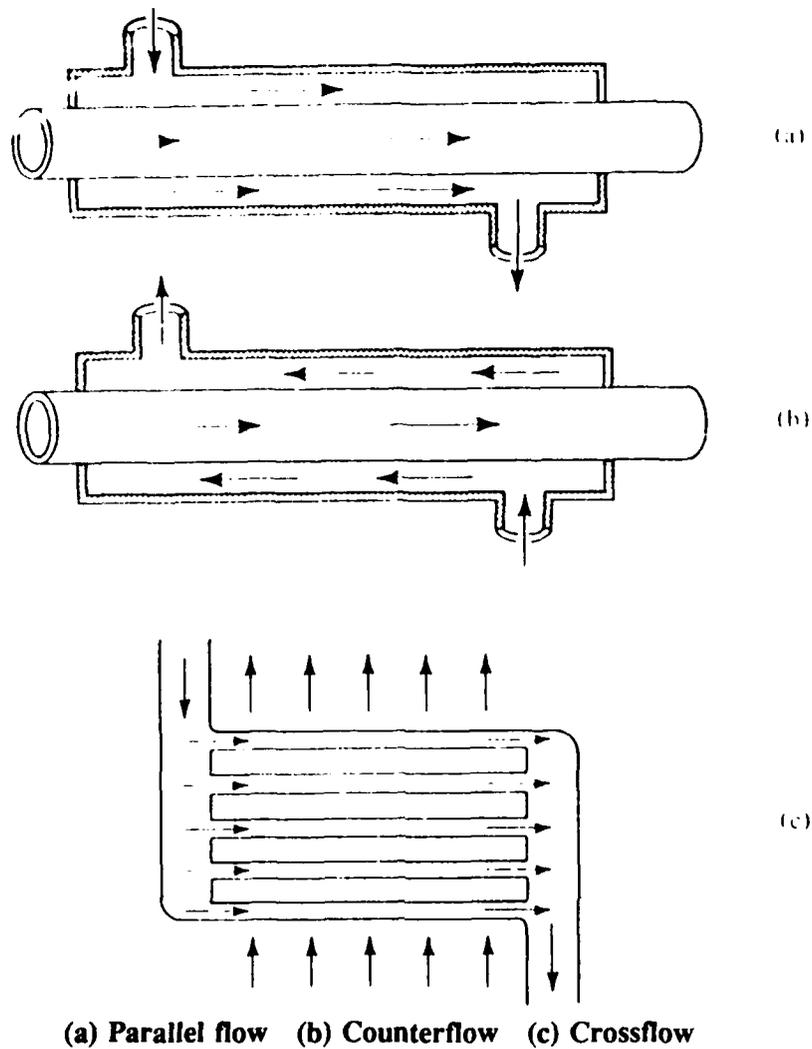
Figure 1. Heat exchanger configurations. (Reprinted from *Engineering Heat Transfer*, West Publishing Company, with permission.)
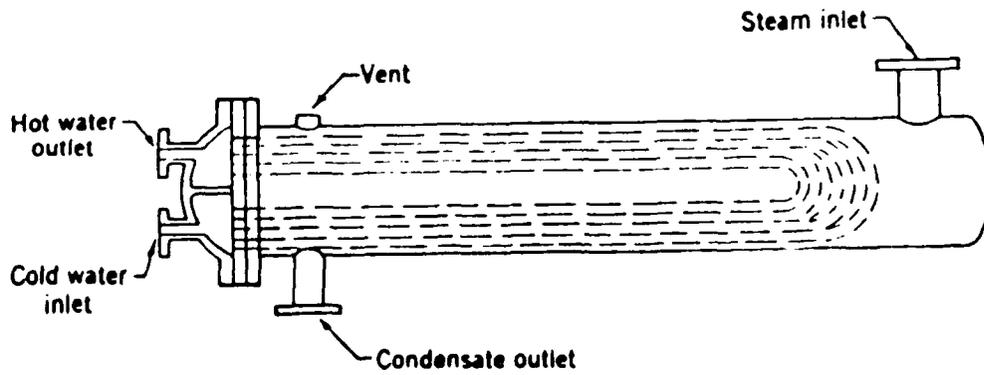
Figure 2. U-tube heat exchanger.

heat exchange were unalloyed metals such as cast iron, nickel, copper, lead or zinc along with their simple alloys such as copper/nickel, steel, copper/zinc and lead alloys. The science of metallurgy expanded the types and varieties of metal and metal alloys, and their range of applications. New metal alloys can endure the conditions under which heat exchangers must operate: high temperature and extreme temperature fluctuation, extreme pH fluctuations, mechanical agitation, and high corrosion potentials. Steel, copper, and nickel are the most common metals used while newer alloys are being developed from stainless steels, superstainless steel alloys, nickel alloys and high performance superalloys of nickel. Chromium interacts with steel, enhancing steel's resistance to corrosion. New ways of alloying and combining alloys with copper are being tested to enhance copper's corrosion resistance. Copper and copper alloys are widely used in the domestic hot water storage heaters discussed in this report.

Domestic Water Storage Heaters

One type of heat exchanger commonly used in Army facilities is the domestic water storage heater. Domestic water refers to water intended for direct human consumption and handling. This includes water for bathing, kitchen (i.e., cooking and dishwashing) and laundry use, janitorial service, and most crucially, for drinking. Most domestic water storage heaters are shell and tube type heat exchangers. Domestic water storage heaters are the focus of this report.

According to Clark,[1] the primary reason for using a storage type water heater instead of a conventional instantaneous heater is to smooth out peak demands on heating systems where there are large changes in the hot water demand, such as in gymnasiums, laundries, dining halls, barracks, etc. For example, in an Army dining hall, hot water demand is extremely high during and after meals, and is almost zero at all other times. If an instantaneous system were used, it would have to be designed to meet the extremely high demand at mealtime. A properly designed storage type system would heat most of the water needed at peak times during nonpeak times. This would substantially reduce the peak heat fluid demand, thereby permitting the use of a smaller boiler and smaller piping for the heating fluid. For this reason, storage type domestic water heaters are in widespread use throughout the Army in barracks, dining halls, hospitals, gymnasiums, and laundries.

Most of the domestic water storage heaters used in the Army consist of a removable U-tube bundle installed in the lower half of a horizontal or vertical cylindrical tank (Figure 3). The tube bundle is usually made of copper or a copper alloy, and the tank is usually steel with a cement lining for protection against corrosion. The heating fluid, which may be steam or high temperature hot water, flows through the U-tube bundle. The heating fluid usually enters through the top portion of the U-tube, flows around and down the U, and out through the bottom portion of the tube (Figure 3). The domestic water to be heated enters the tank under the tube bundle and leaves at the top of the tank. A domestic water storage heater can be classified as a shell and tube type, and is a combination of the parallel, counterflow, and crossflow configurations.

Heat Exchanger Performance

The specific variables that affect the performance of any heat exchanger, including domestic water storage heaters, are: mass flow rates, specific heats and inlet and outlet temperatures of the hot and cold fluids, thermal conductivity of the tube material, tube area, amount of deposits or scaling on the tubes, and the convective heat transfer coefficients on the inside and outside surfaces of the tubes.

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[1] J.A. Clark, "Domestic Water Heater Fundamentals," *Air Conditioning, Heating & Ventilating* (October 1968), pp 87-94.

Figure 3. **Conventional storage water heaters.** (Reprinted from "Domestic Water Heater Fundamentals," *The American Plumbing Engineer*, October 1968, with permission from Association of Energy Engineers, Fairmont Press.)

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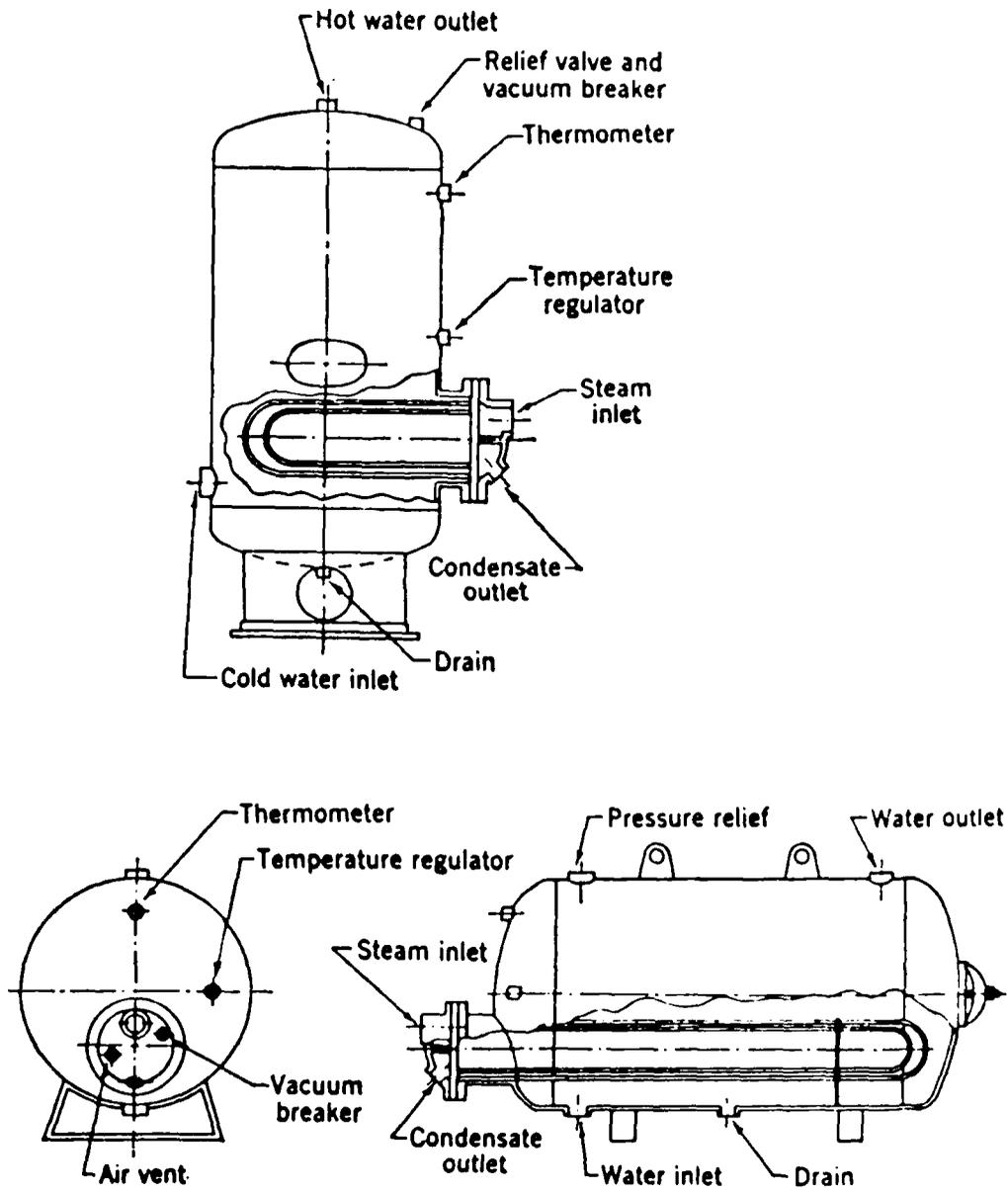These parameters manifest themselves in two different modes of heat transfer in heat exchangers, conduction and convection. Conduction is an exchange of energy by direct interaction between molecules of a substance containing temperature gradients. This phenomenon occurs in gases, liquids, and solids and has a strong basis in the molecular kinetic theory of physics. Conduction is material dependent; thermal conductivity is a property of a material. Convection, on the other hand, may be described as conduction in a fluid as enhanced by the motion of the fluid. Convection is strongly influenced by geometry, flow regime (i.e., laminar or turbulent flow; free or forced convection) and fluid properties.

Conduction in the heat exchanger takes place both through the solid barrier (e.g., the metal heat exchanger tube wall) and in the fluids at the solid boundaries (e.g., the tube wall surfaces). In the fluids, conduction occurs primarily at the solid barrier surfaces, where fluid adheres to the solid surface. The velocity of the fluid molecules at the surface is zero. Heat is conducted into the fluid at the surface and is carried away by the moving fluid.

Convection, unlike conduction, is a heat transfer mode that depends on the velocity of the fluid environment around the solid barrier. Convection occurs, usually near a solid boundary (i.e., tube wall surface), when the fluid surrounding it is set in motion. This motion may be caused in two different ways. The first source of a convective environment is some type of external "pump" that sets the fluid environment, far from the tube surface, in motion. This "pump" may be a fan in the case of a gas, or a water pump in the case of a liquid. When the fluid motion is enhanced by external means, the mode is known as "forced convection." Many times, the convective environment becomes the controlling factor in the heat flow equation because, as the convective heat transfer coefficient becomes larger, the temperature gradient in the solid barrier becomes larger also. For this reason, the efficiency of a heat exchanger depends on the fluid flow rates and inlet geometry. The second type of convective heat transfer occurs when a density gradient arises in the fluid immediately surrounding the wall surface. The density gradient is often a result of the heating or cooling of the fluid by the wall surface. This gradient causes the fluid to begin to seek equilibrium, which results in a natural motion in the fluid, known as natural or free convection. In free convection, farfield streaming is negligible, and the only significant motion is caused by the differential buoyancy described above. In most cases, however, both forced and free convection occur at the solid barrier surface. In these cases, heat transfer through the solid barrier is dependent on the conductive heat transfer term, the free convective heat transfer term, and the forced convective heat transfer term.

The transfer of thermal energy from the hot fluid to the cold fluid is impeded by (1) the tube wall itself, (2) the fluid-to-tube surface interfaces, and (3) fouling on both surfaces of the solid barrier. It is helpful to view this concept of impedance (resistance) to heat flow in terms of an electrical circuit. The temperature difference across the solid barrier can be viewed as a temperature "potential" that is analogous to an electrical potential. The heat that flows from the hot to the cold fluid is analogous to an electrical current that flows from a point of higher electrical potential to a point of lower electrical potential. Thus, the temperature potential causes a heat flow through the solid barrier in much the same way that a voltage potential causes a current flow in a wire. The series of impedances to heat flow listed above are analogous to electrical resistors connected in series. Figure 4 shows how the five impedances to heat flow across a flat plate (two convective at the fluid-to-tube surface interfaces, two due to fouling, and one due to conduction through the solid barrier), and how they can be seen as a series of resistors. Just as Ohm's law can be applied to an electrical network,

$$I = \frac{V_2 - V_1}{R_{equiv}}$$
[Eq 1]

a similar relationship can be applied to heat exchange:[2]

$$Q/A = \frac{T_h - T_c}{(1/U)}$$

[Eq 2]

where Q = the rate of heat transfer from the hot fluid to the cold fluid [BTU/hr]
A = the surface area through which heat is transferred [ft^2]
T_h = temperature of the hot fluid [°F]
T_c = temperature of the cold fluid [°F]
U = the overall heat transfer coefficient [BTU/hr-ft^2-°F].

The overall heat transfer coefficient, U, combines the effects of all of the resistances to heat flow through the solid barrier described above. Using the electrical analogy, U can be viewed as a conductance. The impedances to heat flow can be viewed as electrical resistors in series and can be summed to give an equivalent resistance. Thus:

$$1/U = 1/h_h + R_{f,h} + t/k + R_{f,c} + 1/hc$$

[Eq 3]

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

The fouling factor includes the effects of corrosion and scale incrustation, and also the effect of protective coatings such as those being investigated in this study. The flat plate case demonstrates the principle, and a similar relationship exists for a tube configuration.

The temperature of the hot and cold fluids varies along the length of the heat exchanger. A differential analysis of simple parallel and counterflow heat exchangers yields a mean value for the quantity $(T_h - T_c)$ in Eq 2. This mean value is called the Logarithmic Mean Temperature Difference (LMTD). In the case of a steam-fed heat exchanger, one assumes that the temperature of the hot fluid (steam) does not change as it travels through the heat exchanger; the steam merely condenses. In this special case, Eq 2 can be written as:

$$Q/A = U * LMTD = U * \frac{T_{c,o} - T_{c,i}}{\ln \frac{T_h - T_{c,i}}{T_h - T_{c,o}}}$$

[Eq 4]

---

[2]A metric conversion table is included on p 56.

where $T_{c,o}$ = temperature of the cold fluid at the outlet

$T_{c,i}$ = temperature of the cold fluid at the inlet

T_h = temperature of the hot fluid.

A more complete explanation of the heat transfer relationships is given in Appendix A.

