THE EFFECT OF HARD-WATER SCALE BUILDUP ON WATER HEATER LIFE-CYCLE EFFICIENCY*

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ABSTRACT

The buildup of hard-water scale in water heaters may lead to reduced heat efficiency and may also shorten the heat service life. In the design of advanced gas-fired water heaters it is important to understand the scale-forming mechanism and how scale affects heater performance and life.

This paper describes a 3-year research program being conducted for the Gas Research Institute (GRI) to quantify the effect of scale buildup on the performance of residential water heaters, and to determine the benefits and limitations of common water treatment methods. In this program, the performance of water heaters is being monitored in test laboratories in four cities that have scale forming water supplies. These tests will monitor the efficiency of heaters operating on hard water as scale builds up in the heaters and compare the performance with heaters operating on treated water. Measurements will also be conducted to determine if the water treatment has an adverse effect on corrosion of the water heating system.

During the first year of this program, 10 heaters have been operated on various types of water for the equivalent of 1-year of use in a typical residence. The heaters operating on untreated hard water accumulated up to 5.8 pounds of scale. Heaters operating on soft water accumulated an insignificant amount of scale. Efficiency measurements indicate no measurable difference in performance thus far in these tests. Accelerated testing over the next 2 years will simulate 10 to 15 years of normal heater use, during which time the heater efficiency will be monitored and corrosion tests will be completed.

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INTRODUCTION

Residential water-heater efficiency and service life can be affected by the characteristics of the water supplied to the heater. The heating of hard water, water containing high concentrations of calcium and magnesium, generally causes scale deposits to build up in the heater. Scale deposits on the heat transfer surfaces act as a barrier to the flow of heat into the water, resulting in higher heating surface temperatures. The elevated surface temperatures can reduce the thermal efficiency of the unit, and can also accelerate the gas-side oxidation of the heat transfer surfaces, shortening heater life.

In many hard-water areas, water-heater owners install water softeners. Although a softener does effectively eliminate scale buildup in the heater, there is some concern by water-heater manufacturers that softening the water may increase its corrosivity, thus reducing the service life of the water heater.

Battelle-Columbus Laboratories (Battelle) is conducting a 3-year field test for the Gas Research Institute (GRI) to quantify the effect of scale buildup in residential water heaters, and to determine the benefits and limitations of common water treatment methods. Battelle will be monitoring the performance of gas and electric water heaters under controlled laboratory conditions in several U.S. cities. The selection of the test locations was largely based on the scale forming tendency of the local water supply.

The objectives of the project are to characterize the efficiency degradation of residential gas and electric water heaters in terms of the water quality, and to assess the benefit of on-site water treatment for reducing the effects of scale buildup. This project is intended to provide the basis for identifying methods of maintaining the original thermal efficiency over the life of the heater, and to provide background information for the design of advanced water heaters using new concepts of combustion and heat transfer.

A more detailed report on the results of the first year of this project is presented in Reference 1.

RESEARCH APPROACH

The method used in most of the earlier studies[2,3,4,5*] to determine the effect of scale buildup on heater performance has been to make efficiency measurements on old water heaters. Although this technique has some merit, there is a definite lack of experimental control, which leads to a large variability in the results. For example, the characteristics of the water processed by the heater may have varied considerably over the life of the

*Numbers refer to References at the end of this report.

heater. The thermostat setting may have drifted, or may have been changed from time to time. These factors could affect the type and quantity of scale buildup in the heaters.

Old water heaters may have also experienced some change in burner performance due to corrosion of the burner, or damage to the flue passages. These changes may affect the heater efficiency.

In order to circumvent these problems, we have designed a carefully controlled testing program to characterize the degradation in thermal efficiency of residential water heaters due to scale buildup. In these tests, new heaters will be operated under controlled conditions for up to 2 years in several U.S. cities having highly scaling water supplies. Some heaters will be operated on untreated hard water, others on treated water. The tests will utilize accelerated draw cycles to simulate from 10 to 15 years of performance during the 2-year tests. The tests will include both gas and electric heaters.

The performance of each heater will be monitored throughout the period of the tests. The cold-start recovery efficiency of each heater will be carefully measured three or four times per year. These efficiency measurements will provide the basis for determining the efficiency degradation due to scale buildup, and the results will be compared with the heater operating characteristics and the amount of scale buildup in the heaters.

