ENERGY

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ORNL/Sub-7321/5

Examination and Life Assessment of Field-Tested Heat Pump Water Heaters

December 1982

Prepared by
ENERGY UTILIZATION SYSTEMS, INC.
for
OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the

U. S. DEPARTMENT OF ENERGY

OFFICE OF BUILDINGS ENERGY
RESEARCH AND DEVELOPMENT

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A05 Microfiche A01

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ORNL/Sub-7321/5
Dist. Category UC-95d

EXAMINATION AND LIFE ASSESSMENT OF FIELD-TESTED HEAT PUMP WATER HEATERS

December 1982

Principal Investigators:

William P. Bernardi
Robert P. Blevins
Barry D. Sloane

Report Prepared by

ENERGY UTILIZATION SYSTEMS, INCORPORATED
201 Seco Road
Monroeville, Pennsylvania 15146

Under

Subcontract 7321

for

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. W-7405-eng-26

ABSTRACT

Energy Utilization Systems, Inc. (EUS) has developed an electric heat pump water heater (HPWH) for domestic use. This device is interchangeable with conventional electric or oil-fired water heaters but significantly reduces energy consumption. Using air conditioning technology, the HPWH removes heat from the surrounding air and rejects the heat to its integral water tank. Design, development, and an 85-unit field demonstration of the HPWH were sponsored by the U. S. Department of Energy through the Oak Ridge National Laboratory under contract number 7321. This report presents the results of destructive examination of 20 units which had operated for two years. Life expectancy and the need for redesign are evaluated based on the observations.

FOREWORD

This report is the fifth and final volume in a series of reports documenting the results of work performed by Energy Utilization Systems, Inc. (EUS) under a program sponsored by the Community Systems Division of the United States Department of Energy through the Oak Ridge National Laboratory. The program has accomplished its main objectives which are the design, development, field demonstration, examination, and life assessment of an energy-saving heat pump water heater. As a result of the work described in these volumes, the heat pump water heater has been successfully commercialized by EUS and has already saved millions of kilowatthours of electric energy. With over fifteen manufacturers now marketing them, HPWHs have become a viable energy-saving consumer appliance.

EUS gratefully acknowledges the cooperation of all those involved including the electric utility personnel, other water heater manufacturers, and DOE and ORNL personnel. Special recognition is due to Virgil O. Haynes, the program manager at ORNL, for his guidance throughout this project and to William P. Levins of ORNL for his many valuable technical contributions.

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EXECUTIVE SUMMARY

This report presents the results of the final task of the heat pump water heater development project conducted by Energy Utilization Systems, Inc. This effort was sponsored by the Buildings Equipment Division of the United States Department of Energy through the Oak Ridge National Laboratory.

The project consisted of two phases. Under Phase I the heat pump water heater was designed and engineered; under Phase II it was built and field-tested. This report documents the results of examining a sample of Phase II field-tested integral heat pump water heaters. This final task is known as Phase IIA.

Purpose

Phase IIA of the project aimed at predicting the expected useful life of the heat pump water heater and at identifying any recommended design modifications. To accomplish this aim, 20 field-tested units with approximately two years of service were selected, disassembled, examined, and analyzed. In the course of these destructive tests, all components with a potential for impacting on performance and useful life were scrutinized. Particular attention was given to performance of major components -- the compressor, the tank, the anode, and the condenser. Examination results then formed the basis for assessing unit reliability and recommending design changes to prolong service life.

Results

Examinations support the overall reliability of the heat pump water heater and its major components. Based on operational performance data and subsequent analyses, the following observations and conclusions were made.

- No performance degradation was evident after an average of 25 months of service.

- None of the compressors showed significant wear or signs of premature failure attributable to normal service. Based on this component's performance, the manufacturer (Copeland Corporation) considers a 10-year compressor-life expectancy to be realistic.

- No noticeable performance degradation resulted from scale accumulation on condenser surfaces. Although scale deposits were found on 19 of the 20 condensers, heat transfer capabilities were not affected.

- No performance degradation resulted from dirt accumulations on evaporator fin surfaces. Even 20% airflow blockage had no noticeable effect on performance.

- None of the 20 tanks showed any significant corrosion. Twelve tanks were rust-free. Eight tanks were spot-rusted where the glass lining was either chipped (at inlet and outlet openings) or imperfect. Rust penetration was not measurable.

- A strong correlation was found between the use of water softeners and tank rust-magnesium anode depletion. Of the seven test sites using water softeners, six tanks had rust and five had completely depleted anodes (the other two anodes were severely depleted). With non-softened water, tank life expectancy was estimated to equal that of a conventional water heater (5-10 years).

Design Recommendations

The most significant design recommendation addresses the problem of accelerated anode depletion and tank rusting resulting from the use of water softeners. Length of anode protection may be extended by replacing the sacrificial magnesium anode with a non-depleting, electric-powered anode.

The only other design modification recommended is the addition of an air filter for units installed in dusty or dirty environments. A filter would reduce evaporator clogging which could eventually affect evaporator performance. The filter would, of course, require periodic maintenance.

The modifications identified should sustain continued commercialization of the heat pump water heater as a viable energy-saving alternative to conventional water heaters. The incorporation of these design changes should allow the expected life of the heat pump water heater to reach or exceed 10 years.

1 BACKGROUND AND OBJECTIVES

This report details the results of the final task of the heat pump water heater development effort carried out by Energy Utilization Systems, Inc. (EUS). The work has been conducted under the sponsorship of the Building Equipment Division of the United States Department of Energy (DOE) through the Oak Ridge National Laboratory (ORNL).