The overall heat transfer coefficient U can be used to evaluate heat exchanger performance, including that of domestic water storage heaters that are the focus of this report. Eq 4 was used to calculate the U values throughout the report. Since U is dependent on both conduction and convection, it is not only a function of the tube bundle material and the fluids involved, but also of the specific configuration of the system and the velocities of the fluids within the system. Thus, systems comprised of identical materials and having identical configurations and velocities over the tube surfaces can be compared directly. Systems comprised of identical materials but having different configurations and velocities would be expected to have different U values.
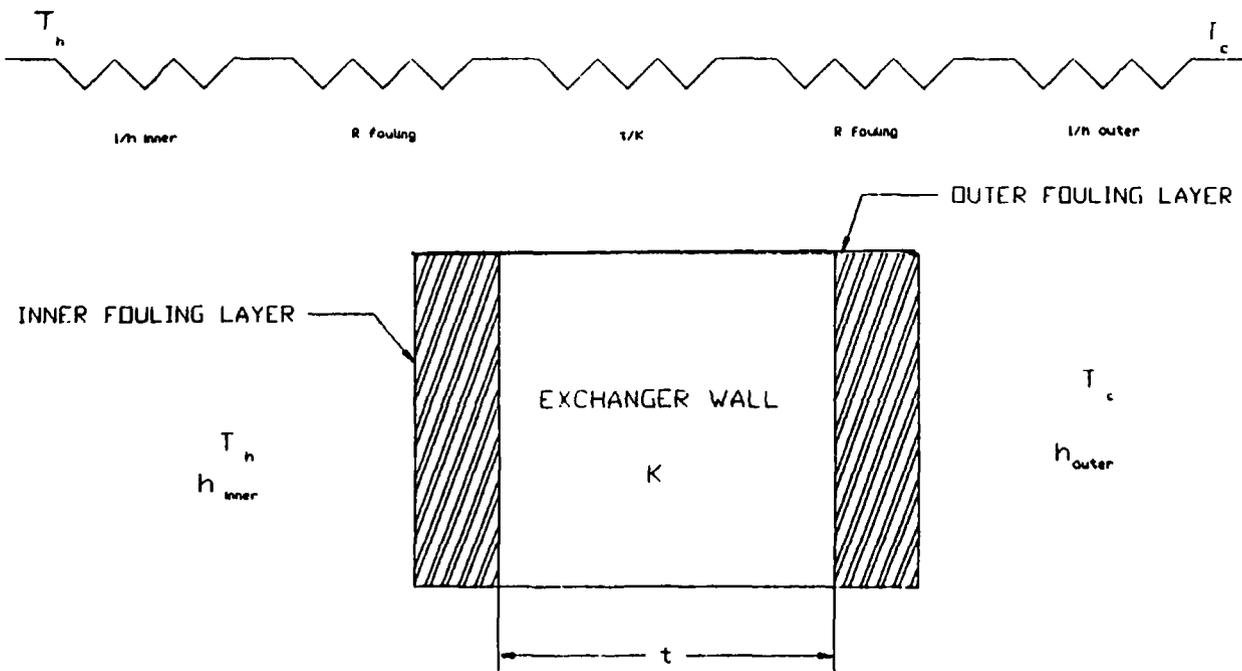
Figure 4. Equivalent resistance for heat transfer through a flat plate.

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3 PROBLEMS ENCOUNTERED IN THE ARMY'S DOMESTIC WATER HEAT EXCHANGERS

What Is Fouling?

Fouling is a persistent problem that limits the efficiency and effectiveness of heat exchangers. Fouling in potable water systems includes scaling and corrosion, both costly problems when allowed to progress. Reducing corrosion and scaling maximizes heat exchanger efficiency and performance and minimizes maintenance costs.

It should be understood that corrosion and scaling are very different processes and that they affect a heat exchanger's performance in different ways. Following are some of the basic concepts of corrosion and scaling and an explanation of their application to domestic (potable) water heat exchangers.

Corrosion

Myers[3] 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. Figure 5 shows a corrosion cell, illustrating galvanic (dissimilar metal) corrosion, but the same concepts apply 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[4] 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.

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[3]J.R. Myers, *Fundamentals and Forms of Corrosion* (Air Force Institute of Technology, 1974), p 1.
[4]Myers, pp 79-80.

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.

Corrosion Problems Observed at Fort Lewis, Washington

A corrosion site survey was conducted in April 1986 at Fort Lewis, Washington, to gather data on the corrosivity of its soil and water. Complete water chemistry data is shown in Appendix B. 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. 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. (The Langelier Index is explained in Appendix C.) Thus, neither water has the tendency to deposit calcium carbonate scale and both should be relatively corrosive.
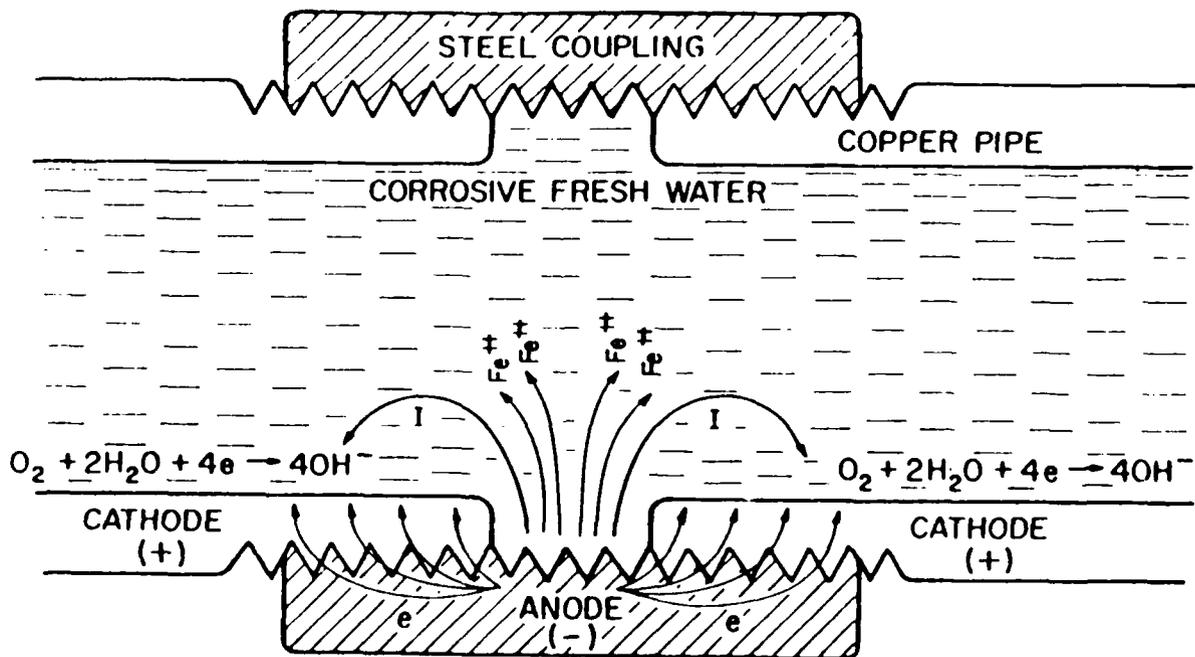

Figure 5. Basic corrosion cell.

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. 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 years.

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 (Figure 6). Erosion of the ends of the tubes in the bundle was observed (Figure 7). 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.

Corrosion Problems Observed at Fort Benjamin Harrison, Indiana

A corrosion site survey was conducted in September 1987 at Fort Benjamin Harrison, Indiana, to gather data on the corrosivity of the soil and water and to examine domestic water heat exchangers. Complete water chemistry data is shown in Appendix B. The water distributed at Fort Harrison is obtained from three wells. Chemical analysis of the water revealed that the water should have no significant tendency to deposit calcium carbonate over the temperature range of 60 to 140 °F because the Langelier indices for the water at 60 and 140 °F respectively were -0.82 and +0.19.

However, both corrosion and scale are problems at Fort Harrison, probably because there have been several significant changes in the water treatment processes over the years. Before 1957, the hardness of the water distributed typically varied between 340 and 350 mg/l. This would be characterized as unusually hard water, and, although other water chemistry parameters for that time are unknown, it is likely that the water tended to deposit significant calcium carbonate scale. In 1957, a softening plant was installed, and the water hardness was maintained in the 70 to 80 mg/l range until mid-1987. This would be characterized as relatively soft water, and at temperatures above 140 °F and at high velocities, it would tend to facilitate erosion corrosion in copper. Reportedly, domestic hot water temperatures routinely exceeded 140 °F in many of the buildings during this time, which could be the cause of the corrosion problems reported in the copper tube bundles in the domestic hot water storage heaters. The relatively soft water was circulated from 1957 to 1987 except for a period during late 1982 and early 1983. During this period, a malfunction in the softening equipment caused unusually hard water (approximately 350 mg/l hardness) to be distributed for several months. In mid-1987, the Fort Harrison Directorate of Engineering and Housing (DEH) began efforts to reduce the temperatures of the hot waters circulated and to raise the hardness of the distribution water to reduce the corrosion problems.

Only the scaling problem was observed during the September 1987 site visit. However, according to DEH personnel, erosion corrosion problems occur in the tube bundles and also in the condensate return lines associated with the heat exchangers. The average life of a tube bundle was reported as approximately 3 to 5 years, and the condensate return lines associated with the domestic water storage

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heaters have been known to fail within 1 year. This agrees with the water chemistry data, since the soft water distributed between 1957 and 1987 is expected to facilitate erosion corrosion of copper.

Scaling

Scaling is a mineral incrustation that manifests itself as a hard deposit on surfaces exposed to water. The deposit builds up over time, and results in loss of thermodynamic efficiency and restricted water flow. Scale is a common occurrence in hot water systems because the solubility of certain dissolved minerals is reduced as the water temperature is increased. Fortunately, the inverse solubility characteristic occurs with only a few of the minerals normally present in water. Calcium, magnesium, carbonate, silicate, sulfate, and hydroxide are constituents that are present and that often form deposits in hot water systems. Water that contains large amounts of dissolved scale-forming ions is known as "hard water." Calcium carbonate is usually the main component of the scale found on heat transfer surfaces in water systems. Three mineral forms of calcium carbonate are known: calcite, aragonite, and vaterite. All three forms have been identified in scale from domestic water systems. Scale deposits are seldom a single, pure mineral since corrosion products and other chemical species are incorporated into the scale during the deposition process.

The prime reaction that forms calcium carbonate scale is initiated by the decomposition of calcium bicarbonate into calcium carbonate:

$$Ca^{2+} \times 2[HCO_3]^- + T_c \longrightarrow CaCO_3(c) + CO_2(g) + H_2O(l)$$

where T_c = critical temperature of calcium bicarbonate decomposition.

Many chemical factors are involved in the formation of scale: calcium and magnesium ion concentration, pH, and presence of other ions, so that scaling may occur at different temperatures. The Langelier saturation index (or calcium carbonate saturation index) is frequently used to determine whether or not water has the tendency to scale. The Langelier index is based on the pH, temperature, calcium concentration, alkalinity, and total dissolved solids concentration of the water. A positive Langelier index indicates that water is oversaturated with respect to calcium carbonate and that it has the tendency to form scale. A negative Langelier index indicates that the water is undersaturated with calcium carbonate and that it does not tend to deposit scale. A negative Langelier index may (but not always) indicate that the water is corrosive. A Langelier index of zero indicates that the water is at equilibrium with respect to calcium carbonate and should neither deposit scale nor be corrosive. Calculation of the Langelier index is described in Appendix C.

Some mechanical factors are also known to influence scale formation and deposition, including water velocity, surface effects, film temperature, design, operating conditions, and surface material. Scale incrustation in heat exchangers usually occurs on the potable waterside surface of the metal tube bundle. The major problem presented by scale formation on the tube bundle is the decrease in thermal conductivity, which results in reduced heat-exchange efficiency and uneconomical heat loss.

The effect that scaling has on heat transfer efficiency can be estimated by considering fouling as a mathematical factor as discussed in Chapter 2.

Factors that slow down scale formation on tube walls are:

1. Relatively high water velocities over heating surfaces

2. Use of the lowest practical heating surface temperature (preferably below calcium bicarbonate decomposition temperature)

3. Good temperature control.

Figure 6. Fort Lewis tube bundle.

Figure 7. Erosion of tube bundle ends at Fort Lewis. (Reprinted from "Domestic Water Heater Fundamentals," *The American Plumbing Engineer*, October 1968, with permission from Association of Energy Engineers, Fairmont Press.)

Scaling Problems Observed at Fort Hood, TX

Fort Hood, TX, is the first site where USACERL observed heat exchanger fouling problems. A corrosion site survey was conducted in March 1986 to gather data on the corrosivity of the soil and water. Complete water chemistry data is shown in Appendix B. Fort Hood distributes two different waters: one at North Fort and one at South Fort. Water distributed at North Fort comes from five wells. The water distributed at South Fort comes from a surface supply (a lake). The survey found that both of Fort Hood's distribution (cold) waters should be mildly corrosive and should not have a tendency to deposit scale. The water distributed at North Fort contains relatively high amounts of chlorides and sulfates and has a low resistivity, and the water distributed at South Fort has a high dissolved oxygen content and low alkalinity. The Langelier indexes of North and South Fort waters, respectively, are -0.3 and -0.7.

However, as noted above, the tendency of a water to deposit scale increases dramatically with temperature, since the solubility of calcium carbonate decreases at higher temperatures. Near a heat exchanger tube bundle, the water temperature increases rapidly. Thus, a water that would not be expected to deposit scale when it is cold may deposit scale when it is heated rapidly at the tube bundle of a heat exchanger. This situation was found at Fort Hood.

After the March 1986 site visit, Fort Hood personnel reported persistent problems with excessive scale formation on the waterside surfaces of the copper tube bundles in the domestic hot water storage heaters located in their dining facilities. A site visit was made on 14 May 1986 to investigate the problem.

One of the troublesome heat exchangers supplies hot water to Building 29006, a dining hall. The unit consists of a vertical cylinder, a cement-lined carbon steel tank (shell) with a copper tube bundle. The tank has a capacity of 2115 gal, and a heating capacity of 1170 gal per hour (gph). The average daily hot water usage is 11,000 gal, almost all of which occurs in the hours during and immediately after meals. The tube bundle is comprised of 13 copper tubes with a 3/4-in. outer diameter. The bundle is 71.5 in. in length. Domestic water in the tank is heated to 140 to 160 °F by the 10 to 12 psi steam flowing through the tube bundle.

According to Fort Hood personnel and maintenance records, the tube bundle in this heat exchanger had to be cleaned every 60 to 90 days to remove excessive scale deposits that formed on the waterside surfaces of the tubes. Removing the scale deposits required draining the tank, removing the tube bundle, and soaking it in a large vat of hydrochloric acid until the scale was dissolved. The scale deposits prevented the water from reaching the required temperature of 140 °F for use in the dining hall, especially during peak periods of operation. During the May 1986 site visit, the tank was drained and the tube bundle was removed for observation (Figure 8). The bundle had been in service since 14 January 1986, and examination revealed that significant scale existed on the waterside surfaces of the tubes. The scale measured approximately 0.07 in. thick, representing a significant loss in heat transfer efficiency. Subsequent microchemical analysis showed that the deposit was comprised primarily of calcium carbonate.

On 14-15 October 1986, another site visit was conducted to examine the domestic hot water heater in Building 87017, another dining facility. This heat exchanger is identical in configuration to the exchanger in Building 29006. Fort Hood personnel had reported severe scaling problems in this exchanger also. According to maintenance records, this exchanger also had to be cleaned every 60 to 90 days to remove excessive scale deposits. During the October site visit, the tank was drained and the tube bundle was removed for examination. The bundle had been in service since December 1985 (approximately 10 months). Measurements revealed that approximately 0.035 to 0.040 in. of scale had formed on the waterside surfaces of the copper tubes. Subsequent microchemical analysis showed that the deposit consisted primarily of calcium carbonate. At this time, the hot water temperature was 110 °F, significantly below the 140 °F required in the dining hall. The bundle was acid cleaned and reinstalled. A second site visit was conducted in January 1987, and the tube bundle was again pulled out and examined. In the three months since the last site visit, scale up to 0.015 in. thick had formed on the waterside surfaces of the tube bundle.

Figure 8. Removal of heat exchanger tube bundle from Bldg 29006, Fort Hood.

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 Appendix B. 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 9). 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. 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 years, and their waterside surfaces were covered with a brownish-colored scale deposit with thicknesses up to 0.14 in. (Figure 10). Subsequent energy dispersive spectroscopy and microchemical analysis revealed that

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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.

Scaling Problems Observed at Fort Benjamin Harrison, IN

Both corrosion and scale were problems at Fort Benjamin Harrison. During the site survey described previously, the scale problem was observed in the field. The domestic water storage heater at Building 421 was drained and the tube bundle was removed for examination (Figure 11). The tank is a horizontal cylinder with a capacity of 1190 gal. The copper U-tube bundle has a diameter of 4 in. and a length of 82 in. Steam (the heating medium) flows through the tube bundle and heats domestic water to approximately 140 °F. According to DEH personnel, the tube bundle had not been cleaned since January 1983 (about 4 1/2 years). Prior to that date, the bundle had been cleaned in October 1982. This unusually frequent cleaning was necessitated by problems with the water softening equipment at the Fort Harrison water treatment plant. Examination of the tube bundle in September 1987 revealed that the tubes were covered with a relatively thick (up to 0.076 in.) layer of white to reddish brown deposit. Subsequent energy dispersive spectroscopy and microchemical analysis showed that the deposit was comprised mostly of calcium carbonate admixed with hydrated iron and manganese oxides. Most likely, the source of the iron and manganese oxides was the domestic water. Again, although the rate of scale deposition is not as high as in the Fort Hood dining halls, it represented a loss in heat transfer efficiency and a significant maintenance problem.

Figure 9. Removal of tube bundle from Bldg D-3348, Fort Bragg.