In addition to the water-heater tests, a study of the scale-forming characteristics of each of the water supplies will be conducted. Using a scaling-rate reference cell designed to simulate the heating action of a water heater, the scaling rate of the hard water will be determined. An analysis of the scale from each test site will be obtained, and the results compared with the water analysis and the scaling rate.

A two-phase research plan has been developed by Battelle to carry out the objectives of this project. Phase I, completed in May, 1983, involved the preliminary investigation of scaling in water heaters and its effect on heater performance. During Phase I, Battelle developed and verified the techniques that will be used to monitor scaling and heater performance in the long-term field tests of Phase II. In Phase II, field-test facilities will be set up in several U.S. cities and the heaters will be operated and monitored over a 2-year period.

DISCUSSION OF RESULTS

Selection of Field Test Locations

In the selection of locations for the water heater tests, it is necessary to identify field sites where the water is sure to deposit at least a moderate amount of scale in heaters. Furthermore, it is desirable to have a wide variety of water characteristics among the chosen field sites. To accomplish the selection, water quality data for a large number of U.S. cities was obtained from local records or by direct phone contact. The Ryznar Index[6], a stability index based on the pH, the total dissolved solids, and the water temperature, was calculated for each water supply. The cities were then catagorized by Ryznar Index into scaling ranges of: (1) severely scaling, (2) heavily scaling, (3) moderately scaling, and (4) nonscaling.

The primary criterion for selection of a test site was that its water exhibit a sufficient degree of scaling to produce a significant amount of scale during the field test program. The degree of scaling was judged by the Ryznar Index.

Several secondary selection criteria were also applied after the cities had been allocated among the three scaling categories. These criteria assured that each scaling range exhibited a balance of other characteristics considered important to siting:

- Individual water quality parameters included in the Ryznar Index plus iron
- Accessibility to major air or highway transportation routes to maximize field crew efficiency
- Approximately equal average population and as broad a distribution of populations as possible
- A dispersed geographical distribution subject to regional water quality conditions that preclude scale buildup.

A list of the test sites selected for the long term tests is presented in Table I along with the major water quality parameters for each site. A more detailed description of the water quality is given in Reference 1.

Development of a Scale Buildup Measurement Technique

The development of an experimental method of monitoring the scaling rates of various water supplies was undertaken. The objective was to obtain a reproducible direct measure of the scaling tendencies of the various water streams feeding the test water heaters, to correlate the determined scaling rates with water-scaling indices such as the Ryznar Index, and to use the results to elucidate the scaling behavior observed in the test water heaters.

TABLE I. Water quality parameters for the selected water heater test sites.

Site	City	Hardness Grains	pH	Ryznar Index	Iron mg/l	Silica
Battelle's Columbus Laboratory	Columbus, Ohio	43	7.4	4.62	0.1	2.7
Water Quality Association	Lisle, Illinois	25	7.1	5.19	0.3	6.4
Roswell Test Facility	Roswell, New Mexico	28	7.2	5.20	0.0	4.2
Marshall Municipal Utilities	Marshall, Minnesota	48	7.1	5.34	0.1	13.2

To achieve these objectives a scale buildup measurement cell was designed and constructed which resembles a miniature water heater. In this unit, water passes upward through a 1-inch ID Pyrex pipe around an axially positioned, 3/8-inch OD silica tube. The silica tube was heated by an internal electrical resistance heating coil. This tube was the substrate on which scale deposition occurs. Electrical power input to the coil, up to 600 watts, was controlled with a variable transformer.

Temperature of the heated, effluent water was monitored with a thermocouple immersed in a copper well near the top of the water column. The flow of water was controlled by a needle valve in the exit line at the top of the unit. Thus, the water in the reference cell was kept under supply line pressure, about 40 psig, which precluded boiling. Temperature of the effluent water was controlled by adjusting the electrical power input and the water flow rate relative to one another. In the experiments for which data are reported, a fixed water flow rate was used and power input was adjusted to give the desired outlet water temperature. Hence the variables were heater surface temperature, heat flux, water temperature, and time.