A heat pump water heater (HPWH) is a device which operates on an electrically-driven vapor-compression cycle and pumps energy from the air in its surroundings to water in a storage tank, thus raising the temperature of the water. Its primary advantage is a significant increase in point-of-use operating efficiency over alternative electric water-heating systems.

Phase I, completed in August 1978, covered the initial development of the HPWH, including conceptual design and engineering. Two types of residential HPWHs were developed under this phase: an integral unit with a self-contained water tank and a retrofit unit for installation on existing water heater tanks. Two project reports issued under this phase {1 and 2} detailed the early research and development efforts.

Phase II of this project involved field demonstration of the HPWH. The demonstration was designed to test the operating efficiency and reliability of the device by subjecting the system to a wide range of actual user environments. Under Phase II a pilot-run facility was designed and constructed {3} to assemble and test units. Eighty-five integral and 15 retrofit units were built, tested, and shipped to 20 electric utility companies that had agreed to participate in the field demonstration. These utilities arranged for installation of the prototype HPWHs in customers' homes and monitored the units' operation for one year. The 15 retrofits were removed from the test program early in the demonstration because of installation difficulties.

The field demonstration of the 85 integral units concluded at the end of December 1980. The field demonstration provided a total of 643 unit-months of operational data which showed an average coefficient of performance (COP) of 1.93. This COP translates into an average operating-cost savings of 48% compared to electric resistance water heating. The final demonstration report {4} was issued in June 1981.

Phase IIA, the final work phase, which is covered by this report, involved the selection, teardown, examination, and analysis of 20 of the field-tested HPWHs. This work was conducted to evaluate:

- The effects of long-term operation on the compressor system.
- The propensity for condenser fouling as a function of water quality and resulting impacts on performance.
- The effects and interactions of the tank, anode, and condenser as a function of varying water quality and resulting impacts on tank life.

Phase IIA was implemented to provide information on the expected useful life of the HPWHs and to identify any design modifications that would prolong unit life.

The expected useful life of a HPWH is an extremely important economic consideration. Although a HPWH offers significant daily energy savings, it costs more initially than conventional water heaters. To justify its purchase, the HPWH's useful life must be long enough both to recover the original investment (payback) and to provide an adequate return on investment. If, for example, a HPWH costs $800 more than a standard

water heater and saves the consumer $160 per year in operating costs, then the unit must last at least five years for the consumer to break even. The longer the unit lasts beyond the break-even point, the more attractive the investment option.

This report focuses on examinations conducted on 20 field-tested HPWHs to determine expected useful life. It describes the examination-testing methods used, the results, the conclusions, and the recommended design modifications.

2 METHODOLOGY

This section discusses the method used to examine heat pump water heater information from the field test data. Section 2.1 identifies the criteria used to select the sample units; Section 2.2 describes the disassembly procedures and the examination methods used; and Section 2.3 describes the data evaluation and correlation methods used.

2.1 UNIT SELECTION CRITERIA

Three selection criteria were used to determine which of the 85 integral heat pump water heater units represented the best sample for analysis. Early in the planning stage it was determined that the sample would consist of 20 units. As the first criterion, these units should represent exposures to diverse water qualities. Water quality was considered important because it impacts on both condenser scaling and tank degradation. As the second criterion, the units should not have been subjected to extremely adverse conditions that could distort any findings on compressor wear and life. As the third criterion, the units should have a good data history. Units having low-quality or inconsistent data would be excluded.

After these selection criteria were established, the operating histories of all 85 field demonstration units were reviewed. Available data on regional water hardness levels were also reviewed. As a result, 32 units were identified as being the best candidates for examination. Utility personnel were then contacted to obtain tentative participation approval from the candidate homeowners. Water-sample bottles and accompanying questionnaires forwarded to participating utilities were used to obtain water samples and related information from each of the 32 sites. The water-sample questionnaire appears in Appendix A.

A Pittsburgh, Pennsylvania, testing laboratory determined the hardness of each water sample (see Section 3). Test results were used to categorize units and to select the final 20 units to be analyzed. Water hardness was believed to be the major water quality variable affecting unit performance and longevity. Thus water hardness was used to determine which 20 of the 32 units warranted a more thorough (and costly) chemical analysis. The final 20 units selected were chosen to obtain an equal distribution across the hardness range encountered.

All candidate utilities were then contacted and advised of the final selection. In exchange for the field demonstration units, each participant was offered a new, warranted, freight-prepaid, factory-built HPWH. The homeowner and the utility were responsible for unit change-out, and the demonstration units were returned, freight-collect, to EUS. The 20 replacement units were shipped from the Johnson City, Tennessee, factory in August 1981. Most of the demonstration units were returned to EUS by November 1981, but the last unit was not received until February 1982. During the HPWH unit change-outs, the homeowners were requested to complete a brief participant questionnaire concerning drainage sludge, unit operational history, and owner comments. This questionnaire is also presented in Appendix A.

2.2 HEAT PUMP WATER HEATER DISASSEMBLY AND EXAMINATION METHODS

Examination involved three phases: general receipt inspection; detailed disassembly and examination of the heat pump water heater and components; and examination of compressor internals.

To ensure collecting consistently valid information for each returned unit, a standard inspection and teardown procedure was developed. An examination checklist covering all inspection and teardown steps was prepared and filled out for each unit as the work progressed. The compressor teardowns were performed following another standard procedure. Appendix B shows the general teardown procedure, the examination checklist, and the compressor teardown procedure.

Because the returned units had been carefully selected for their operating characteristics and external physical conditions, it was important that no significant damage was incurred during return shipment to the EUS laboratory. Therefore, as each HPWH arrived, the crate and unit were carefully examined. Any damage or mishandling was to be noted and photographed; however, no significant shipping damage was found. The units were then labeled with the name of the participating utility and the unit number.