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Figure 10. Closeup of scale-incrusted heat exchanger tube bundle from Fort Bragg.
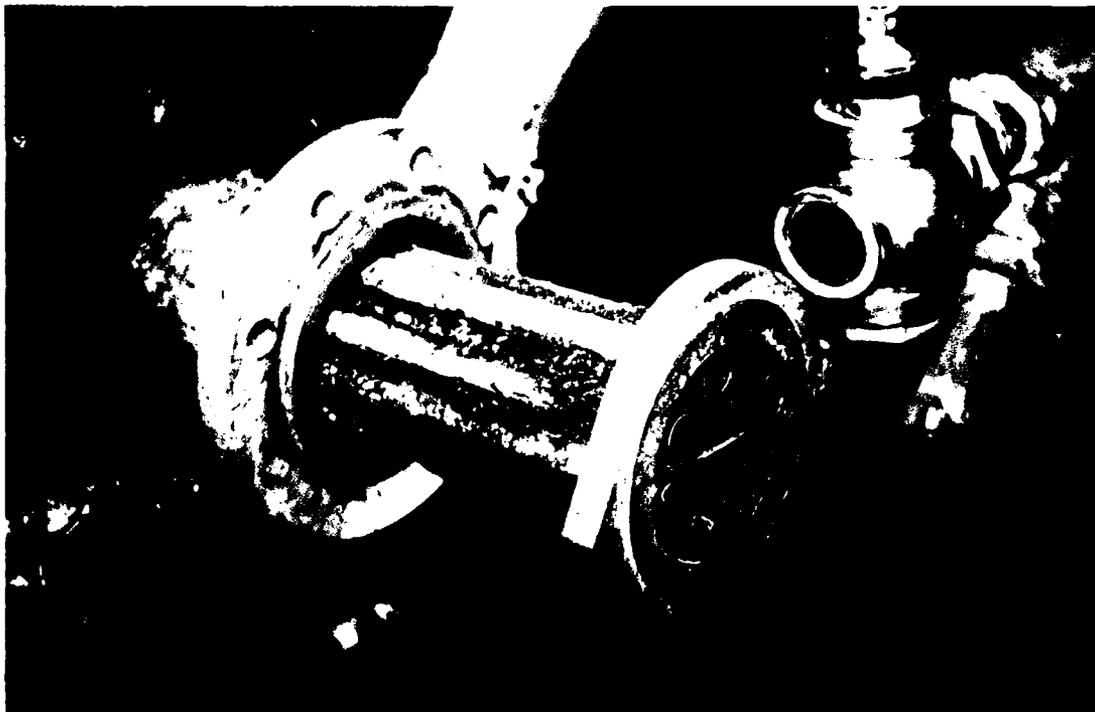
Figure 11. Removal of heat exchanger tube bundle from Bldg 421, Fort Benjamin Harrison.

4 METHODS OF MITIGATING FOULING PROBLEMS IN EXISTING POTABLE WATER HEAT EXCHANGERS

Several techniques can be used to mitigate fouling problems. Some applications focus on the prevention of the fouling process, while others focus on cleaning and rehabilitation of the system after fouling has occurred. Some alternatives used to deal with fouling will be discussed. The alternatives, along with their average costs, advantages, and disadvantages, are summarized in Table 1.

Acid Cleaning

The acid-cleaning technique is frequently used at Army installations with severe scaling problems. This technique only works for localized scaling problems, such as those that occur in a heat exchanger, and then the technique is performed after the scale has formed. It involves immersing the scaled tube bundles in a large vat of hydrochloric acid until the scale is dissolved. It is a labor-intensive process that poses a significant safety hazard for the personnel involved. Special precautions and techniques must also be used for disposal of the acid. In addition, the heat exchanger is shut down for the entire cleaning period, which may be up to a full day, depending upon the thickness and adherence of the deposit. This results in costs to the installation and inconvenience to personnel because alternate facilities must be used for dining, bathing, laundry, etc.

Water Treatment

Water treatment can be used for either corrosion or scaling problems. In this method, scaling problems are treated by means of lime softening or ion exchange. Some chemical scale inhibitors may also be used, but they are not widely used in domestic water systems for reasons of health and potability. In lime softening, the calcium, magnesium, and bicarbonate ions are precipitated out of the water before the water enters the distribution system. The water usually undergoes additional processes such as sedimentation and filtration to remove the precipitated material. Since the pH of the water is raised during lime softening, the final step in the process is to adjust the pH by adding mineral acid or carbon dioxide so that the water neither precipitates nor dissolves calcium carbonate.

In ion exchange, the water is passed through a bed of ion-exchange resin. Ions from the resin such as sodium or hydrogen, which are much less likely to form scale than calcium and magnesium ions, are substituted for potential scale-forming ions from the water such as calcium and magnesium. The ion-exchange resin must be periodically regenerated.

Corrosion problems are usually treated by the addition of chemicals to the water. Various types of phosphates, including inorganic polyphosphates and hexametaphosphates are some of the more common treatments used. It should be noted that the use of chemical scale and corrosion inhibitors in potable water systems is strictly regulated for reasons of health and safety.

Chemical treatment of the water is an effective method of mitigating fouling problems, and can be used on both localized and widespread problems. However, the investment in equipment and chemicals is often expensive, and time and money must be spent to maintain the system (e.g., regenerate the softeners, change chemical tanks, etc.) and to monitor it to ensure proper operation.

Table 1

Summary of Fouling Mitigation Alternatives

Alternatives	Life Cycle Cost ($)	Continuous Maintenance	Problems Remedied
Acid cleaning	50,281	Yes	Scale only
Chemical feed water treatment	5,812	Yes	Corrosion and scale
Ion exchange water treatment	70,791	Yes	Scale only
Phenolic coating	2,019	No	Corrosion and scale
Carbon dioxide treatment	7,684	Yes	Scale only

Carbon Dioxide Treatment

Field studies by the Illinois State Water Survey have demonstrated a technique the Water Survey has practiced for over 30 years that uses carbon dioxide to control scaling.[5] While this technique is not in common use, the Water Survey has successfully used it to control scaling at a number of state facilities throughout Illinois. The technique involves adding carbon dioxide to the water before it enters the piping system. Addition of carbon dioxide lowers the pH of the water and, at the proper concentration, actually reverses the scaling reaction and dissolves deposited scale. This method is especially applicable to systems in which the scale consists mostly of calcium carbonate, but can also be used to dissolve other mineral deposits whose solubility increases at reduced pH. These studies have shown that scale deposits in potable water systems can be removed using the carbon dioxide technique without detrimental effects to occupants or equipment. Carbon dioxide treatment is a highly effective technique for removing scale deposits, but its application must be carefully monitored. When applied in excess, carbon dioxide can itself cause corrosion of the system.

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[5]T.M. Prakash, et al., *Carbon Dioxide Treatment for Scale Removal and Control in Potable Water Systems,* Technical Report N-87/16/ADA184346 (U.S. Army Construction Engineering Research Laboratory [USACERL], May 1987), p. 31.

5 DEVELOPMENT AND LABORATORY TESTING OF COATING SYSTEM

Feasibility Study of Protective Coatings

Protective coatings have been used for many years in industrial applications to prevent corrosion and scale buildup on metals exposed to a variety of harsh environments. They have not, however, been commonly used in domestic water systems.

It was proposed that perhaps a protective coating could be applied to the domestic waterside surfaces of the tube bundle in a domestic hot water storage heater to protect against scale deposition and corrosion. In the case of scaling, a coating with a "slick" surface to prevent the adherence of scale to the tube bundle surface is desirable. Protective coatings are best for localized corrosion or scaling problems (such as heat exchanger tube bundles), but are somewhat impractical for widespread problems (such as scaling throughout an entire piping system) because they typically involve application processes that cannot be performed in situ.

The chief advantages of protective coatings that have been observed by industry are that they require virtually no regular maintenance or monitoring, they are relatively inexpensive, and they can provide excellent protection against both scale buildup and degradation due to corrosion, thereby reducing maintenance costs and increasing the service life. A good coating will result in a reduction of heat exchanger capital cost since a coated base metal tube bundle can be used instead of a more expensive metal alloy bundle. The low maintenance/no monitoring feature is especially important to the Army, since many Army installations have undergone manpower cutbacks and cannot spare the personnel necessary to perform extra maintenance/monitoring tasks.

Although the heat transfer coefficient of a coated bundle will not degrade over time as it does when scale builds up on an uncoated bundle, the coating itself will reduce the heat transfer coefficient by a certain amount (related to the type and thickness of coating), which will remain approximately constant over the life of the system.

A suitable protective coating for use in potable water heat exchangers must meet several criteria:

1. It must resist scaling and corrosion, thereby increasing service life

2. It must not reduce heat transfer so much that it prevents the exchanger from meeting peak hot water demands

3. It must be approved by the Surgeon General for use in potable water systems

4. It must be able to be easily applied to a large structure such as a tube bundle

5. It must be cost effective

6. It must be able to withstand the high temperatures.

Candidate coatings were identified and leading coating manufacturers were surveyed to determine which coatings would be applicable to the heat exchanger fouling problem. The findings are summarized here.

Epoxy resin coatings harden by a catalytic reaction between coating chemicals. The resins harden first by partial solvent evaporation, then by crosslinking of molecules. This results in an extremely durable coating that is frequently used in applications requiring resistance to hard wear. They are used

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in joining technology, marine paints, and condensers in nuclear power plants. Although epoxy resin is an excellent protector, its poor heat transfer capabilities make it unsuitable for use in heat exchangers. Some epoxy resins are impregnated with metallic particles to increase heat transfer, but the particles can cause surface roughness. Another drawback is that since epoxies must be mixed to promote a catalytic reaction for hardening, there is a great deal of waste in using epoxies with a dipping tank large enough to accommodate a large tube bundle. Spraying is not a suitable application method, since it makes thickness difficult to control.

Teflon[6] coatings are widely used in a variety of applications, most notably in nonstick cookware. Teflon provides a "slick" surface that resists the adherence of scale and other foulants, and that is easily applied and baked into the substrate. Teflon is FDA approved for use in food type applications. A Teflon-Ryton coating has also been developed and is suitable for some heat exchange applications.

Electroless nickel coating involves the deposition of a very thin layer of nickel on the substrate. It is extremely resistant to corrosion and results in virtually no loss in heat transfer capability. Electroless nickel can be deposited uniformly in places that are difficult to reach, such as in the spaces between the tubes in a tube bundle. However, a polished white metal surface finish is required prior to applying electroless nickel to either a steel or copper tube bundle, resulting in a high initial cost for substrate surface preparation prior to plating with the electroless nickel. Electroless nickel does not make a surface "slick"; any roughness or imperfections in the substrate will be present on the coated surface also. In addition, application of the coating to a large tube bundle may be difficult, since most manufacturers of the coating do not have tanks large enough to accommodate these bundles. The coating has not been tested on heat exchangers before, and the wear resistance of the coating under the conditions found in heat exchangers is not known.

Baked-on phenolic coatings meet all of the criteria described above. They have been used in industrial type heat exchangers for many years, but had not been used in potable water heat exchange applications before this investigation. The phenolic coatings do not require a highly polished surface prior to coating; they require an acid cleaned and abrasive blasted (white metal SSPC-5-63) surface free of grease or oils. They may be applied by spraying or dipping. It was found that the dipping (immersion) method of application was most suitable for the heat exchanger tube bundles.

Development of the Coating

USACERL together with Heresite-Saekaphen Inc., Manitowoc, Wisconsin, developed a modified version of Heresite's baked-on phenolic (thermosetting resin) coating system utilized on condenser tubes. Industry uses the unmodified coating system to reduce buildup and corrosion on nonferrous metals and alloy steels exposed to river, sea, brackish, and circulating cooling water.

The modified baked-on phenolic coating system was designed to prevent scaling and corrosion of copper tube bundles in potable water heat exchangers. The main difference between the modified system and the original coating is the application of a clear, nonpigmented top coat (baking phenolic), which results in a smooth, glossy finish. This type of surface is highly resistant to scale adherence. Joint laboratory testing of the modified baked-on phenolic coating system was initiated with the Illinois State Water Survey.

Components of Coating System

The coating system consists of three components: (1) a wash primer, (2) a pigmented base coating, and (3) a clear, glossy top coat. The glossy top coat is extremely smooth and resists the adherence of scale. The wash primer is composed of a combination of a polyvinyl butyral and a heat-hardening phenolic resin. It weighs 7.2 lb/gal, and it contains approximately 11 percent nonvolatile solids by weight. The pigmented base coating is a baking phenolic consisting of heat-hardening phenolic resins, pigments of the earth type, and softening agents. It weighs 10.5 lb/gal, and contains approximately 52 percent nonvolatile solids by weight. The clear nonpigmented top coat is a baking phenolic containing approximately 50 percent nonvolatile solids by weight. It weighs 8.8 lb/gal.

Application Procedure

The coating system application procedure involves several steps. First, the surface must be correctly prepared to ensure proper adherence of the coating. If the bundle has been in service prior to coating, it is necessary to remove any surface scale deposits. High pressure air is blown across the tube bundle to remove loose scale. The bundle is then immersed in a dilute solution of hydrochloric acid to remove the remaining scale and is then rinsed with clear water. The exposed tube surfaces are abrasively cleaned with white metal blast in compliance with the Steel Structures Painting Council (SSPC) Regulation SSPC-SP-5. If the insides of the tubes are to be coated at the tube sheet to prevent erosion, they are abrasively cleaned for 3 seconds per tube at 50 psi. The open tube ends are plugged with rubber stoppers and one coat of wash primer is applied by flooding. If erosion of the insides of the tubes at or near the tube sheet is a concern, the wash primer is brushed inside the tubes for a short distance (about 6 to 8 in.). The bundle is then baked at 135 °C.

The next step is to apply the pigmented baking phenolic. The tubes are again plugged with rubber stoppers and the bundle is immersed in, flooded, or sprayed with the pigmented baking phenolic coating. The spray method of application was found to be unsuitable for the tube bundles that were used in this study. This is because it is difficult to obtain perfect, uniform coverage of the bundles with spraying, particularly in the areas between the tubes. If erosion of the insides of the tubes at the tube sheet is a problem, pigmented baking phenolic may be brushed inside the tubes for a short distance (again, about 6 to 8 in.). The rubber stoppers are removed, the bundle is drained and excess coating is removed with a brush. The solvent is allowed to flash off, then the bundle is baked in an oven. The temperature in the oven is raised 40 °C every 30 minutes until it reaches 160 °C. It is baked at 160 °C for 30 minutes. The bundle is removed from the oven, cooled to room temperature, and sanded with fine grit emery cloth to remove imperfections. The procedure of applying and baking the pigmented phenolic coating is repeated until the coating has a dry film thickness of 4 to 6 mils (approximately four coats).

The next step is to apply the clear nonpigmented coating. The tubes are again plugged with rubber stoppers, and the pigment-coated bundle is immersed in or flooded with the clear baking phenolic coating. The rubber stoppers are removed and the clear coating may be brushed inside the tubes. Excess coating is brushed off. The solvent is allowed to flash off, then the bundle is baked. The temperature in the oven is raised 40 °C every 30 minutes until it reaches 160 °C, and then it is baked at 160 °C for 30 minutes. The bundle is removed from the oven, cooled to room temperature, and sanded with 400-A grit emery cloth to remove imperfections. A second coat of clear baking phenolic is applied in the same manner. It is brushed to remove the excess coating, and an additional coat of clear phenolic is sprayed on. The bundle is then baked in the same manner as the pigmented coating above. The coating is inspected for defects and touched up, if necessary.

To repair a defect, the surface is first prepared by sanding the affected area to clean metal, feathering the edge of the coating, and roughening the coating surrounding the damaged area. The

sanded area is then washed with ethyl alcohol. A thin (1 to 1.5 mil dry film thickness) coat of the pigmented coating is brushed onto the area, overlapping the adjacent roughened coating. The tube may be baked in an oven, or the patched area may be heated with a torch, heat lamp, or electric hot air gun. Approximately three more coats of pigment are applied in this manner, with intermediate baking between coats. One or two coats of the clear coating are applied in the same way, again with intermediate baking between coats.

The last step is the final cure of the coating system. The bundle is placed in the oven and the temperature is raised 40 °C every 30 minutes until it reaches 220 °C. It is baked at this temperature for 2 to 4 hours to reach the final cure color, which is high-gloss dark maroon. The coating is then reinspected for any defects, which may be repaired as described in the preceding paragraph. The total dry film thickness should be 6 to 8 mils.

Laboratory Investigation

The laboratory study, performed in conjunction with the Illinois State Water Survey, was conducted to qualitatively compare the heat transfer performance of a coated tube bundle with both bare and scaled tube bundles.

Experimental Water Heater Assembly

An experimental water heater assembly was installed in a mechanical room located at the Illinois State Water Survey Research Center (Figure 12). A small steam-fired water heater was purchased, along with several identical tube bundles. The tank capacity was 12 gal. The tube bundles were comprised of copper tubes with a 0.750-in. outer diameter and 0.032-in. wall thickness. Each bundle contained four tubes bent into a U-configuration rolled into a carbon steel sheet.

Steam was supplied to the experimental heater by a low pressure, gas-fired, fire tube boiler. Steam pressure generally ranged between 8 and 12 psig during the test runs. Condensed steam was returned to the boiler feedwater system through steam traps and return piping. A steam trap was installed in the steam leg at the inlet to the tube bundle to remove excess condensate and to assure saturated steam heat transfer conditions. The storage tank and piping were insulated to reduce heat losses.