Run times were in the range 2 to 50 hours for experiments to date, and were varied with the rates of scaling. Runs were terminated when scale deposits reached apparently weighable proportions and before the deposits attained thicknesses sufficient to result in the sloughing off of portions of the deposits. The amount of scale was determined by removing the substrate from the reference cell, oven drying it at 230 F, and weighing it before and after removal of the scale. As a cross check, the scraped-off scale was collected and weighed separately.

The scale-buildup measurement cell has operated very satisfactorily and can be used to rapidly investigate ranges of water-heater operating conditions, while providing for direct observation of the results. In addition, if operated with standard power input, water flow rate, and effluent water temperature, the unit can be used to make standard determinations of the scaling tendencies of various waters.

Using the device and procedures just described, experiments were run at three temperatures with untreated (Battelle Well No. 1) water, 140, 160, 180 F, and at 160 F with phosphate-treated water. The results of these experiments showed a strong increase in scale buildup rate as the temperatures increased from 140 to 180 F. Adding polyphosphate to the hard water (5 to 10 ppm) significantly reduced the scale buildup in this test device. The increase in scale buildup rate as the bulk water temperature increases is in agreement with data reported by J. M. Krappe.[2]

Laboratory Investigation of Water-Heater Scaling

Description of Water-Heater Testing Facility. A water-heater testing facility was constructed at Battelle in order to conduct preliminary, short-term tests of heater performance when operating on hard water. The overall objective of the short-term tests was to find a satisfactory method of measuring the degradation in operating efficiency due to scale buildup within the heaters. The operation of this facility provided an opportunity to develop accurate and efficient testing procedures, and to establish an effective experimental approach for the long-term tests to be conducted in several U.S. cities.

A photograph of the Battelle water-heater laboratory is presented in Figure 1, showing the gas-fired residential water heaters on the left and the electric water heaters on the right. The heaters can be connected to one of four water supply lines: hard well water (from Battelle Well No. 1), softened water, polyphosphate-treated water, and soft water that is subsequently treated with polyphosphate.

Each heater was connected to a 1-1/4-inch PVC water supply manifold and to a common 2-inch PVC drain line. A water meter was installed in each heater supply line. The flow out of the heater is controlled by a solenoid valve in series with a flow orifice. The solenoid valve is actuated by a timer that was set to open the valve for a certain time period at selected times during the day. The flow orifice was sized to 0.16 inches diameter to produce 3 gallons per minute flow rate out of the heater while maintaining approximately 40 psig water pressure in the heater.

Each heater also has an individual gas or electric meter to monitor energy consumption. Btu meters were installed to monitor the energy in the heated water from the heaters.

Water-Heater Selection for Testing. Typical residential water heaters were selected for this testing program, and both gas and electric units were included. The gas heaters have a 40 gallon tank with a 40,000 Btu/hr gas input rate. A 3-inch center flue was used rather than a standard 4-inch flue to achieve a higher energy flux density.

The electric heaters have a 52 gallon tank with a single high watt density 5500 watt electrical heating element. Other heater specifications were selected to be representative of the most popular residential water heaters.

Scale Buildup in Test Heaters. The ten test heaters were operated in the Battelle water heater laboratory for up to 4 months. The water throughput and operating characteristics of the heaters is presented in Table II. At the end of the tests, the heaters were drained and the viewing ports were opened for photographs of the scale deposits. The tanks were then carefully cleaned out and the scale deposits from each heater were collected, dryed, and weighed. The weight of scale removed from each tank is presented in Table II.

Photographs of six of the tested heaters are presented in Figures 2 and 3. The hard-water heaters (G-2, E-2) and the soft-water heaters (G-5, E-5) have heated in excess of 26,000 gallons of water, slightly over 1 year of typical residential use for an average family (i.e., 23,400 gal.). The phosphate heaters have heated more than 18,000 gallons, slightly less than 1 year of typical residential use.

The buildup of scale in the hard-water heaters is obviously much greater than in either the soft-water heaters or the polyphosphate-treated-water heaters. The differences in the way scale forms in gas and electric heaters can be seen by comparing the hard-water gas heater with the hard-water electric heater. The large flakes generated in the gas heater are contrasted with the granular nature of the scale in the electric heater.

The scale-buildup data for the hard-water heaters are compared with the heaters operating on treated water in Figure 4. The data are determined by

Figure 1. GRI water-heater laboratory at Battelle-Columbus.

Table II. Scale buildup in water heaters.