The main portion of the examination comprised the actual inspections and disassembly of the units. The heat pump and tank operations were generally performed separately but, because the heat pump condenser is located inside the tank, the disassembly sequence required alternating work between the two assemblies.

The first set of operations involved inspecting, disconnecting, and removing the heat pump cabinet assembly from the condenser and tank. The inside of the cabinet was photographed before removal to record any unusual conditions of the components, the amount of dirt or rust, evidence of leaks, etc. After the cabinet was removed, the heat pump was disassembled and each component examined for signs of physical wear. Thermal expansion valve (TXV) bulb location and attachment were noted before removal. The evaporator was first examined for dirt accumulation and blockage. It was then removed and purged with dry nitrogen to determine whether any compressor oil had collected. Any oil found in the evaporator was collected, its volume measured, and then put into the compressor. Fan motors were checked for dirt and signs of overheating; fan blades were checked for dirt and loose hubs.

After the heat pump was removed, disassembly shifted to the tank. The electric resistance elements and the magnesium anode rod had to be removed so that the condenser could be removed without altering any scale or corrosion on these components. When possible, scale thickness on the resistance elements was measured. Condition of the anode was noted, and

the anode was weighed to measure remaining useful life. The resistance elements and anode were then labeled and photographed.

The condenser was then removed and inspected for scale or corrosion, for physical wear, and for integrity of brazed connections. The condenser was photographed, and any scale thickness was measured at several locations on the tubing. The condenser was then purged with dry nitrogen to determine whether any compressor oil had settled in the coil; the oil was collected, its volume measured, and then put into the compressor. The compressor was then sealed and labeled for shipment to Copeland Corporation, the compressor manufacturer, for analysis.

The final set of operations in the main portion of the examination involved water tank disassembly and inspection. The temperature and pressure (T & P) valve, drain valve, and inlet and outlet fittings were removed and examined for corrosion, scale, or cracks. The sheet metal wrapper was removed from the tank, and the insulation was inspected for uniformity of thickness and evidence of wetting. Finally, the insulation was removed, and the tank was flame-cut in half, circumferentially, to allow internal inspection. The weld seams, tank walls, and threaded fittings were inspected for signs of corrosion. Relative amounts and types of sediment in the tank bottom were recorded, and any unusual conditions were noted. The tank halves were then labeled and photographed.

The last step in the teardown procedure involved compressor disassembly and evaluation. All 20 compressors were shipped to Copeland Corporation's laboratory in Sidney, Ohio. The EUS project manager and a design engineer were present for the teardowns, which generally involved cutting open the compressor shell and performing the electrical and mechanical inspections listed in Appendix B.

Information and photographs from the inspections were then compiled for each unit and used for the analytical evaluations described in Section 3.

2.3 DATA EVALUATION AND CORRELATION METHODS

Several analytical methods were used to evaluate the interaction of unit performance and life with water quality and length of service.

The first analysis was performed to determine any time-dependent degradation in unit performance attributable to condenser scaling. The units involved had service times ranging from 21 to 29 months with an average of 25 months. Performance data on these units were typically available {4} for the first 12 to 15 months of operation. The monthly coefficients of performance (COPs) for the 20 units were first normalized to reflect COPs at nominal operating conditions (ambient temperature (TA) of $70^{o}F$, delivery water temperature (TH) of $140^{o}F$, and supply water temperature (TI) of $60^{o}F$) using the formula

$$COP_{normalized} = COP_{actual} + \{(60^{o}F - TI_{actual})(-0.0015)\} + \{(140^{o}F - TH_{actual})(-0.003)\} + \{(70^{o}F - TA_{actual})(0.0104)\},$$

A detailed explanation of the derivation of this formula can be found in Section 6 of reference 4. The normalization process was conducted to eliminate any performance variations caused by varying operating conditions, thereby allowing direct comparison of unit performance over time. Once the monthly COPs of the sample units were normalized, each unit's performance history was plotted using a linear regression technique. The resulting slopes of the COP-vs-time plots derived in this manner would indicate relative performance degradation. A negative slope would imply performance degradation over time; a positive slope would imply performance improvement over time; and a slope at or near zero would indicate no change in performance over time. Because the preselection criteria excluded units with damaged compressors, any degradation was assumed to be attributable to normal wear (e.g., condenser scaling, evaporator clogging, normal compressor wear, etc.). A correlation coefficient was also calculated for each linear regression to test the validity of the analytical results.

Water sample analysis results were evaluated concurrently with the unit performance history analyses. Langelier saturation {5} and Palin indices {6} were calculated for each water sample at 100°F and 140°F. Both indices measure water's propensity to be corrosive, protective (scaling), or balanced at different temperatures. The two indices differ in the way they are determined, and each was derived to cross-check the other. Once the indices were calculated, each water sample was classified (from 1 to 4) for each index. A classification of 1 indicated an ideal water balance, i.e., one that was neither corrosive nor scaling; a classification of 2 indicated that the water was slightly corrosive or scaling but still represented an acceptable balance; a classification of 3 represented water that had scale-forming tendencies; and a classification of 4 represented water that was potentially corrosive. The calculated indices and resulting water classifications were then used to evaluate and qualify the empirical findings of the unit examinations in the area of tank-condenser-anode interaction.

To provide a common point of reference and to cross-check the written observations, all photographs were re-examined after the teardowns were completed. Tank and condenser conditions were then recorded.

Finally, an overall review of all data and analytical results was conducted to uncover any possible correlations or connections between the various observations and data compiled and any unit performance attributes. Section 3 presents the results of these analyses and a summary of all observations.