A Btu meter was installed to monitor the water heater output. The meter consisted of two low mass temperature probes, a water meter, and a microprocessor unit that totaled gallon and Btu quantities on digital registers. Type T thermocouples connected to battery-operated digital thermometers were installed to monitor water temperatures. The water flow rate was continuously indicated by a variable area flow meter, which was used to set a regulating valve to obtain the desired flow rate. Steam usage was monitored by collecting and measuring the amount of condensate produced during a timed interval. Steam pressure was measured at the inlet and outlet of the heat exchanger using standard pressure gauges.

Test Procedure

The experimental tube bundles were cleaned by immersing them in chloroform solvent to remove surface oils. They were then scrubbed with warm soapy water and rinsed with deionized water. One of the bundles was coated with the baked-on phenolic coating system. The other bundles were left uncoated.

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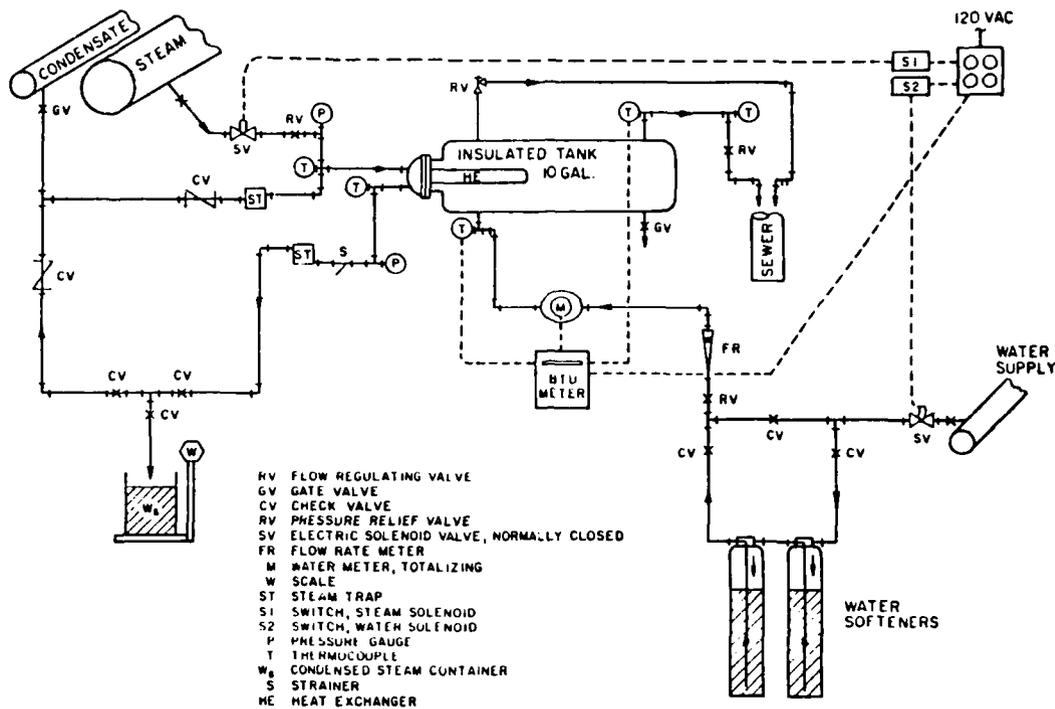
Figure 12. Schematic of experimental heat exchanger setup at Illinois State Water Survey.

The experiment was divided into three phases, to determine the overall heat transfer coefficient (U) for: (1) an uncoated, unscaled bundle, (2) an uncoated, scaled bundle, and (3) a coated bundle. The same bundle was used for phases 1 and 2. The system was operated at a pressure of 60 psig (controlled at the tank outlet) throughout all phases of the testing to avoid problems with undissolved carbon dioxide bubbles in the tank.

For the first phase of the lab test, a clean, uncoated bundle was installed in the test heat exchanger shell. The potable water used during the test was Champaign (Illinois) distribution water, which has a slightly positive Langelier index. This water would not be expected to be corrosive or to deposit scale. The chemistry of the water was altered to give it a scaling potential, but not so as to force scale deposition. Two tanks containing calcite were installed upstream from the heat exchanger as a source of additional calcium and alkalinity. Carbon dioxide gas was injected on the inlet side of the calcite tanks to reduce the solution pH and increase the calcite dissolution rate. The heat exchanger was operated with this water at a flow rate of 1 gpm. Inlet and outlet fluid temperatures and Btu measurements were recorded for each test run. The heat transfer coefficient for each tube bundle was calculated using Eq 1 and 2 (pp 12, 13). To provide an internal check on the accuracy of the measurements, three independent methods were used to determine the overall heat transfer coefficient of the bundles. The first method involved using a direct reading of energy usage from the Btu meter, and dividing that usage by the amount of time elapsed to calculate the waterside heat transfer rate Q_w. The second method involved using the measured water inlet and outlet temperatures and the controlled flow rate to calculate an estimated heat transfer rate, Q_e. The third method involved using the measured steam inlet and outlet temperatures, their associated enthalpies and the measured steam usage to calculate a steamside heat transfer rate, Q_s. Good agreement was usually observed for these three rates. However, the Q_w rate is considered the most correct when the flow rate is above 0.8 gpm (the limitation of the flow meter).

For phase 2 of the test, the same tube bundle remained in operation, and the same conditions were used, except that scale deposition was forced. This was accomplished by adding a sodium hydroxide solution to the effluent from the calcite tanks to neutralize the carbon dioxide and to increase the solution pH as needed for scaling to occur. After scaling occurred, the same parameters as in phase 1 were measured and the same calculations were performed.

For phase 3 of the test, the uncoated tube bundle was removed from the test apparatus and a coated tube bundle was installed in its place. The Champaign water was not modified for this test. The test apparatus was again operated at 1 gpm, and the same parameters were measured as in the previous phases.

Laboratory Test Results and Discussion

The overall heat transfer coefficient of the uncoated, unscaled copper tube bundle averaged 218 Btu/hr-ft^2-°F in the laboratory setup at a flow rate of 1 gpm. Results from one of the experimental runs are shown in Figure 13. It was found that the heat transfer coefficient remained nearly constant with time.

The heat transfer coefficient of the scaled bundle was measured at 74 Btu/hr-ft^2-°F in the laboratory setup at a flow rate of 1 gpm. Results from one of the experimental runs are shown in Figure 14. Note that the bundle was scaled before the measurements were taken; time zero in the figure does not correspond to an unscaled bundle. This represents a reduction in heat transfer capabilities of 66 percent below the bare copper bundle. One limitation of this test is that, despite many attempts, it was not possible to produce the dense, brittle, tightly adherent scale deposits that were seen in the field. X-ray diffraction results (Figure 15) show that the calcium carbonate deposits found in the tests (aragonite) are similar to those found in the field.

The heat transfer coefficient of the phenolic coated tube bundle averaged 149 Btu/hr-ft^2-°F in the laboratory setup at a flow rate of 1 gpm. Results from one of the experimental runs are shown in Figure 16. Although it is a 31 percent reduction in heat transfer capability compared to the uncoated, unscaled bundle, it represents a 100 percent improvement over the scaled bundle. The coefficient of the coated bundle remains relatively constant with time.

In summary, the results of the laboratory test show that scaling dramatically reduces the heat transfer capabilities of the copper tube bundle. Although the coating reduces the heat transfer coefficient below that of a bare copper bundle, it is significantly better than the scaled, uncoated bundle. In addition, the heat transfer coefficient of the coated bundle will remain relatively constant with time, while the scaled, uncoated bundle will continue to degrade.
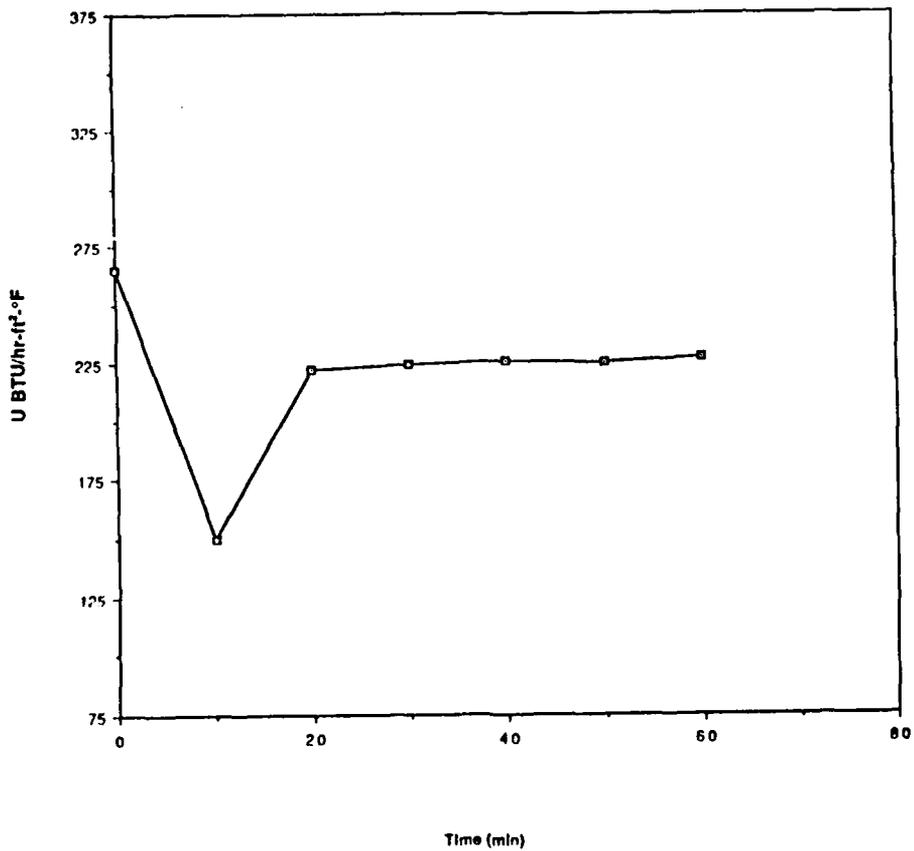
Figure 13. Heat transfer coefficient for uncoated, unscaled bundle.
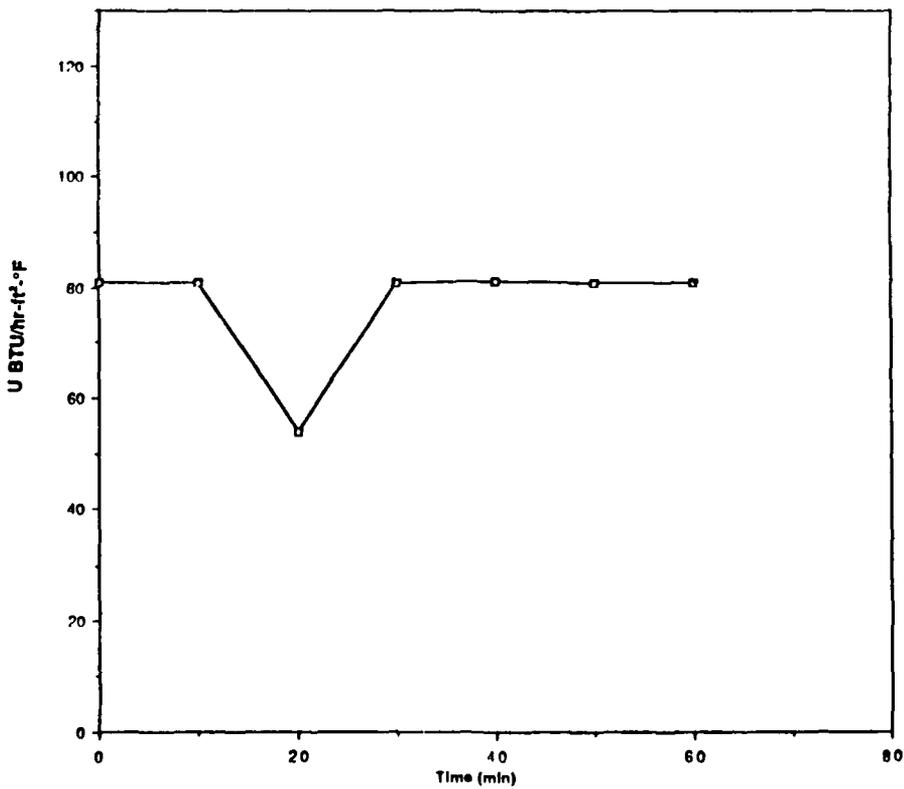
Figure 14. Heat transfer coefficient for scaled, uncoated bundle.

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200251 12/ 7/88 S= 0.010 T= 2.000 IWT #1644, CERL HE P10, 35KV-100MA METH
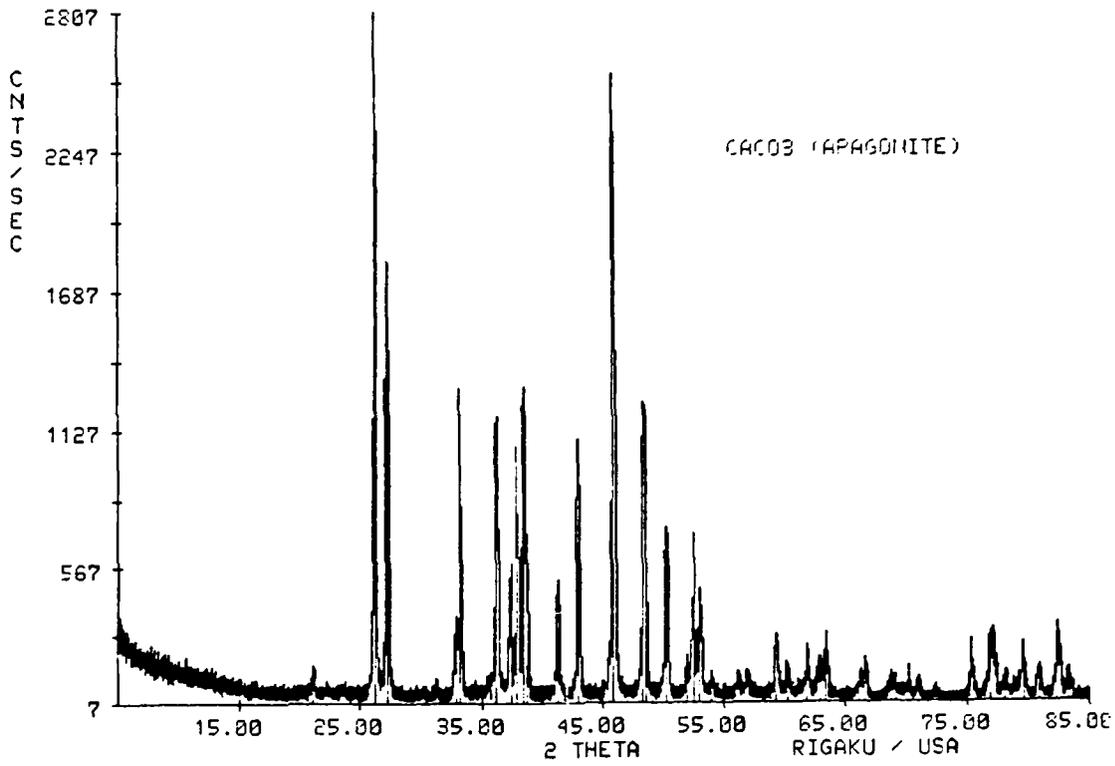PDF(1)=5,453

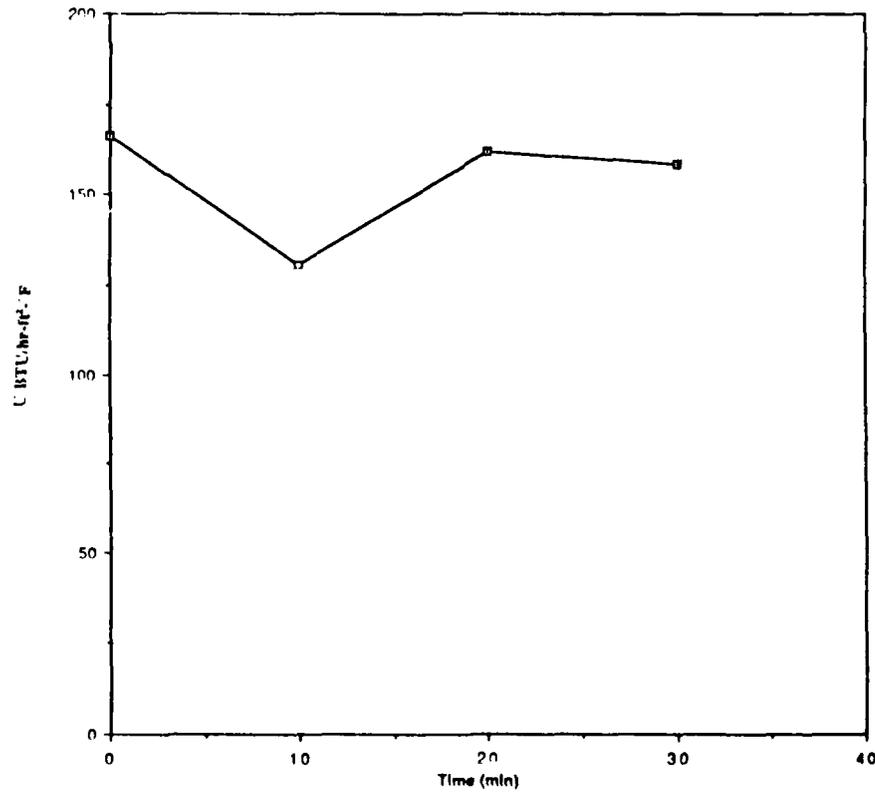**Figure 15. Chemical analysis of laboratory scale deposit.**

Figure 16. Heat transfer coefficient for coated bundle.