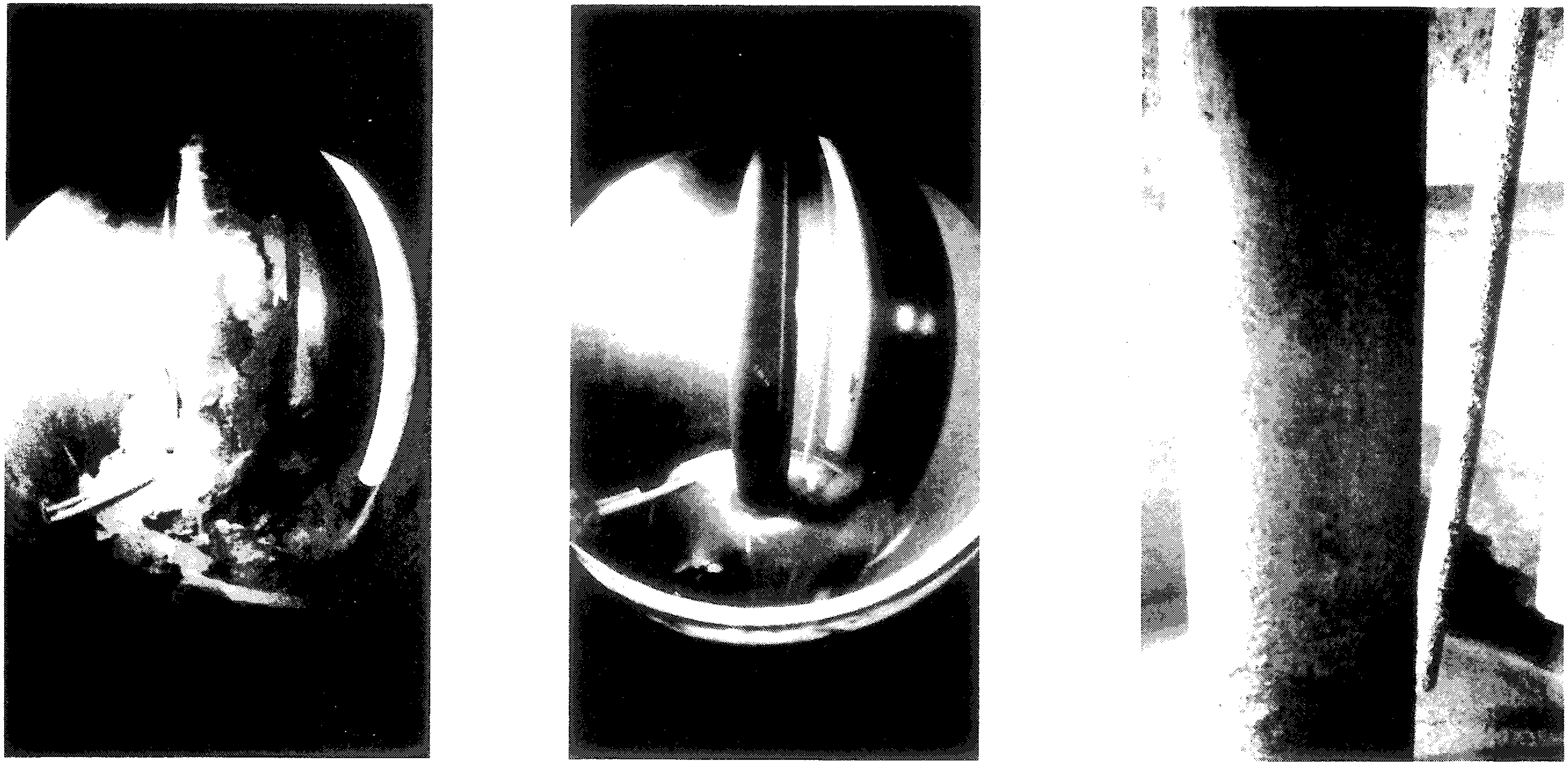
Sample	Heater(1) No.	Date Sample Removed	Water Thru-put, gal.	Water Type	Thermostat Shut off F	Outlet Water Temperature F	Weight of Scale, lb	Weight of TDS in Raw Water, lb(2)	Percent of TDS Deposited in Heater, %
1	G-1	5/10/83	6,800	Raw	136	136	0.11	39.8	0.28
2	E-1	5/10/83	7,000	Raw	135	135	0.77	41.0	1.88
3	G-2	5/10/83	31,400	Raw	158	175(3)	5.82	184.0	3.16
4	E-2	5/9/83	28,700	Raw	146(154)(4)	146(154)(4)	2.95	168.1	1.75
5	G-3	5/11/83	6,100	Raw	156	156	0.03	35.7	0.07
6	E-3	5/9/83	6,200	Raw	150	150	1.75	36.3	4.81
7	G-5	5/10/83	27,300	Soft	156	166(3)	0.03	160.0	0.02
8	E-5	5/9/83	26,100	Soft	156	156	0.06	152.9	0.04
9	G-8	5/10/83	22,600	Phosphate	158	172(3)	0.03	132.4	0.02
10	E-8	5/9/83	18,700	Phosphate	156	156	0.95	109.6	0.86