3 EXAMINATION RESULTS

This section presents the results of examinations conducted on the 20-unit sample of field-tested integral heat pump water heaters. Two types of pre-examination observations are summarized in Section 3.1: unit information obtained from the two participant questionnaires and the water sample analysis; and background information on water quality and its effects on scaling and corrosion. Sections 3.2 through 3.5 discuss examination results separately for each of four HPWH functional subassemblies: the condenser, the tank and anode, the heat pump section, and the compressor. Section 3.6 summarizes the examination findings and their significance.

3.1 PRE-EXAMINATION OBSERVATIONS

3.1.1 Questionnaire Summary and Water Sample Results

Two brief questionnaires were used to obtain information on site water sources (in addition to the information provided by the water samples) and to determine the condition of the units before removal from service. The two questionnaires appear in Appendix A.

A water sample questionnaire and accompanying water sample bottle were sent to each potential program participant. The purpose of the questionnaire was to provide instructions on the proper sampling method, to identify the water source (well, municipal supply, etc.), and to determine whether a water softener was used in the supply line to the heat pump water heater. The water samples were analyzed to determine the following parameters: pH, total hardness, calcium hardness, magnesium hardness, alkalinity, and total dissolved solids. (The effects of these parameters on corrosion and scaling are discussed in Section 3.1.2.) Table 3.1

summarizes the results of the water sample analyses and selected water sample questionnaire data. Fifteen sites were supplied by municipal or utility water companies; five used well water. Water softeners of various manufacture had been installed in the supply lines of seven water heaters; however, the data indicate that two were not "softening" the water when sampled. Two of the homes having a water softener were supplied by well water.

The second questionnaire dealt strictly with operation of the heat pump water heaters. Its purpose was to identify any changes in the condition of the units between the end of the data collection phase of the program and the time the units were removed from service for the current phase. It also served to double-check problems that may not have been reported previously such as condensate leakage or excessive noise. One particular question was intended to ensure that, if significant sludge had accumulated in the tank, at least a qualitative indication of sludge type and amount would be recorded.

The information collected through this questionnaire is summarized in Table 3.2. Seven units contained noticeable sludge; two units showed signs of tank fitting corrosion or water leaks at the time of removal; two other units appeared to be losing refrigerant charge before removal from service; and one unit had been exhibiting occasional compressor "hammering" (banging noises in the compressor during operation). These conditions are discussed along with other related information in Sections 3.2 through 3.5.

Table 3.1

WATER SAMPLE ANALYSIS AND SITE INFORMATION

Utility/Unit	Water Source	Water Softener	pH	Total Hardness mg/l $CaCO_3$	Calcium Hardness mg/l Ca{mg/l $CaCO_3$}	Magnesium Hardness mg/l Mg{mg/l $CaCO_3$}	Alkalinity mg/l $CaCO_3$	Total Dissolved Solids (ppm)
Florida Power & Light								
Unit #1	Utility	No	7.72	105.2	20.9 {52.3}	12.9 {45.2}	35.0	184
Unit #2	Utility	No	9.04	94.7	19.3 {48.3}	11.3 {39.6}	35.0	176
Unit #3	Utility	No	8.19	82.8	23.7 {59.3}	5.7 {20.0}	37.0	360
Unit #4	Utility	No	8.38	81.1	22.9 {57.3}	5.9 {20.7}	52.0	224
Indianapolis Power & Light								
Unit #1	Utility	Yes	7.78	249.8[b]	62.3 {155.7}	23.0 {80.5}	152.0	416
Unit #2	Well[a]	Yes[a, b]	7.84	21.9	0.0 {0.0}	5.3 {18.6}	340.0	708
Unit #4	Utility	Yes	7.50	0.5	0.0 {0.0}	0.1 {0.4}	150.0	288
Kansas Gas & Electric								
Unit #1	Utility	No	7.88	103.7	18.1 {45.2}	14.3 {50.1}	85.0	348
Unit #2	Utility	No	7.76	125.1	24.9 {62.2}	15.3 {53.6}	110.0	436
Unit #3	Utility	No	8.30	113.5	22.1 {55.3}	14.2 {49.8}	87.0	3
Unit #4	Utility	No	7.30	345.0	99.8 {249.2}	23.4 {81.9}	330.5	576
Pacific Gas & Electric								
Unit #1	Well	No	7.24	116.6	22.1 {55.2}	15.0 {52.5}	130.0	288
Unit #3	Utility	Yes	8.37	12.5	0.0 {0.0}	3.1 {10.9}	339.0	440
Unit #4	Well	No	7.31	270.2	52.1 {130.0}	34.2 {119.7}	271.0	364
Public Service of Indiana								
Unit #1	Well	No	7.48	310.1	78.0 {194.9}	28.1 {98.4}	275.5	412
Unit #3	Utility	Yes	7.63	16.5	0.0 {0.0}	4.0 {14.0}	294.0	556
Unit #4	Utility	Yes	7.67	239.8[b]	60.3 {150.7}	21.7 {76.0}	286.0	536
Somerset Rural Electric Coop								
Unit #1	Well	Yes	7.68	3.5	0.0 {0.0}	0.9 {3.2}	110.0	80
Unit #2	Utility	No	4.71	28.4	0.8 {2.0}	6.4 {22.4}	3.0	24
Unit #3	Utility	No	4.21	19.4	0.0 {0.0}	4.7 {16.5}	7.0	16

[a]Participant switched from utility water to well water in July of 1980. A water softener was installed at that time.

[b]Water softener evidently was ineffective when water sample was taken.