6 FIELD TEST OF COATING SYSTEM

Field Test Approach

The effectiveness of the baked-on phenolic coating system as a scale inhibitor in potable water heat exchangers was first field tested in Fort Hood's Building 29006, a dining hall chosen as the first test site for the coating because it represented a severe scaling environment. A second test bundle was subsequently installed in the other troublesome dining hall heat exchanger at Fort Hood Building 87017. The coating applicator for all of the field tests was Heresite-Saekaphen, Inc. The two original test bundles were coated using a spray-on method of application. Field tests (described below) revealed that, due to the irregular shape of the tube bundle, it was virtually impossible to achieve perfect, even coverage of the surface with the spray-on method. An immersion method of application was used to coat all subsequent bundles.

Field Test Results: Spray-On Application of the Coating

The first coated test bundle was installed in Bldg 29006 at Fort Hood. As noted in Chapter 3, an examination of the bare copper tube bundle from Bldg 29006 on 14 May 1986 revealed that scale approximately 0.07 in. thick had accumulated on its waterside surfaces since the last cleaning on 14 January 1986. After this examination, a clean copper tube bundle was installed in Bldg 29006 and the scaled tube bundle was shipped to the coating applicator, where it was acid cleaned to remove the heavy scale deposits. The waterside (outer) surface of the bundle was then coated with four coats (i.e., about 0.004 to 0.006 in.) of the pigmented baking phenolic and two coats (i.e. about 0.002 in.) of the clear baking phenolic top coating as described in Chapter 5. The coating was applied with a spray gun.

On 17 July 1986, the tube bundle was removed from the heat exchanger in Bldg 29006 and replaced with the specially coated bundle. The bundle that was removed had been in service since 14 May, and its waterside surface was covered with a deposit of calcium carbonate scale approximately 0.008 in. thick. Figure 17 shows the scaled bundle in comparison to the specially coated bundle.

On 7 October 1986, an inspection of the coated bundle revealed a few areas of minor, localized, scale formation on the copper tubes. The thickness of the scale, which was mostly on the steam inlet side of the coil, was less than 0.001 in. This represents an 87 percent reduction below the 0.008-in. layer that had formed on the bare copper tube bundle that had been in service for a comparable period of time. Moreover, only a small portion of the surface was affected. Microchemical analysis revealed that the scale was composed primarily of calcium carbonate. The scale was loosely adherent and could be easily removed by gentle wiping. The deposition seemed to have occurred in areas where the circulation of the water in the tank was such that the loosely adherent scale could not be naturally removed by the "washing" action of the incoming water. Also observed was some minor delamination (separation from the pigmented base coat) of the clear topcoating. The coating manufacturer noted that this problem could have occurred because of overbaking during the application process. However, the general appearance of the copper tubes was not significantly different than when it had been installed 82 days earlier. Its performance represents a dramatic improvement over that of the original uncoated tube bundle. The coated bundle was reinstalled immediately following the examination.

A site visit performed on 14-15 October 1986 to examine the heat exchanger in Bldg 87017 revealed that approximately 0.035 to 0.040 in. of calcium carbonate scale had formed on the waterside surfaces of the bundle since its last cleaning in December 1985. A small "booster" water heater had been installed on the hot water outlet because the exchanger itself was unable to maintain the 140 °F water temperature required in the dining hall. During the site visit, the hot water temperature was

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Figure 17. Scaled vs coated tube bundle, Bldg 29006, Fort Hood.

measured at 110 °F. After the October site visit, the scaled bundle was replaced with a bare, clean copper bundle and the scaled bundle was shipped to the coating applicator where it was acid cleaned to remove the scale deposit. A different coating system was devised to prevent the slight delamination that had occurred in Bldg 29006. The system consisted of applying four coats (0.004- to 0.006-in. dry film thickness) of the pigmented baking phenolic base coat, and two coats (0.002-in. dry film thickness) of a mixture consisting of 50 percent pigmented coat and 50 percent clear coat. It was hypothesized that the 50/50 top coat combination would have greater resistance to delamination than the original clear top coat. The new coating system was applied to the bundle from Bldg 87017 using a spray gun following the same procedure as before.

On 8 January 1987, the tube bundle was removed from the heat exchanger in Bldg 87017 and replaced with the specially coated bundle. The removed bundle had been in service since 14 October and its waterside surface was covered with a deposit of calcium carbonate scale approximately 0.015 in. thick. Figure 18 shows the scaled bundle (left) in comparison to the specially coated bundle.

In February 1987, a circular chart recording system was installed to monitor the temperature of the hot water produced by the heat exchanger in 29006. The battery-operated recorder used a 7-day, 8-in. diameter circular chart to report the data, to verify that the 140 °F minimum temperature was maintained under normal operating conditions and to ensure that the coating did not significantly impede the transfer of heat. During the period that hot water temperatures were recorded, the temperature averaged approximately 160 °F. At high demand, the temperature occasionally dropped below 140 °F, but never below 120 °F. This was a vast improvement over the scaled, uncoated bundles. At peak times, the exchanger routinely operated significantly above its design capacity. Figure 19 shows a typical day of recorded hot water temperature data; water temperature drops during and after the three mealtimes, and is maintained between 190 and 200 °F during the night, when water is not used. Figure 20 shows a typical week of recorded hot water temperature data. The circular chart recording was continued through August 1987.

Also in February 1987, a totalizing turbine-type water flowmeter was installed on the cold water inlet to the tank to monitor the consumption of water, to determine whether or not the 1170 gph design capacity of the unit was exceeded. Monitoring of the flow meter over a period of several months revealed that the hot water usage rate was approximately 11,000 gal/day, the majority of which took place during and immediately after meals. During a typical mealtime, 5,000 gallons of water were used during a 3-hour period, averaging a rate of 1667 gal per hour, 42 percent in excess of the design capacity of the heater. Thus, even under ideal conditions with perfectly clean tube bundles, the exchanger would not be expected to be able to meet the high demand during mealtimes. therefore, the occasional drops below 140 °F were attributable to use of the exchanger beyond its design capacity, and not to the coating of the bundles.

On 14 April 1987, a field inspection of both Bldg 29006 and 87017 was conducted. Examination of the coil from 29006 revealed that most of the bundle was covered with a thin layer of calcium carbonate scale less than 0.001 in. thick. The scale was brownish-colored and loosely adherent. Small areas did exist, especially near the steam inlet and between the tubes, where scale was as thick as 0.04 to 0.05 in. As in the October field inspection, some delamination of the clear topcoating was observed. The bundle was temporarily removed for cleaning. Most of the scale could be removed by simply exposing the tube bundle to a high pressure hot water cleaning at the vehicle washing center.

The coil in Bldg 87017 was also pulled and inspected. This tube bundle, installed on 8 January 1987, used the coating system with the 50/50 top coat described above. Scale accumulation was more severe, with thicknesses reaching 0.08 in. near the steam inlet. However, the scale was loosely adherent and powdery, and could be removed with the pressure washer used at Bldg 29006. The coated bundle was reinstalled after cleaning.

Figure 18. Scaled vs coated tube bundle, Bldg 87017, Fort Hood.
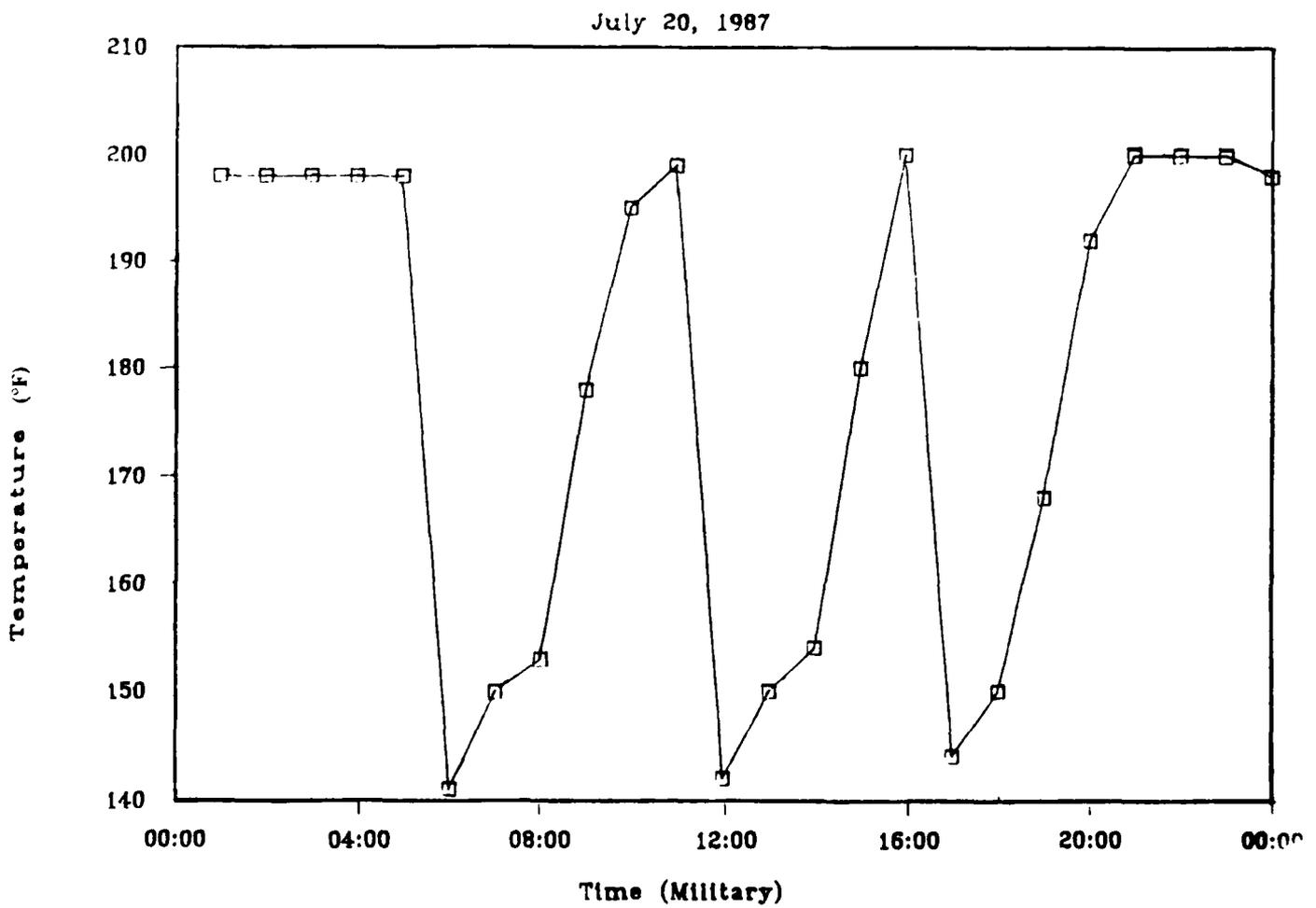
Figure 19. Typical day of hot water temperature data for sprayed-on coating recorded by circle chart, Bldg 29006, Fort Hood.

In summary, the original spray-coated bundle was successful in maintaining the hot water temperature at an acceptable level. The bundle with the 50/50 top coat mixture was somewhat less successful, but was an improvement over a bare, scaled bundle. The need to acid clean the bundles was eliminated. This is significant not only from a maintenance cost standpoint, but also from safety and environmental standpoints. From a safety standpoint, the coating eliminated the need for Fort Hood personnel to handle and work with acid. Environmentally, it eliminated the need for disposing of the large quantities of acid previously required for cleaning.

Field Test Results: Immersion Application of Coating

To further improve the quality of the coated tube bundles and to assure that all surfaces receive uniform coverage, it was decided to use and test an immersion method of coating application. This involved constructing dipping tanks large enough to accommodate the tube bundles. The application procedure remained the same as before, except that the tube bundles were immersed in the dipping tanks filled with the coating mixture instead of being sprayed.

Two new tube bundles were coated by the new application procedure. The original coating mixture was used, four coats of the pigmented baking phenolic base coat and two coats of the clear phenolic top coat.
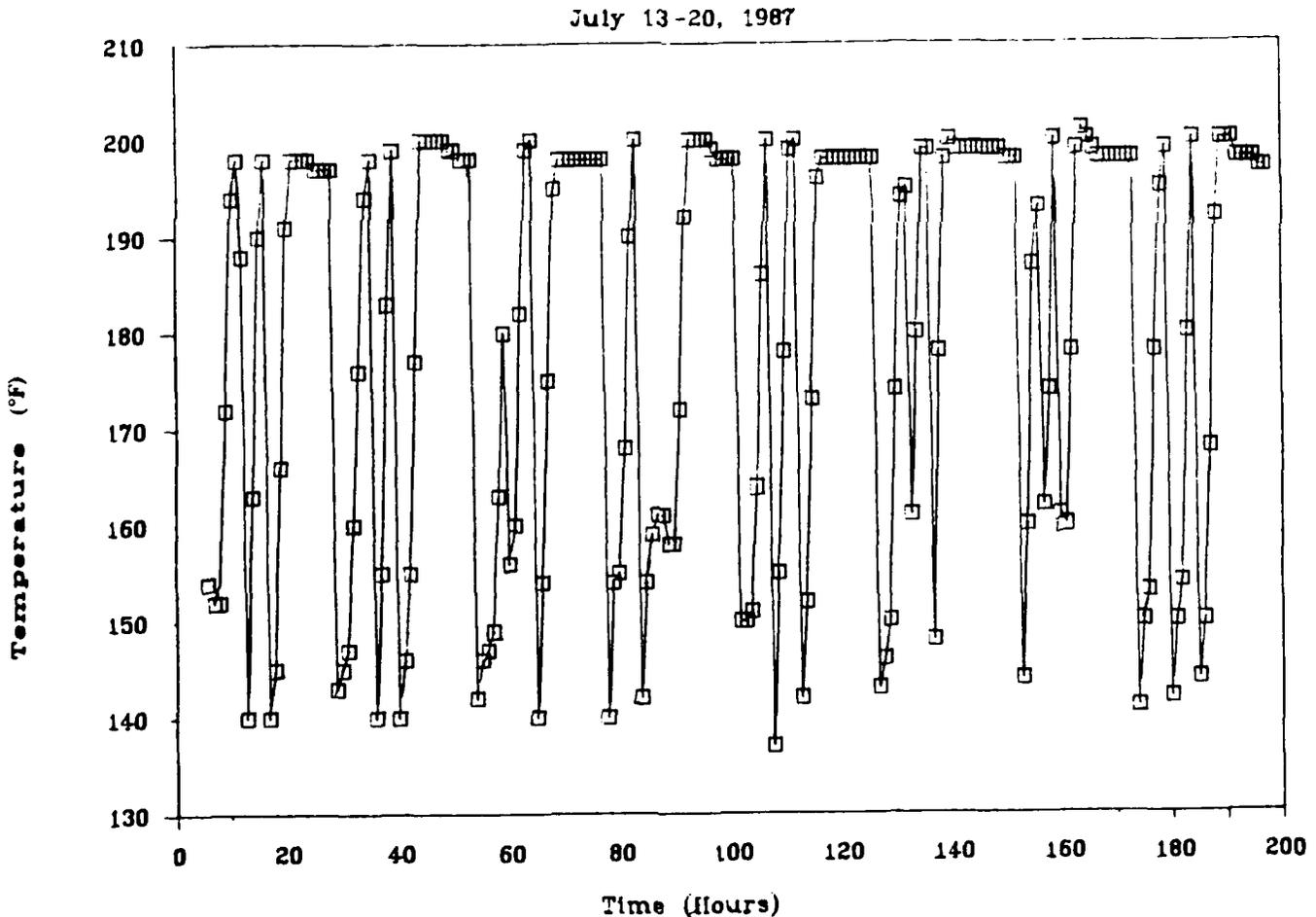

Figure 20. **Typical week of hot water temperature data for sprayed-on coating, Bldg 29006, Fort Hood.**

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On 6 January 1988, one of the new dip-coated bundles was installed in Bldg 29006. The old bundle, which is the original coated bundle, had been in service for 18 months without requiring acid cleaning. The dip-coated bundle has been in service from January 1988 to the present.

The second dip-coated coil was installed in 87017 on 10 March 1988. The bundle that had been removed was the 50/50 top-coated bundle, which had been in service since April 1987 without requiring acid cleaning. The dip-coated bundle has been in service from March 1988 to the present.

To improve the quality of data collection, a new monitoring system was installed and became operational in both buildings in late May 1988. The system collects each of the four parameters required to calculate the overall heat transfer coefficient (U) of a heat exchanger: the steam temperature entering the coils, the cold water temperature entering the shell, the hot water temperature leaving the shell, and the flow rate of the cold water entering the shell. The new system is comprised of a portable four-channel data logger that records temperature data from three Type J thermocouples and flow data from a paddlewheel type flowmeter. The data logger and playback system stores data provided by each of the sensors for 30 days. The recorded data can then be downloaded into an IBM PC (or compatible) for analysis. Figure 21 is a schematic showing the location of each of the sensors in the heat exchanger system.