(1) G-1, Gas Heater No. 1
E-1, Electric Heater No. 1

(2) Total Hardness (as $CaCo_3$) in raw water = 41 grains/gal = 0.00586 lb/gal.

(3) These heaters exhibited a significant amount of stratification during operation.

(4) The thermostat on this heater was changed resulting in a high operating temperature during the last 1/4 of the test period.

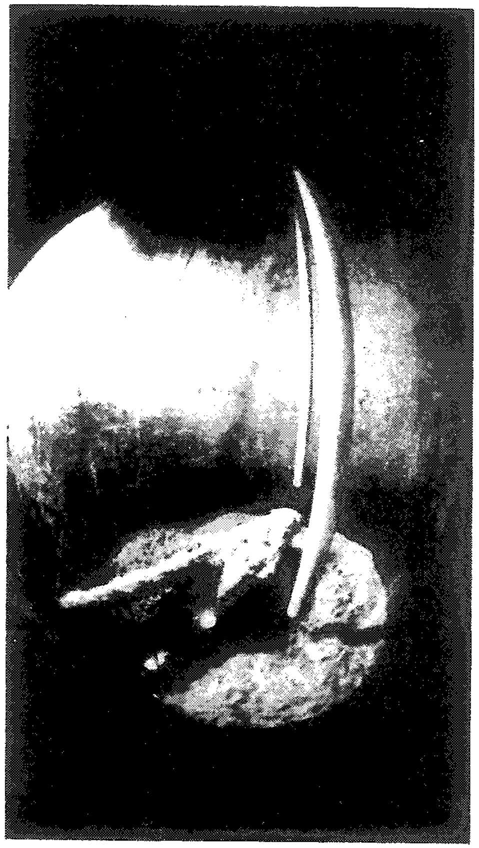


HEATER G-2
42 GRAIN HARD WATER
31,000 GAL THROUGHPUT
175 F OUTLET TEMP

HEATER G-5
SOFTENED WATER
27,000 GAL THROUGHPUT
166 F OUTLET TEMP

HEATER G-8
PHOSPHATE TREATED WATER
23,000 GAL THROUGHPUT
172 F OUTLET TEMP

Figure 2. Photographs of scale buildup in gas-fired water heaters.



HEATER E-2
42 GRAIN HARD WATER
29,000 GAL THROUGHPUT
150 F OUTLET TEMP

HEATER E-5
SOFTENED WATER
26,000 GAL THROUGHPUT
156 F OUTLET TEMP

HEATER E-8
PHOSPHATE TREATED WATER
19,000 GAL THROUGHPUT
156 F OUTLET TEMP

Figure 3. Photographs of builup in electric water heaters.