Table 3.2

PARTICIPANT QUESTIONNAIRE SUMMARY

Utility/Unit	Sludge/ Sludge Color	Thermostat Setting (Top/Bottom)	Thermostat Changes	Times Serviced	Noise Level Change	Excess Condensation	Other
Florida Power & Light							
Unit #1	No	130/140	0	1 (A)	No	No	Note 1
Unit #2	Yes/White	120/130	0	1	No	No	--
Unit #3	Yes/Rust	110/110	1	0	Louder	No	Note 2
Unit #4	No	130/138	0	Several (B)	No	No	--
Indianapolis Power & Light							
Unit #1	Yes/Black	140	0	0	Louder	No	Note 3
Unit #2	No	140	0	1 (A)	Louder (C)	No	--
Unit #4	Yes/Black	140	0	0	No	No	--
Kansas Gas & Electric							
Unit #1	No	145	2 (D)	1 (A)	Louder	No	--
Unit #2	No	145	2 (A, D)	2 (A)	Louder	No	Note 4
Unit #3	Yes/Brown	140	3 (D)	0	Louder	No	--
Unit #4	No	145	1 (A)	0	Louder	No	--
Pacific Gas & Electric							
Unit #1	No	130	1	4	Louder (E)	No	Note 5
Unit #3	No	140	0	1	No	Yes (F)	--
Unit #4	Yes/White	130	0	1 (A)	Louder (E)	Yes (F)	--
Public Service of Indiana							
Unit #1	No	140	0	0	No	No	--
Unit #3	No	130	1	1	Louder (C)	No	--
Unit #4	No	140	0	0	Louder (C)	Yes (G)	--
Somerset Rural Electric Coop							
Unit #1	Yes/Rust	140	0	1	No	No	Note 6
Unit #2	No	140	0	1	No	No	--
Unit #3	No	120	1	0	No	No	--

(A)- Installation problem or setting change
(B)- Water leaks and refrigerant leaks
(C)- Fan screen and sheet metal vibrations
(D)- Calibration adjustments during monitoring phase
(E)- Wire evaporator guard loose; tightening corrected problem
(F)- Excessive condensation until drain pan changed
(G)- Clogged drain tube; cleaning corrected problem

Note 1 - Hot water outlet pointing down
Note 2 - Corrosion at bottom tank fitting
Note 3 - Water leak at lower thermostat a few days before removal
Note 4 - Occasional compressor hammering
Note 5 - Suspected slow leak (2 months to lose charge)
Note 6 - Appeared to lose charge just before removal

3.1.2 Water Qualities Conducive to Corrosion and Scaling

Because the field-tested HPWHs use a standard electric water heater tank, supply water quality was not expected to affect scaling and corrosion rates any differently than it affects conventional electric resistance and gas-fired or oil-fired domestic water heaters. Although the HPWH tank does contain a copper condenser coil not found in the standard tank, the coil's tin plating was expected to reduce galvanic interaction with the tank and anode by making the electrochemical potential of the condenser close to that of the tank and anode.

Carbonate scale formation on heat-transfer surfaces decreases as the temperature decreases. Thus, because the HPWH condenser operates at a lower temperature than the heater elements of conventional water heaters ($\sim 180^{o}F$ vs $\sim 280^{o}F$), less scale would be expected to form in the HPWH. In regard to the loose scale found in these tanks, the field-test procedure called for alternating the water heater operation, on a weekly basis, between the HPWH system and the electric resistance-heater system. Therefore, it was believed that there would have been less loose scale if the units were operated only as HPWHs.

The following discussion is based on technical publications {7, 8,} that address scaling and corrosion and on telephone interviews with technical personnel employed by the field unit tank supplier and another leading domestic water heater tank manufacturer. Corrosion and scaling mechanisms are briefly explained to provide background information for later discussions.

Corrosion is the destruction of metal through chemical or electrochemical reaction with its environment. These reactions can occur through direct chemical attack, galvanic corrosion, or concentration cell corrosion.

Direct chemical corrosion occurs when metal reacts chemically with other elements to form a non-metallic compound.

Galvanic corrosion occurs when two dissimilar metals in contact with each other are placed in an electrically conducting solution. A voltage or potential is created based on the relative tendencies of the two metals to go into solution. Electrons are carried through the solution from one metal to the other via ion flow. For galvanic corrosion to occur, there must be a simultaneous release of electrons at the anode and acceptance of electrons at the cathode. The electrons released at the anode are products of the formation of metal ions through oxidation of the metal.

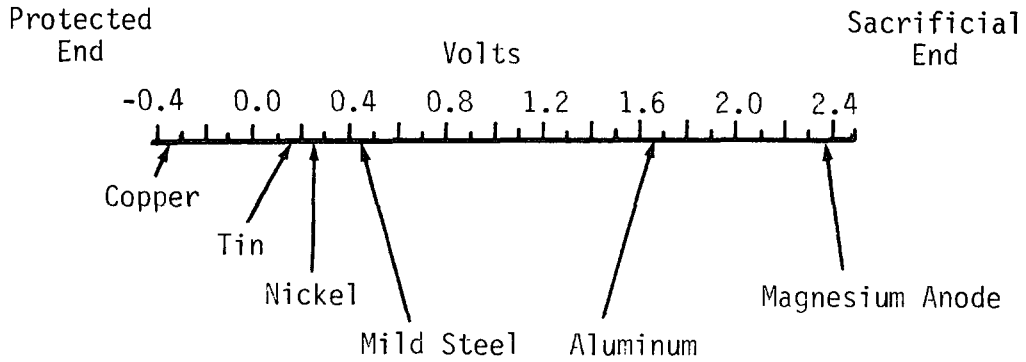
Concentration cell corrosion, a form of galvanic corrosion, occurs when an electric current is induced by different reactant concentrations at two locations on the same piece of metal. When rust or scale accumulates at the bottom of a steel tank, a stagnation region may be created that permits the establishment of a concentration gradient which, in turn, may cause tank corrosion. Crevices or foreign material deposits on a metal surface may produce conditions favorable to corrosion cell development. The concentration cell can be composed of metal ions or oxygen depending on whether the crevice concentration is higher in dissolved metal ions (cathodic) or higher in oxygen concentration (anodic) than the bulk electrolyte concentration.