Data collected by the data logging system between June 1988 and April 1989 was compiled and analyzed. (Bldg 29006 was shut down for repairs on the drainage system between March and August 1988; thus, data was not collected during that time.) Recording in Bldg 29006 began in August 1988. Figure 22 shows a plot of hot water temperature for both buildings for the period June 1988 to May 1989. The temperature was generally maintained above 140 °F for both buildings during this period. Figure 23 shows a plot of flow rate during the same period. Water usage remained approximately constant between June 1988 and January 1989 in Bldg 87017, and for unknown reasons increased sharply for the remainder of the test period. A plot of the steam temperature is shown in Figure 24. The steam temperature remained relatively constant throughout the test period at approximately 235 °F. A plot of the cold water temperature for the test period is shown in Figure 25. Since the water is from a surface supply, the temperature rises during the summer and drops in the winter, as would be expected. Figure 26 shows a plot of the calculated U value for the exchangers based on the data collected. U did not degrade over time, signifying that scale buildup was not occurring. The fluctuations in the coefficient during the latter part of the recording period occur with the fluctuations in water usage (Figure 23).

In summary, the immersion-coated bundles have been proven highly successful in the field. The hot water temperature has been successfully maintained at or above 140 °F, scale buildup has not occurred, and the tube bundles have not been pulled out since their installation in early 1988.
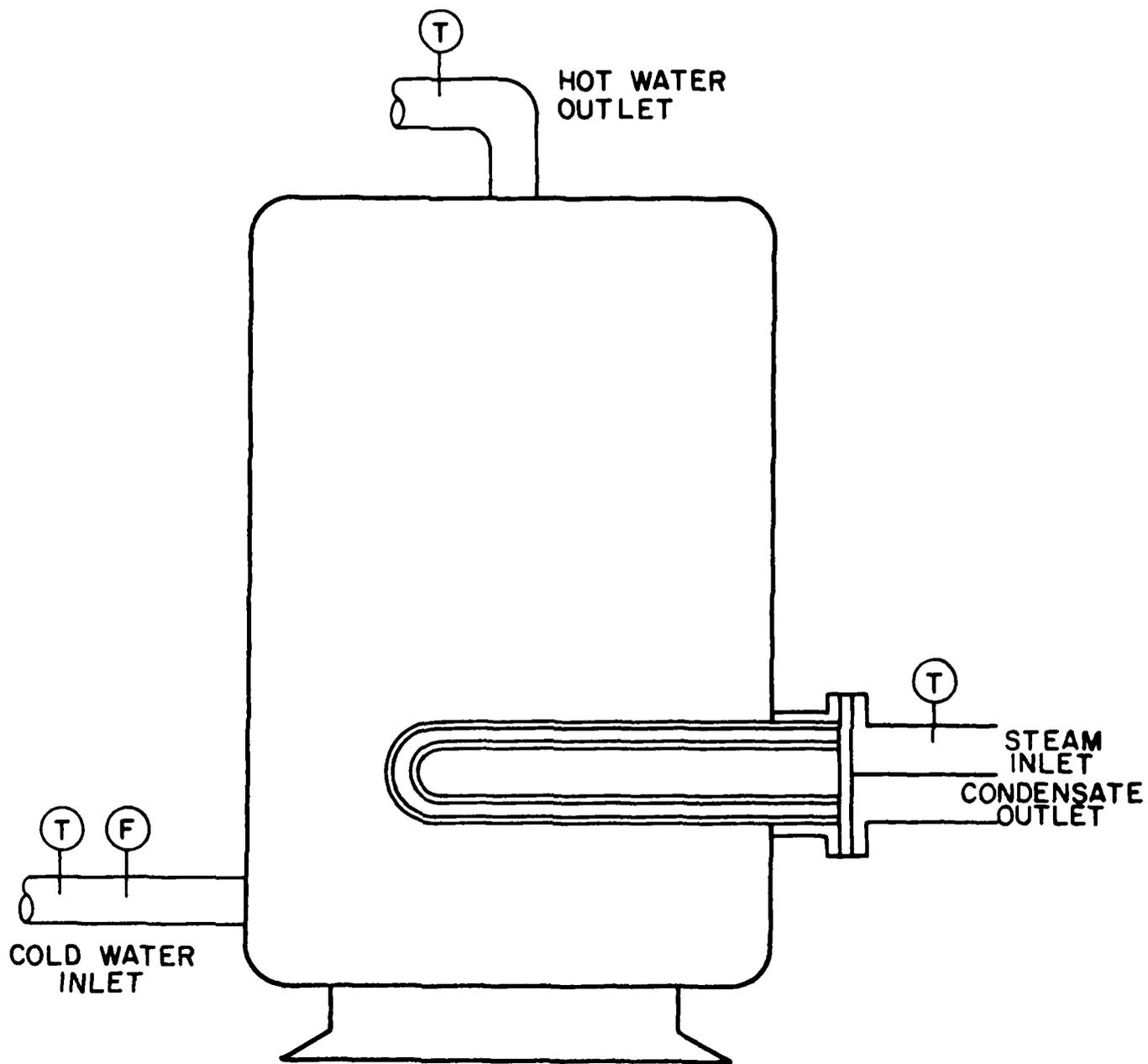
Figure 21. Placement of sensors on heat exchangers at Fort Hood.

Figure 22. Hot water temperature data for immersion-applied coating, Fort Hood.
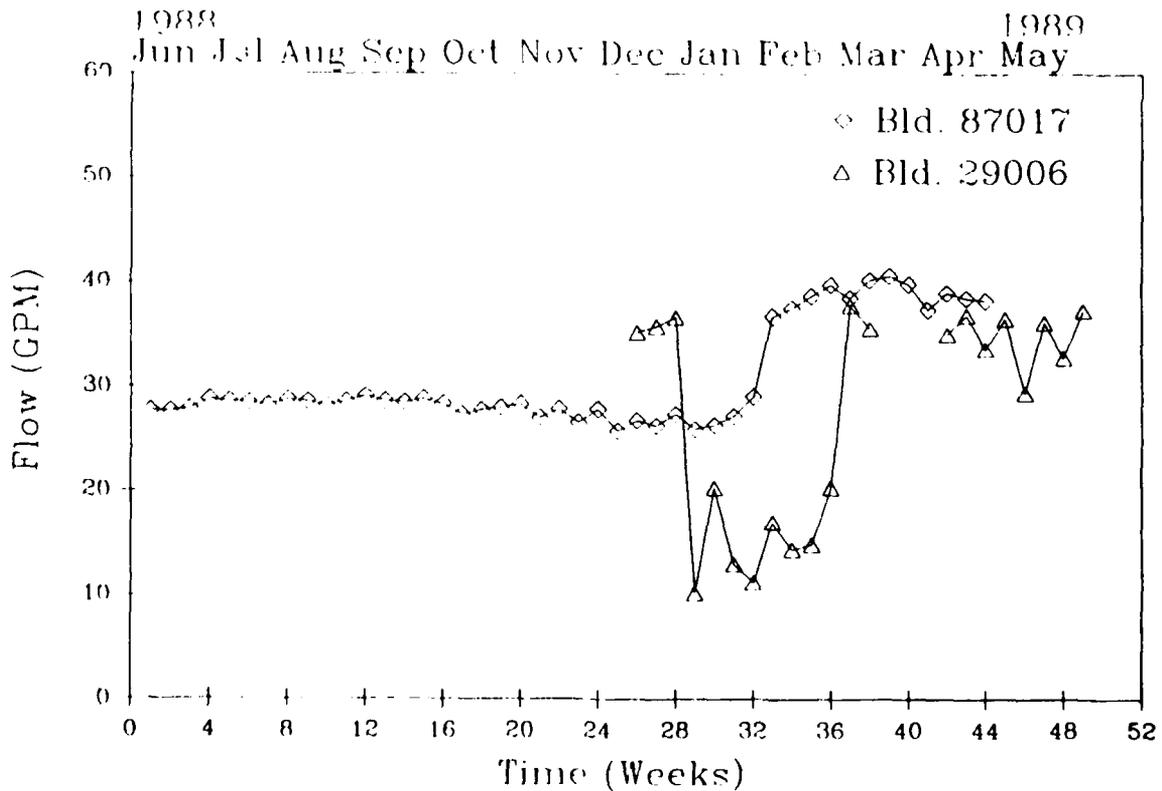
Figure 23. Flow rate data for immersion-applied coating, Fort Hood.

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Figure 24. **Steam temperature data for immersion-applied coating, Fort Hood.** (Reprinted from *Efficient Boiler Operations Sourcebook*, with permission from Association of Energy Engineerings, 700 Indiana Trail, Lilburn, GA, 30247, Fairmont Press.)
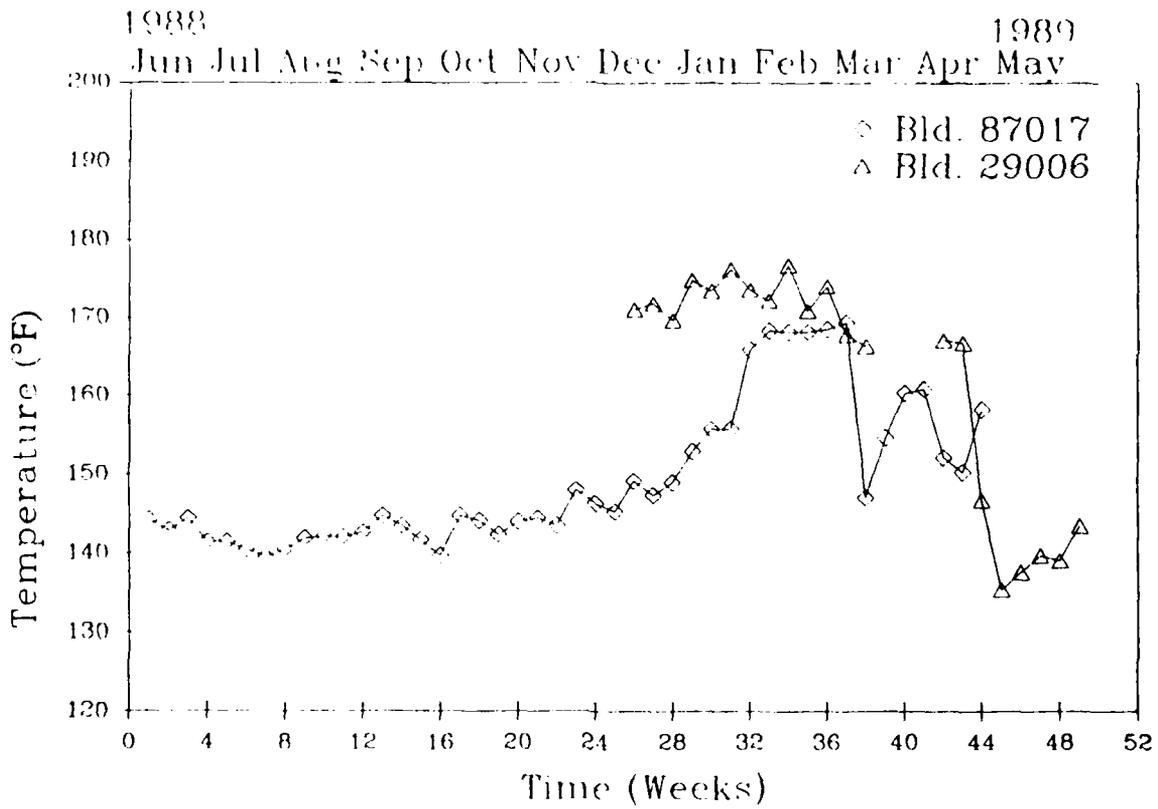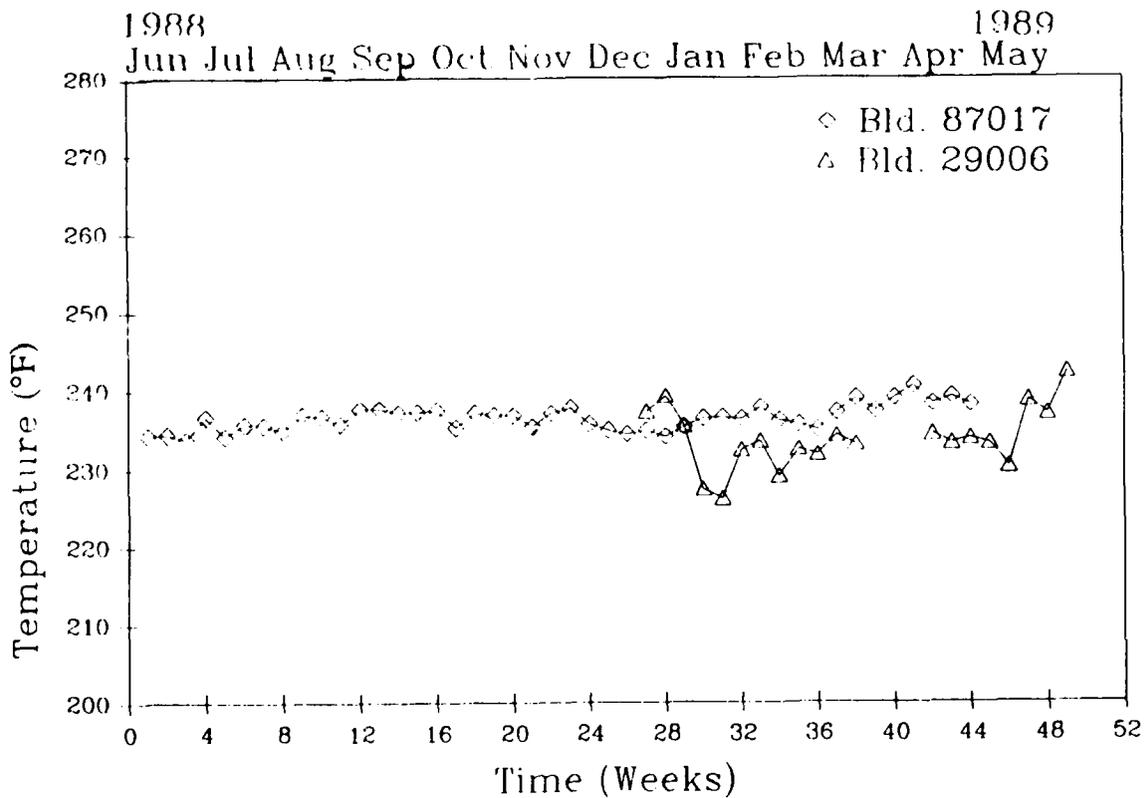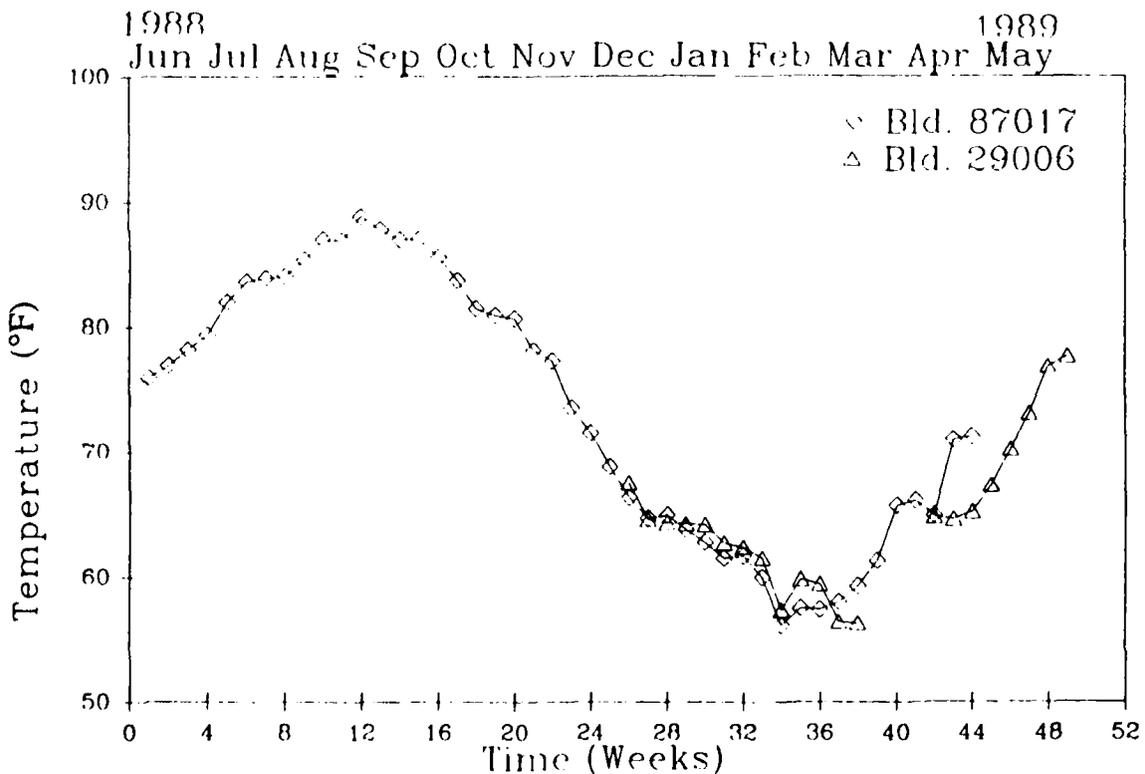