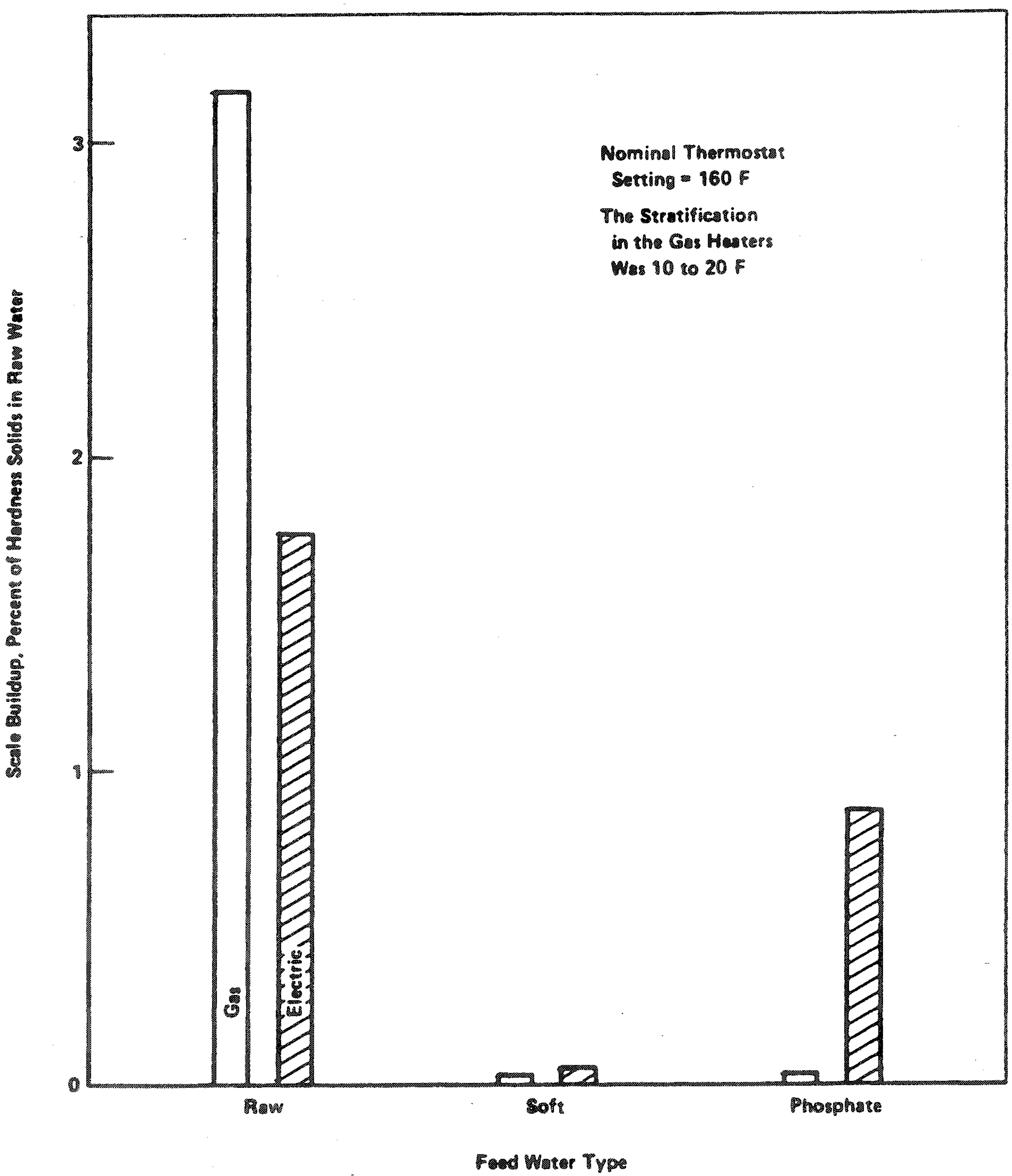


Figure 4. Scale buildup in water heaters tested at Battelle.

dividing the scale weight by the calcium and magnesium hardness in the hard water (41 grains/gallon as $CaCO_3$) times the total water throughput. The results are given in percent.

The scale deposits in the heaters operating on softened water and the gas heater operating on phosphate-treated water were very slight. The electric heater operating on phosphate-treated water generated approximately one-half the amount of scale deposited in the hard-water electric heater.

The phosphate treatment is effective in suppressing scale formation at temperatures below a certain threshold temperature. At the threshold temperature the polyphosphates break down into orthophosphate which is ineffective in suppressing scale formation. The high density heating element used in the present tests is apparently generating water temperatures in excess of the threshold temperature, thus reducing the effectiveness of the phosphate treatment in the electric heater.

Water-Heater Scale Analysis. The scale removed from each water heater was analyzed in order to determine the major components of the scale, and to determine the effect of water treatment on scale composition.

The results indicate that the major constituent of the hard-water scale is calcium carbonate. The soft-water scale is mostly aluminum and very little calcium carbonate (the water heaters tested contained an aluminum anode).