All three types of corrosion undoubtedly occur in water heater tanks. Galvanic action is, however, the most common underlying cause of tank corrosion.

Figure 3.1 is a graphic presentation of the materials used in the HPWH tank. The figure shows each material's potential (in volts), which indicates its tendency to go into solution (with respect to hydrogen in an open circuit).

Figure 3.1

ELECTROMOTIVE POTENTIAL OF MATERIALS IN HEAT PUMP WATER HEATER TANK



*Although the electromotive force series for pure metals indicates their solution potentials, it must be remembered that these potentials are based on open-circuit voltages with no current flow and also apply to 1 molar solution. With current flow the potentials of the anode and cathode move toward each other.

Virtually all domestic water heater tanks now marketed are constructed of the same materials. The top, bottom, and tank walls are made of mild steel and are lined with specially formulated glass. The layer of glass should be thin enough and flexible enough to accommodate tank movement during pressure and thermal expansions. The glass should also, however, be thick enough to minimize inclusions and completely coat the tank's steel walls. Because of this necessary compromise between flexibility and protection, glass lining tends to contain some inclusions or imperfections. According to tank manufacturers, a defect-free, flexible lining is producible but prohibitively expensive with present technology. Consequently, all tank manufacturers install either a magnesium or aluminum sacrificial anode in each tank to protect steel base-metal areas that are exposed to the water because of defects in the glass liner.

Like corrosion, scale has many complex causes. Scale forms when a scaling agent concentration exceeds its solubility limit at a given temperature, pressure, pH, and other solute concentrations. When the solubility limit is exceeded, the solute usually begins to precipitate out of solution until equilibrium is reached.

Two quantitative tools have been developed to predict scaling: the Langelier and Palin indices. These indices take into account the temperature, calcium hardness, pH, alkalinity, and total dissolved solids as determined by a water analysis. Each index yields a numerical value indicating the water's tendency to be scale-forming or corrosive. Both measurements are based on saturation chemistry. Although neither applies in all cases, both are relatively simple and reasonably accurate predictions for water in which the primary scaling agent is calcium carbonate. For the overwhelming majority of natural water supplies, calcium and magnesium ions are the primary scale-forming agent. The Langelier and Palin indices are, therefore, appropriate predictors of scale-forming or corrosive water for most water heater applications.

The occurrence and rate of galvanic corrosion and scale formation can vary radically with different water supplies and can involve complex chemical relationships. This fact and the almost limitless combinations of compounds and chemical elements found in many water supplies make predicting corrosion and scaling tenuous. An additional complication results from the wide variations in water quality and chemistry that occur at any one site over time and season.

Tank manufacturers and other researchers have, however, agreed on some tendencies toward corrosion or scaling with certain types of water:

1. Factors that tend to increase scale formation tend to decrease corrosion and vice versa.
2. Higher total dissolved solids (TDS) tend to increase pH and to increase scale formation (since the solids are usually carbonate salts). Higher TDS does, however, also increase conductivity,

thereby intensifying galvanic corrosion in non-scaling water and decreasing sacrificial anode life.

3. Lower pH tends to increase corrosion compared to neutral pH; higher pH tends to increase scale formation.

Tank manufacturers have also reported the following experiences:

1. Acidic supply water with high sulfur content is common to a large number of tank corrosion problems.
2. Some geographic locations are or are suspected of being problem areas for heat exchanger scaling (Sarasota, Fla., and San Diego, Cal.) or for tank corrosion (Atlanta, Ga., Chicago, Ill., and the Eastern Pennsylvania area including Philadelphia).

3.2 CONDENSER CONDITIONS

All but one of the condensers examined showed some scaling, and all condensers showed varying magnesium deposits from the anode. The thicknesses and types of scaling ranged from extremely fine coatings of powdery or loose residue on nine condensers to a tight scale measuring 1 to 5 mils thick on another nine condensers. As mentioned, one condenser showed no scaling at all and another condenser was coated with a thick black scale (an average of 20 mils thick).

Figures 3.2 through 3.5 show the types of scaling observed. Table 3.3 briefly describes the condition of each condenser. The table also shows the results of the water sample analysis for the 20 units. Several attempts were made, using both calculated Langelier and Palin indices, to explain why some condensers showed powdery scaling and some showed tight, more occlusive scaling, but these correlation attempts proved unsuccessful.

Some observations can be made, however, by examining the total dissolved solids and calcium hardness of the water samples. As Table 3.3 shows, all 11 condensers exhibiting tight scale had operated in water with total dissolved solids (TDS) exceeding 288 parts per million (ppm). The condenser with the heaviest scale (Kansas Gas & Electric Unit #4)

Figure 3.2

CONDENSER WITH NO SCALE
(Somerset Rural Electric Cooperative Unit #1)