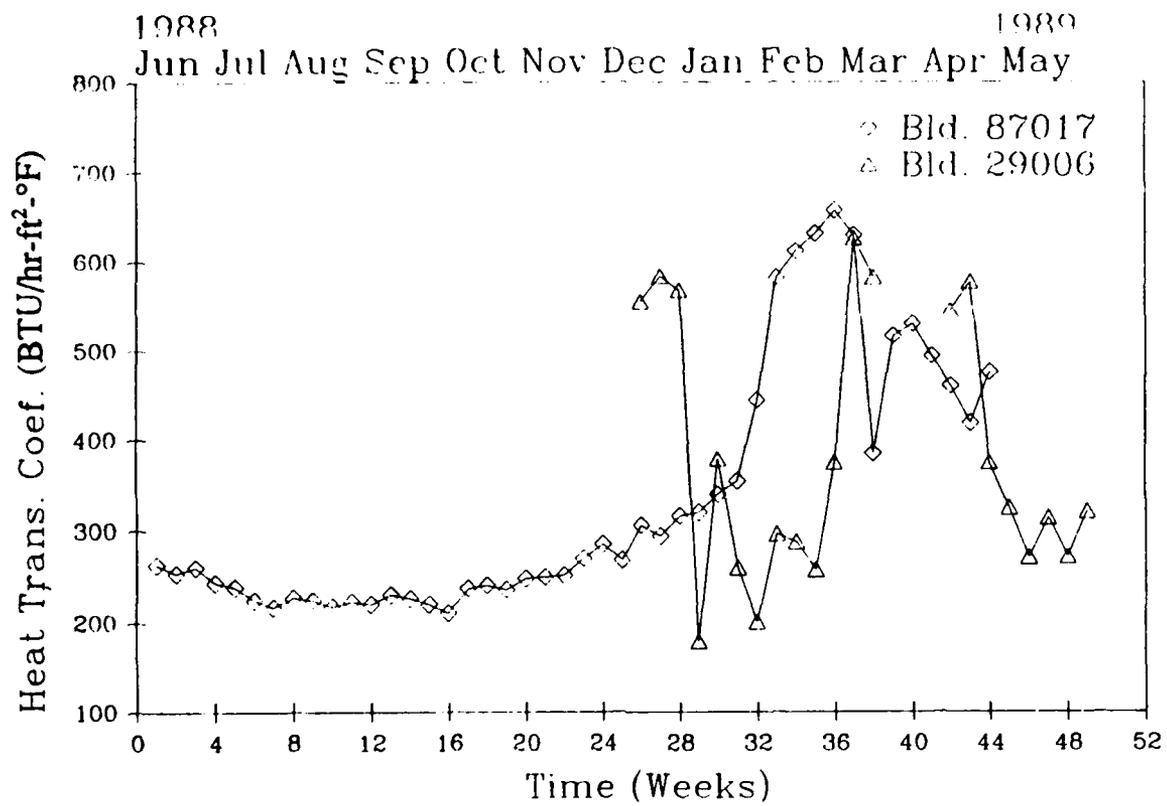**Figure 25. Cold water temperature data for immersion-applied coating, Fort Hood.**

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Figure 26. U-values for immersion-applied coating, Fort Hood.

7 COST ANALYSIS AND RETURN ON INVESTMENT

Cost of Heat Exchanger Fouling at Army Installations

A study was performed at the three installations surveyed to determine the cost of scaling and corrosion in heat exchangers. Fouling problems are no longer distinguished by DEH administration because they have occurred for so long that their costs have become an accepted part of the overall operations and maintenance budget.

Heat Exchanger Energy Loss Economics

Three levels of costs were studied to estimate the cost of heat exchanger fouling. The first level was direct costs such as labor, materials and energy losses. Labor and material costs were taken from the IFS database at each installation (where applicable). The second level was operations and maintenance costs associated with the direct costs such as travel time, inventory time, and telephone time. These were generated by the DEH cost estimating section. The third level was of the overall cost of downtime.

Direct Costs: Labor and Materials

Each maintenance or repair action has associated labor and material costs. Since most water heater maintenance actions require the tank to be drained and the tube bundle to be pulled, cost estimates are made on this basis. Thus, labor and materials costs include the cost of manpower and supplies for draining the storage tank, pulling the exchanger, cleaning or repairing the tube bundle, replacing the tube bundle, and refilling the storage tank. This takes into account shop overhead and the base estimate for time required to do a typical job.

Energy Losses

How to enter energy loss into cost calculations is a complex issue. If there is a daily energy loss caused by the reduction in heat transfer at the tube bundle, a method for quantifying that loss would have to be determined to account for it in the overall cost analysis.

Daily energy loss due to fouling might be expected to take place at the heat exchanger itself. Steam admitted through a control valve flows through the heat exchanger tubes. The steam trap associated with the exchanger (providing it is operating correctly) will not release the steam from the tube bundle until it has condensed and released its thermal energy to the potable water in the tank. When the steam has condensed, the trap opens and the hot condensate is pumped or drained into the return lines. The valve then admits more steam into the tube bundle. Thus, the steam remains in the tube bundle and does not return to the steam plant until it has condensed and imparted its heat of vaporization to the potable water in the tank. The same amount of heat is transferred from the steam to the water under both fouled and clean conditions, except that when the tube bundle is fouled, the transfer takes place at a slower rate. (The U-value for a fouled heat exchanger is lower than that of a clean exchanger.) Thus, during a period of peak demand, there will not be enough heat transferred to produce the amount of hot water being demanded. Energy is not really lost in a fouled heat exchanger; its rate of transfer between the steam and potable water is merely slower. Thus, within the heat exchanger, the energy economic losses due to fouling would be close to zero.

Daily energy loss might be expected to take place in the condensate return lines. Steam held within the tube bundle returns to its condensed form, whether the bundle is scaled or not. A given quantity of steam condenses into the same amount of liquid at approximately the same temperature no

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Daily energy loss might be expected to take place in the condensate return lines. Steam held within the tube bundle returns to its condensed form, whether the bundle is scaled or not. A given quantity of steam condenses into the same amount of liquid at approximately the same temperature no

Finally, the demand from potable hot water might be only a very small component of the total load on the boiler plant. The boiler might not be sensitive to the reduced thermal transfer of a few heat exchangers in a network, when compared to the other overall demand for building heat, losses in steam lines, and losses in condensate return lines.

The preceding discussion shows that energy losses that occur during the daily operation of the heat exchanger network are so small that they could not be accurately modelled. If such a model were to be attempted, it would be contingent upon so many assumptions that the results would be questionable. Thus, energy losses that occur during the daily operation of the heat exchanger network were not included in this analysis.

Another cost of fouling, which does not occur on a daily basis, but does occur when the tank is drained down for any type of maintenance and repairs, is the cost of thermal energy lost during the draindown process. The heated water drained from the tank represents a measurable loss and is calculated. The cost of the energy used to reheat the water and the metal in the tank to the operating temperature is also considered.

Calculations (Appendix D) show that the average cost of draining a 1000 gal tank with 140 °F hot water is $12.80.

Operations and Maintenance Costs Associated With Direct Costs

Certain labor costs involved in replacing heat exchangers and maintaining a heat exchanger inventory are not usually included in the Engineered Performance Data Base by which DEH labor estimates are created for a job. These costs are individually described per DEH shop operations, and includes such items as the costs of ordering new heat exchangers (i.e., writing and monitoring requisitions), maintaining an inventory, selecting the correct exchanger to meet specifications when ordering, and inspecting exchangers.

Downtime

Downtime costs include costs incurred when potable hot water is unavailable for the 6 to 12 hours it takes to clean or repair a heat exchanger. Downtime refers to interference with job productivity for the troops, and any other deviation from the normal routine that causes extra costs to be incurred by the installation. This category would include things such as the cost of soldiers finding another location to bathe, eat, and do laundry, and the cost of using disposable utensils in a dining hall.

Economic Losses at Fort Lewis

Most heat exchanger problems at Fort Lewis are due to corrosion. Costs result from leak repair, tube bundle replacement, and downtime. The plumbing shop is the central point of contact for all heat exchanger repairs. Repair and replacement actions at Fort Lewis may be conducted in three different ways, all of which generate costs. The first is to directly replace or repair the heat exchanger using parts in inventory. The second approach is to advertise for competitive bids for a heat exchanger replacement, a process that can take 6 to 8 weeks and a large amount of administrative time, since the heat exchangers at Fort Lewis are not standardized. The third approach is to do emergency repair at times of critical failure, at which time the plumbing shop must drop all other work and work on the heat exchanger until it is repaired, disrupting the normal scheduling of other jobs.

Economic and performance data collected at Fort Lewis was obtained from three sources. The first source of information was the plumbing shop supervisor and assistant supervisor, who provided information concerning downtime, the time it takes to repair a leaking exchanger, and the heat

exchanger inventory stocking procedures. The second source of information was the Installation Facilities System (IFS) database, which tracks all of the labor expenditures and costs associated with the work activity done for the repair and replacement of heat exchangers. The third source of information was the DEH cost estimating section. A generic approach to determine the costs associated with the repair and replacement of heat exchangers was developed in coordination with the cost estimating section. To develop this approach, the plumbing shop supervisor helped to identify a generic procedure for repair and replacement of heat exchangers. This procedure was then simulated by the DEH cost estimating computer system, Facilities Engineering Job Estimating System (FEJE), to arrive at an overall generic cost.

When costs were tabulated (Appendix E), it was found that Fort Lewis, with 97 heat exchanger units, spends approximately $60,624 per year on heat exchanger fouling (Table 2).

Table 2

Breakdown of Annual Fouling Costs at Fort Lewis

Direct costs	
Labor	$ 16,302
Materials	11,200
Associated losses	
Tank draindown	512
Operations and maintenance	610
Downtime	32,000
Total annual cost of fouling	$ 60,624

Economic Losses at Fort Hood

Heat exchanger problems at Fort Hood result from scaling. Thus, the tube bundles do not require frequent leak repairs and replacement but do require relatively frequent acid cleaning; two of the dining hall heat exchangers must to be shut down and acid cleaned every 60 to 90 days. Over 100 other heat exchangers in barracks and other facilities scale at a slower rate, and require removal and acid cleaning at 1 to 5 year intervals. This represents a significant burden upon the plumbing shop. There are also some problems with erosion at the "U" bend in the tube bundle, but this is less serious than the scaling problem.

To gain an understanding of the heat exchanger problem, an interview was conducted with the DEH Assistant Chief of Operations and Maintenance who stated that the two dining hall exchangers were the most severe problem, most likely because these exchangers are operated above their maximum capacity during peak hours (an assertion verified by actual field data). The heat exchanger was apparently underdesigned when it was built in the early 1970s to promote energy conservation. Labor and material data were obtained from the IFS database. The procedure for determining costs is similar to that used at Fort Lewis.

When the economic loss calculations were performed (Appendix F), the two dining hall exchangers were analyzed separately, and the remaining 112 steam-fed exchangers were analyzed as a group. Fort

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Hood spends approximately $10,129 per year for the two dining hall heat exchangers in Buildings 29006 and 87017 alone, approximately $46,794 per year for the remaining 112 heat exchangers, for a total of $56,923 annually on heat exchanger scaling (Table 3).

Economic Losses at Fort Benjamin Harrison

Both corrosion and scaling problems had been observed at Fort Harrison. Data at Fort Harrison were obtained from the plumbing shop supervisor and the estimating section. The codes for the IFS data base are not collected in the same manner as those at other forts and are not retrievable or comparable.

Table 3

Breakdown of Annual Fouling Costs at Fort Hood

Costs	Dining Halls	All Others
Direct costs		
Labor	$ 4,504	$ 10,645
Materials	1,700	8,500
Associated losses		
Tank draindown	325	769
Acid disposal	144	624
Operations and maintenance	0	256
Downtime		
Paper plates in Dining Hall	3,600	0
Downtime for troops	0	26,000
Subtotal	$ 10,129	$ 46,794
Total annual cost of fouling	$ 56,923	

Since there is no standard size or length for tube bundles at Fort Harrison, each bundle must be custom manufactured, and a logical inventory of extra bundles cannot be kept on hand. Thus, the tube bundles are expensive compared to those at other installations, and it takes 12 to 16 weeks to procure and build a new exchanger.

When the economic loss calculations were performed (Appendix G), it was found that Fort Benjamin Harrison spends approximately $19,569 per year on heat exchanger fouling over 53 heat exchanger units (Table 4). Note that Fort Harrison is significantly smaller in size than the other forts analyzed in this report.

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Average Costs of Heat Exchanger Fouling in the Army

According to the cost analyses, the total cost of heat exchanger fouling per year at the three installations studied was $137,116. Since there was a total of 116 failures requiring repair actions, this is an average cost of $1182 per repair action. This can be broken down into separate categories for sealing and corrosion. There are 64 scale-related failures per year at Fort Hood for a total cost of $56,923, or $889 per scale-related failure. There is a total of 52 corrosion-related failures per year at Fort Lewis and Fort Benjamin Harrison for a combined cost of $80,193, or $1542 per corrosion-related failure.

Table 4

Breakdown of Annual Fouling Costs at Fort Benjamin Harrison

Direct costs	
Labor	$ 3,985
Materials	10,400
Associated losses	
Tank draindown	154
Operations and maintenance	230
Downtime	4,800
Total annual cost of fouling	$ 19,569

Cost Comparison of Various Scaling Mitigation Techniques

The life cycle cost of each alternative described in Chapter 4 was evaluated for a system like the dining hall water storage heaters at Fort Hood. An average daily hot water usage of 11,000 gal was assumed. The tank was assumed to have a 2115 gal capacity and tube bundle length was assumed to be 71.5 in. comprised of 13, 3/4-in. diameter copper U-tubes. The water was assumed to have a chemical composition like the water at Fort Hood (Appendix B). The alternatives were analyzed using the CERL-developed Life Cycle Cost in Design (LCCID)[7] computer program. The LCCID program uses the methods in the Office of Management and the Budget (OMB) Circular A-94, which sets forth the standard criteria for the federal sector for general types of economic analysis. This method specifies a discount rate of 10 percent, and an analysis period of 20 years. The analysis (Table 5) showed that the baked-on phenolic coating system, with a 20-year life cycle cost of $2019, was the most economical method to prevent fouling in an environment similar to Fort Hood's. Note that in a corrosive water situation, where the most common alternative would be water treatment by chemical feed, the coating would still be the most economical solution.

[7]L.K. Lawrie and D.A. Beranek, *Development and Use of the Life Cycle Cost in Design Computer Program (LCCID)*, TRE85/07/ADA162522 (USACERL, November 1985).

Table 5

Life Cycle Cost Analysis for Scale Mitigation Techniques

Alternative	Description of Cost	Cost ($)	Payment Dates
A:	Chemical feed pump	430	Year 0
	Meter assembly	500	Year 0
	Chemicals	431	Annual
	Labor	108	Annual
	Life cycle cost:	5,812	
B:	Water softener (2 banks)	6,000	Year 0
	Salt	3,500	Annual
	Resin regeneration	500	Annual
	Labor	3,100	Annual
	Replace resin	500	Every 5 yrs
	Life cycle cost:	70,791	
C:	Acid cleaning*	5,064	Annual
	Life cycle cost:	50,281	
D:	Coating (or recoating)	600	Every 5 yrs
	Tank draindown	27	Every 5 yrs
	Labor	216	Every 5 yrs
	Life cycle cost:	2,019	
E:	Equipment	600	Year 0
	Carbon dioxide	361	Annual
	Labor	432	Annual
	Life cycle cost:	7,684	

* From previous tabulation of Fort Hood dining hall heat exchangers costs.
  Assumes cleaning every 60 days.
  Includes labor, materials, tank draindown, downtime, and acid disposal.

8 CONCLUSIONS

This investigation has shown that shown that domestic hot water heat exchanger degradation is a significant problem at Army installations where the water has scale-forming or corrosive properties. Scale deposition results in the reduction of a unit's heat transfer capability. Corrosion eventually results in leaks in the metal tube bundles that are used to convey the heating fluid. It was found that both problems result in significant increases in maintenance and repair costs.

The immersion-applied, baked-on phenolic coating system appears quite promising in mitigating scale buildup in domestic hot water storage heaters. It has maintained hot water temperatures at an acceptable level and has eliminated the need for acid cleaning of the tube bundles in the severe scaling conditions at Fort Hood for more than 18 months. In the past, the bundles had to be removed and acid cleaned every 60 to 90 days. This is significant not only from a maintenance cost standpoint, but also from safety and environmental standpoints. The coating system frees site personnel from handling and working with acid, and from acid disposal. Although the coating does reduce the heat transfer coefficient of the tube bundle (218 to 149 Btu/hr-ft^2), it represents a vast improvement over the reduction in heat transfer caused by a layer of scale (218 to 74 Btu/hr-ft^2). The most successful coating system formulation consisted of four coats of the pigmented phenolic base coat and two coats of the clear phenolic top coat. The coating is cost effective in the scaling environment. It is projected that the coating will also be successful and cost effective in corrosive environments.

9 FUTURE INVESTIGATIONS

Several methods to solve or reduce the scaling effects on a tube bundle inside a heat exchanger are worthy of more investigation. Three of these methods are: application of a Teflon-Ryton coating to be applied to a standard metallic heat exchanger tube bundle, use of an all-polymer flexible pure teflon tube bundle, and use of an all-polymer flexible teflon with graphite-impregnated tube bundle.

The first option, the Teflon-Ryton coating on standard copper tubing, is a dual coating. Ryton is a polyphenylene sulfide made by Phillips Petroleum. The coating can be sprayed onto the copper tube bundle or the tube bundle can be submerged into the coating. Once the coating is applied, the Ryton tends to be attracted to the surface of the copper tubing so that there are two distinct layers, one of Ryton and one of Teflon, with a transition layer between. After the coating is applied, the unit is then baked at 425 °F to create a hard, slick surface.