The water heaters operating on phosphate treated water contain scale that is approximately 80 percent calcium carbonate and 20 percent phosphorus. The other constituents are similar in percentage to the hard-water scale.

A comparison between the gas and electric heaters shows a consistently higher level of sulfate and silica in the electric heater scale. Since both sulfate and silica are expected to precipitate at a relatively higher rate as the water temperature increases, these results support the proposition that the scale formation in the electric heater occurs at a higher temperature than in the gas heater.

Water-Heater Recovery Efficiency Measurements. The cold-start recovery efficiency of five gas and five electric heaters was monitored during 4 months of accelerated operation. One pair of heaters operating on hard water heated more than 30,000 gallons of water during this period. As shown in Table II, the gas heater accumulated 5.8 lb of scale and the electric heater accumulated 2.9 lb of scale. Neither heater showed a degradation in thermal recovery efficiency during the testing period. The buildup of scale in these heaters was apparently not sufficient to affect thermal performance.

The cold-start recovery efficiency of the gas heaters was typically 70 percent, and for the electric heaters was 97 percent.

Operating Efficiency Determination Using Btu Meters. Btu meters were used to monitor the operating efficiency of a gas and an electric water heater during cyclic operation. The overall operating efficiency was determined by dividing the total Btu output by the total energy input as recorded by the gas or electric meter.

Although a large amount of scale had collected in both heaters, the operating efficiency remained relatively constant. During the test period, scale buildup around the electric heaters caused three elements to burn out. Each burnout occurred after a throughput of approximately 7000 gallons of hard water.

The operating efficiency of the gas heaters was typically 65 percent, and for the electric heaters was 93 percent. The operating efficiency is lower than the recovery efficiency because the operating efficiency includes the standby losses between draw cycles.

In a typical residence using only 64 gallons of hot water per day, the standby losses would further reduce the operating or service efficiency. The estimated operating efficiency for these heaters operating in a typical residence is 60 percent for gas and 87 percent for electric.

It should be noted that the Btu meter method of calculating operating efficiency reflects a hot start recovery efficiency, whereas the DOE method uses cold start recovery efficiency and measured standby losses to estimate the service efficiency based on a hot water usage rate of 64.3 gallons per day.

Several reasons are postulated as to why no appreciable changes had occurred in the efficiency of these heaters due to scale buildup. In the gas heater, the scale on the center flue pipe of the gas heater appears to continually flake off and collect in the bottom of the heater. This keeps the heating effectiveness of the flue pipe relatively high. A slight degradation in heating efficiency through the bottom dome surface will be offset by higher temperature flue products entering the flue pipe, and correspondingly higher heat transfer rates through the flue pipe section. Also, calculations indicate that a very large thickness of scale would have to collect before appreciable changes in heating efficiency would occur.

In the electric heater, the main change that occurs as scale builds up around the heating element is that the element operates at a higher temperature. Eventually the element reaches the sheath melting temperature, causing the heating element to burn out. However, the overall heating efficiency of the element appears to remains fairly constant during its lifetime.

CONCLUSIONS

1. The buildup of scale in water heaters operating on hard water has been reported[2] to be dependent on temperature, increasing rapidly as the temperature increases above 100 F. This result has been confirmed in the present tests.

2. The scale accumulation in water heaters was found mainly on the high temperature heated surfaces: the flue and bottom plate in gas heaters and the electric heating element in electric heaters.

3. Small amounts of scale accumulation in water heaters (less than 10 lbs) appears to have a negligible effect on heater performance.

4. Scale buildup in an electric water heater causes the heating element to burn out. The copper sheathed, high density heating elements regularly failed after heating approximately 7000 gallons of 41 grain hard water.

5. The method found to be most effective for monitoring scale buildup in water heaters is by direct observation through view ports in the tank wall, and removal of the scale for drying and weighing.

6. Water heaters operating on softened water experienced only about 1 percent of the scale buildup experienced by an identical heater operating on hard water.

7. Treating hard water with polyphosphate was found to be as effective as water softening in reducing scale in the gas heaters tested.

8. In an electric heater with a high watt density heating element, the effect of the polyphosphate treatment was to reduce the amount of scale buildup to approximately half that experienced by an identical heater operating on hard water. No element burnout was experienced.

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