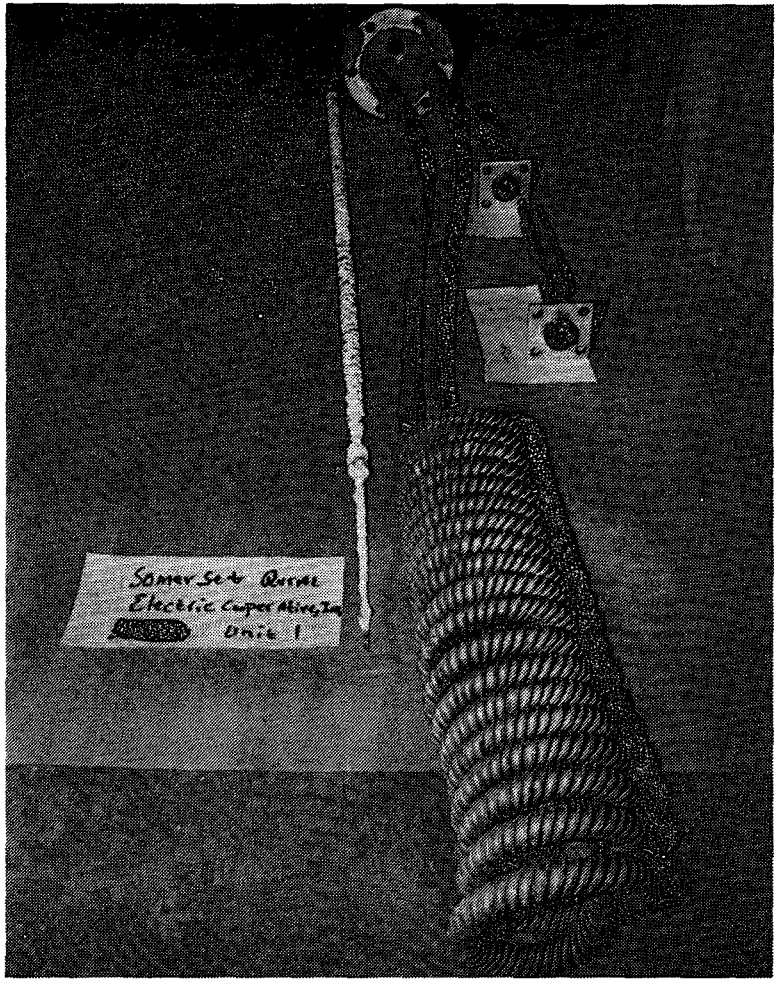


Figure 3.3

CONDENSER WITH POWDERY SCALE
(Florida Power & Light Unit #2)

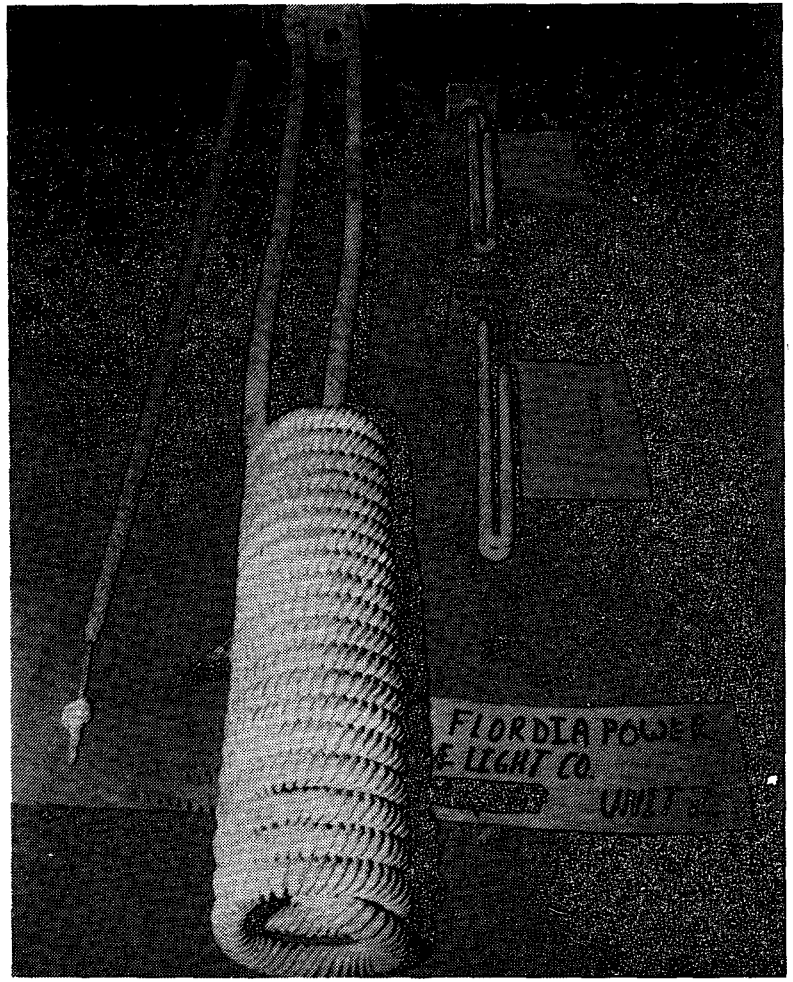


Figure 3.4

CONDENSER WITH TIGHT SCALE
(Florida Power & Light Unit #3)