This type of coating is already used in a wide range of applications, from coatings on frying pans to easy release coatings in corrosive chemical pumps. The main benefit of such a coating is that it will not allow scale to adhere to the surface of the tube bundle. The coating, however, will lower the coefficient of heat transfer, U. The effects of the coating compared to scaling need to be investigated to determine if the coating would be more economical in the long run.

The second and third options differ only in the thermal conductivity of their different material. These options involve replacing the standard metallic tube bundle with an all-polymer bundle. The bundle is composed of many flexible, small diameter (approximately 1/8 to 1/4 in.) tubes composed of Teflon (or Teflon impregnated with carbon). The surface is not as slick and may not resist the adherence of scale as effectively as Teflon-Ryton, although it will resist scaling better than bare copper. The use of many small tubes increases the surface area of the bundle, thereby improving the heat transfer rate to a level comparable to that of a metal tube bundle. Finally, the tube bundle may be impregnated with graphite to increase the thermal conductivity of the polymer material. This system will not only provide a scale resistant surface, but it will also provide flexible tubing that can be shaken or vibrated to easily dislodge any scaling that may be present. The tubes are designed to move or vibrate slightly during the course of system operation.

This type of system is currently used in heat exchangers in harsh chemical environments that would deteriorate copper or other metal tubing, but has not yet been applied to a potable water heat exchange system. The suitability of the graphite-impregnated polymer for use in potable water systems is unknown and will require extensive testing and investigation. Since the flexible tubing can survive in harsh environments, it is expected to have a very long life in potable water systems. Further analysis is needed to determine the actual heat transfer coefficient of each polymer to help decide the feasibility of these systems. The heat transfer coefficients of these materials are expected to be lower than that of clean copper, but the lower coefficient may still prove more efficient in the long run because of longer service life and the less frequent cleaning requirements of the polymers.

METRIC CONVERSION TABLE

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.)	=	3.785412 l
1 gal (U.S.)/min	=	0.0630902 l/sec
1 mil	=	0.0000245 m
1 inch	=	25.4 mm = .0245 m
1 lb	=	0.453592 kg
1 lb/in² (psi)	=	6894.76 Pas
1 lb/gal (U.S)	=	0.1198264 kg/l

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APPENDIX A:

DERIVATION OF HEAT TRANSFER RELATIONSHIPS

For two fluids at constant temperatures separated by a *plane* metal wall, the rate of heat transfer from the hot fluid to the cold fluid per unit area is:

$$Q/A = h_h (T_h - T_1) = k(\frac{T_1 - T_2}{t}) = h_c(T_2 - T_c) \qquad \text{[Eq A1]}$$

where Q = the rate of heat transfer from the hot fluid to the cold fluid [Btu/hr]
  A = surface area of the metal wall [ft]
  k = the thermal conductivity of the wall material [Btu/hr-ft-°F]
  t = the thickness of the wall [ft]
  T_h = temperature of the hot fluid [°F]
  T_c = temperature of the cold fluid [°F]
  T_1 = temperature of the hot side of the metal wall [°F]
  T_2 = temperature of the cold side of the metal wall [°F]
  h_h = convective heat transfer coefficient on the hot side of the metal wall [Btu/hr-ft^2-°F]
  h_c = convective heat transfer coefficient on the cold side of the metal wall [Btu/hr-ft^2-°F].

The effects of both conduction through the metal wall and convection at the wall surfaces can be expressed in terms of an overall heat transfer coefficient, U. The rate of heat transfer can then be expressed as:

$$Q/A = U(T_h - T_c) \qquad \text{[Eq A2]}$$

where U, the overall heat transfer coefficient, is given by:

$$1/U = 1/h_h + t/k + 1/h_c \qquad \text{[Eq A3]}$$

Heat exchangers are usually not in the form of a plane wall. However, the same principles can be applied to a tube. A heat transfer equation similar to equation A1 can be written for a tube with heat exchanger fluids flowing on its outside and inside, and can be applied to the shell and tube heat exchanger. It is assumed below that the hot fluid is flowing on the inside of the tube and the cold fluid is flowing on the outside. For this case, the equation for overall heat transfer can be redefined as:

$$Q = 2\pi r_o L h_o(T_2 - T_c) = \frac{2\pi kL(T_1 - T_2)}{\ln(r_o/r_i)} = 2\pi r_i L h_i(T_h - T_1) \qquad \text{[Eq A4]}$$

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where T_h = temperature of the hot fluid
T_c = temperature of the cold fluid
T_1 = temperature of the hot side of the tube wall
T_2 = temperature of the cold side of the tube wall
h_o = convective heat transfer coefficient on the hot side of the tube wall
h_i = convective heat transfer coefficient on the cold side of the tube wall
L = length of tube
r_o = outer radius of tube
r_i = inner radius of tube
k = thermal conductivity of tube material.

As above, this equation can be simplified as:

$$Q = A_oU_o * (T_h - T_c) = A_iU_i * (T_h - T_c)$$ [Eq A5]

where

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{r_o}{k} \ln(\frac{r_o}{r_i}) + (\frac{r_o}{r_i}) \frac{1}{h_i}$$ [Eq A6]

and

$$\frac{1}{U_i} = (\frac{r_i}{r_o}) \frac{1}{h_o} + \frac{r_i}{k} \ln(\frac{r_o}{r_i}) + \frac{1}{h_i}$$ [Eq A7]

U_o is the overall heat transfer coefficient based on the outside tube area; U_i is the overall heat transfer coefficient based on the inside tube area. Since from equation A5, $U_oA_o = U_iA_i = UA$, we may simplify the overall heat transfer equation. Thus, Eq A5 may be written as:

$$Q = UA(T_h - T_c)$$ [Eq A8]

The temperature of the hot and cold fluids varies along the length of the heat exchanger. A differential analysis of simple parallel and counterflow heat exchangers yields a mean value for the quantity $(T_h - T_c)$ in Eq 2. This mean value is called the Logarithmic Mean Temperature Difference (LMTD). The LMTD is given by:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln ([\Delta T_1]/[\Delta T_2])}$$ [Eq A9]

Delta T_1 and delta T_2 correspond to the end-point temperature differences in the exchanger. In a parallel flow exchanger, the temperature difference between the hot and cold fluids is initially large but decays rapidly along the length of the exchanger, approaching zero asymptotically. For the parallel flow heat exchanger:

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$$\Delta T_1 = T_{h,i} - T_{c,i} \qquad \text{[Eq A10]}$$

$$\Delta T_2 = T_{h,o} - T_{c,o} \qquad \text{[Eq A11]}$$

where $T_{c,o}$ =   temperature of the cold fluid at the outlet
         $T_{c,i}$ =   temperature of the cold fluid at the inlet
         $T_{h,o}$ =   temperature of the hot fluid at the outlet
         $T_{h,i}$ =   temperature of the hot fluid at the inlet.

In a counterflow heat exchanger:

$$\Delta T_1 = T_{h,i} - T_{c,o} \qquad \text{[Eq A12]}$$

$$\Delta T_2 = T_{h,o} - T_{c,i} \qquad \text{[Eq A13]}$$

In the steam-fed heat exchangers in this report, we can make the approximation that the temperature of the steam does not change significantly over the length of the exchanger; it merely condenses. Thus, $T_{h,i} = T_{h,o}$ and:

$$\text{LMTD} = \frac{T_{c,o} - T_{c,i}}{\ln \left(\dfrac{T_h - T_{c,i}}{T_h - T_{c,o}} \right)} \qquad \text{[Eq A14]}$$

Therefore, the expression for the total amount of heat transferred from the hot fluid to the cold fluid is:

$$Q/A = U * \frac{T_{c,o} - T_{c,i}}{\ln \left(\dfrac{T_h - T_{c,i}}{T_h - T_{c,o}} \right)} \qquad \text{[Eq A15]}$$

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APPENDIX B:

WATER CHEMISTRY DATA FOR ARMY INSTALLATIONS
SURVEYED

Water chemistry data from the installations at which the heat exchanger problem was investigated was obtained during the site visits. The temperature, pH, sulfide content, dissolved carbon dioxide content, and dissolved oxygen content were measured on site. Additional chemical composition data were determined in the laboratory from samples that were collected during the site visits. The Langelier Index is calculated from the chemical composition data using the method presented in Appendix C. Water chemistry data from Fort Lewis is presented in Table B1, data from Fort Benjamin Harrison is presented in Table B2, data from Fort Hood is presented in Table B3, and data from Fort Bragg is presented in Table B4.

Table B1

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	4.0
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.

Table B2

Fort Benjamin Harrison Distribution Water Chemistry
Data (Sampled at Bldg. 421)

Constituent/Property*	Cold Water	Hot Water
Temperature, °C	21	52
Dissolved carbon dioxide (CO_2)	21	37
Dissolved oxygen (O_2)	6	2
pH	6.9	7.1
Sulfide	0	0
Resistivity, ohm-cm	1450	
Chloride, as Cl	36	
Sulfate, as SO_4	45.6	
Alkalinity, as $CaCO_3$	279	
Total dissolved solids	429	
Hardness, as $CaCO_3$	123	
Calcium, as Ca	31.2	
Magnesium, as Mg	11	
Zinc, as Zn	0.20	
Iron, as Fe	0.50	
Copper, as Cu	<0.01	
Manganese, as Mn	<0.01	
Sodium, as Na	152	
Silica, as SiO_2	10	
Langelier index	-0.82	+0.2

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* All units are milligrams per liter (mg/l) unless otherwise noted.

Table B3

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.

Table B4

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.

APPENDIX C:

THE LANGELIER SATURATION INDEX

The Langelier saturation index (or calcium carbonate saturation index) is frequently used to determine whether water has the tendency to be scaling or nonscaling. A positive Langelier index indicates that water is oversaturated with respect to calcium carbonate and that it has the tendency to form scale. A negative Langelier index indicates that the water is undersaturated with calcium carbonate and that it does not tend to deposit scale. A negative Langelier index may (but does not always) indicate that water is corrosive. A Langelier index of zero indicates that the water is at equilibrium with respect to calcium carbonate and should neither deposit scale nor be corrosive. The Langelier index is calculated as follows:

$$L.I. = pH - pH_s \qquad [Eq\ C1]$$

where pH = the actual pH of the water
pH_s = calcium carbonate saturation pH

The calcium carbonate saturation pH, pH_s, is calculated as follows:

$$pH_s = A + B - \log(Ca) - \log(Alkalinity) \qquad [Eq\ C2]$$

where A = constant based on water temperature
B = constant based on total dissolved solids concentration
Ca = concentration of calcium as $CaCO_3$ in mg/l
Alkalinity = alkalinity as $CaCO_3$ in mg/l.

The constants A and B are given in Table B1.

APPENDIX D:

COST OF ENERGY LOSS FROM WATER STORAGE HEATER
TANK DRAINDOWN

It was established in Chapter 7 that the only energy cost due to heat exchanger fouling that will be considered in the cost analysis is the cost of draining down the storage tank. This includes the cost of the energy lost from the water drained out of the tank, the energy needed to reheat the tank metal from room temperature to operating temperature, and the energy needed to heat the new water in the tank. The calculation of the cost of energy loss can be made, dependent on the following definitions and assumptions.

The terms used in the calculations are defined as:

1. Q_1 = energy lost from water drained out of tank

2. Q_2 = energy to reheat tank metal from ambient temperature

3. Q_3 = energy to heat new water

4. Q_T = total energy lost per draindown

5. T_c = temperature of entering cold water

6. T_h = temperature of exiting hot water

7. T_a = ambient temperature.

The assumptions required for the calculations are:

1. Tank capacity = 1000 gal

2. Tank is made of steel and weighs 20,000 lb

3. $T_c = 50 \,°F$

4. $T_h = 140 \,°F$

5. $T_a = 70 \,°F$

6. Fuel costs $0.50 per therm

7. Boiler and steam transmission system is 65 percent efficient.

Calculation:

$$Q_1 = mc_{H2O}(T_h - T_c)$$
$$= 1000 \text{ gal} * 8.31 \text{ lb/gal} * 1 \text{ Btu/lb-°F} * (140\text{-}50)$$
$$= 747900 \text{ Btu}$$

$$\text{Cost } (Q_1) = (747000 \text{ Btu})/(100000 \text{ Btu/therm}) * \$0.50/\text{therm}$$
$$= \$3.74$$

$$Q_2 = mc_{steel}(T_h - T_a)$$
$$= 20000 \text{ lb} * 0.12 \text{ Btu/lb-F} * (140\text{-}70)$$
$$= 168,000 \text{ Btu}$$

$$\text{Cost } (Q_2) = \$0.84$$

$$Q_3 = Q_1$$

$$Q_T = \text{Cost } (Q_1 + Q_2 + Q_3)/\text{Efficiency}$$
$$= (3.74 + 0.84 + 3.74)/0.65$$
$$= \$12.80 \text{ per 1000 gal draindown}$$

APPENDIX E:

COST OF HEAT EXCHANGER FOULING AT FORT LEWIS, WASHINGTON

Fort Lewis has four kinds of hot water facilities (Table E1).

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

   - 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.

   - From IFS: Base direct labor rate: $15.25 per hour (including overhead and material burden); Hours spent on heat exchanger repairs: 1069

   - From DEH Personnel: New tube bundle costs: $1400

     Total annual direct labor cost = $15.25 * 1069 hrs = $16,302

     Direct materials cost = 8 replacements * $1400 = $11,200

2. Associated losses:

     Tank draindown: $12.80 per action * 40 actions = $580

3. Operations and maintenance: From DEH Personnel: 1 hr per job to order/inspect/specify exchangers

     40 jobs * 1 hr * $15.25/hr = $610

4. Downtime: the downtime calculation depends on the following assumptions:

- Since average repair takes about 6 hours (acco. :ng to DEH personnel), assume that soldiers in that building will be inconvenienced for one 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 1/2 hour per repair to go to alternate facilities

1/2 hr * $8.00/hr * 40 jobs * 200 soldiers = $32,000

5. Total cost:

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

Table E1

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

APPENDIX F:

COST OF HEAT EXCHANGER FOULING AT FORT HOOD, TEXAS

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 is a total of 12 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:

1. Direct costs (dining halls)

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

    - From DEH personnel: Average repair action takes 11 hours (2 workers); new tube bundle costs $1700; capacity of tanks = 2115 gallons

    Direct labor cost = $17.06 * 2 workers * 11 hrs * 12 repairs = $4504

    Direct materials cost = 1 replacement * $1700 = $1700

2. Associated losses (dining halls)

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

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.

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 tabulations of data supplied by DEH personnel, the remaining 112 heat exchangers are removed and cleaned an average of once every 2.25 years. 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 hours; (2 workers); new tube bundle costs $1700; average tank capacity = 1155 gal

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Direct labor cost = $17.06 * 2 workers * 6 hrs * 52 repairs = $10,645

Direct materials cost = 5 replacements * $1700 = $8500

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

Tank draindown: $12.80 per 1000 gal * 1.155 * 52 actions = $769

Acid disposal: $12.00 per action * 52 actions = $624

3. Operations and maintenance (all other steam-fed exchangers): From DEH personnel: 3 hrs per replacement to order/specify/inspect exchangers

5 replacements * $17.06/hr * 3 hrs = $256

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

- Since average repair takes about 6 hours (according to DEH personnel), assume that soldiers in that building will be inconvenienced for one day. "Inconvenienced" means that they will have to find alternate facilities at which to bathe and/or do laundry.

- A barracks houses 125 soldiers.

- The troop loses 1/2 hour per repair to go to alternate facilities.

1/2 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

6. Fort Hood total: $46,794 + 10,129 = $56,923

APPENDIX G:

COST OF HEAT EXCHANGER FOULING AT FORT BENJAMIN HARRISON, INDIANA

Heat Exchanger Inventory

There are 53 potable hot water heat exchangers in 10 buildings.

Average Annual Number of Repair Actions

According to DEH personnel, there are 12 repair actions per year. (Table G1).

Table G1

Fort Harrison Heat Exchanger Repairs

Type	Number	Time Required
Replacement	4	15 hr
Shop repair	4	8 hr
Close tube and replace	4	3 hr
Total	12	104 hr

1. Direct costs:

   • From EPS standards: Labor rate = $19.16/hr

   • From DEH personnel: New tube bundle costs $2600.

   Direct labor cost = $19.16/hr * 2 workers * 104 hrs. = $3985

   Material cost = $2600 * 4 replacements = $10,400

2. Associated losses:

   Tank draindown: $12.80 * 12 actions = $154

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3. Operations and maintenance: (From DEH personnel) It takes about 1 hr per repair action to order/specify/inspect, etc.

$$1 \text{ hr} * \$19.16/\text{hr} * 12 \text{ actions} = \$230$$

4. Downtime: The downtime calculation depends on the follow assumptions:

- Since average repair takes about 8 to 9 hr, assume that soldiers in that building will be inconvenienced for one day (they will have to find alternate facilities at which to bathe and/or do laundry).

- A barracks houses 100 soldiers.

- The troop loses 1/2 hr per repair to go to alternate facilities.

$$1/2 \text{ hr} * 100 \text{ soldiers} * \$8/\text{hr} * 12 \text{ repairs} = \$4800$$

5. Total cost:

Labor	$ 3,985
Materials	10,400
Associated Losses	154
Operations/Maintenance	230
Downtime	4,800
Total	$ 19,569

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