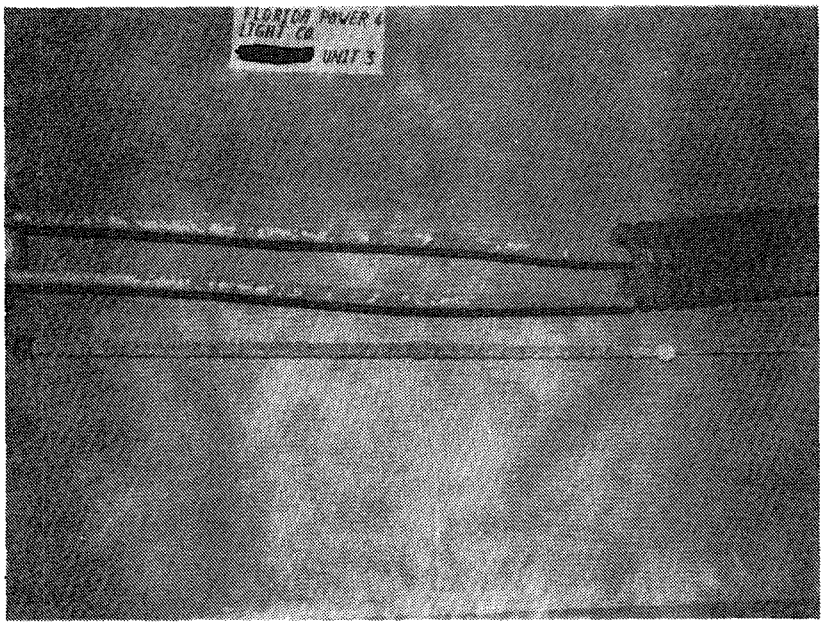


Figure 3.5

CONDENSER WITH THICK TIGHT SCALE
(Kansas Gas & Electric Unit #4)

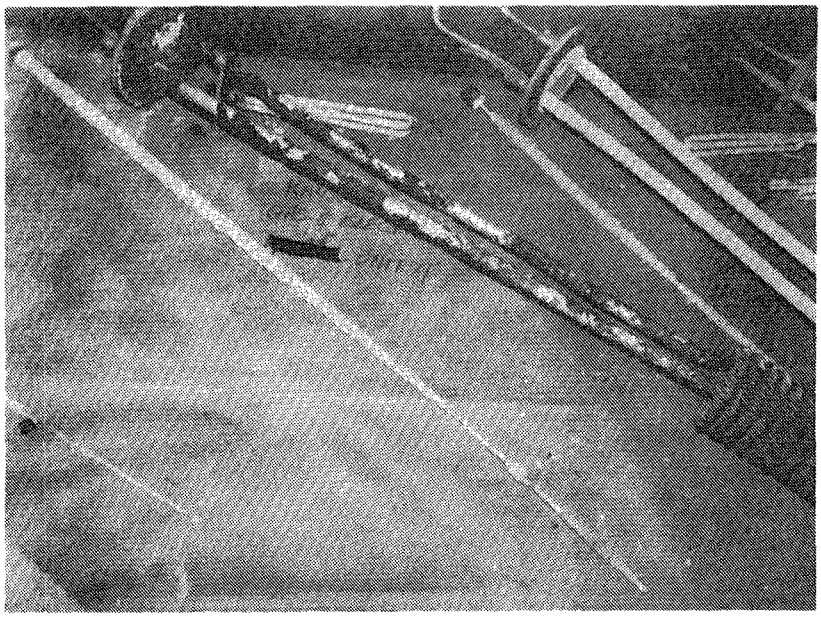


Table 3.3

WATER CHEMISTRY AND CONDENSER SCALING

Utility/Unit	TDS (ppm)	Ca Hardness (mg/l $CaCO_3$)	Condenser Scaling Condition
Florida Power & Light			
Unit #1	184	52.3	White/light brown powdery scale
Unit #2	176	48.3	White powdery scale
Unit #3	360	59.3	Dark brown tight scale
Unit #4	224	57.3	Light powdery scale
Indianapolis Power & Light			
Unit #1	416	155.7	Light brown tight scale
Unit #2	708	0	Very light brown tight scale
Unit #4	288	0	Light brown tight scale
Kansas Gas & Electric			
Unit #1	348	45.2	White powdery scale
Unit #2	436	62.2	White powdery scale
Unit #3	3	55.3	Brown powdery scale
Unit #4	576	249.2	Thick black tight scale
Pacific Gas & Electric			
Unit #1	288	55.2	Brown/yellow tight scale
Unit #3	440	0	Brown tight scale
Unit #4	364	130	Brown tight scale
Public Service of Indiana			
Unit #1	412	194.9	Brown tight scale
Unit #3	556	0	Brown/white tight scale
Unit #4	536	150.7	Brown tight scale
Somerset Rural Electric Coop			
Unit #1	80	0	No scale
Unit #2	24	2	Brown powdery scale
Unit #3	16	0	White loose scale

had operated in water with the highest TDS and calcium hardness at 576 ppm and 249.2 mg/l $CaCO_3$ respectively. The average TDS for the 11 units with tight scaling was 449 ppm; the average calcium hardness level was 91 mg/l $CaCo_3$. The average TDS for the eight units with loose or powdery scale was 177 ppm; the average calcium hardness was 51 mg/l $CaCO_3$. The latter units had all operated in water with TDS levels of 224 ppm or less with two exceptions. Kansas Gas & Electric Units #1 and #2 had TDS levels of 348 and 436 ppm respectively. The powdery scale on these two condensers was far heavier than on other units in this grouping. The unit with no scale accumulation had operated in water with 80 ppm TDS and 0 hardness.

The 20 tin-plated copper condensers were also examined for extent of corrosion. No corrosion was found. As shown in Figure 3.1 the cathodic galvanic potential of tin relative to all other materials in the tank and the close proximity of the protective anode make galvanic corrosion of the condenser highly unlikely. Since the condenser is the hottest surface in the tank, it is most conducive to scale formation. Condenser scaling was observed even in corrosion-conducive water where tank rust was observed.

The primary objective of this examination phase was to determine the potential impact of scale on a condenser's heat transfer capabilities and, consequently, on the unit's performance. Performance histories were reviewed for the 19 units with condenser scaling. As discussed in Section 2, the monthly COPs of the test units were first normalized to eliminate the effects of varying operating conditions.

These normalized COPs were then regressed in an attempt to evaluate whether any performance degradation occurred over time. Table 3.4 lists the 19 units with condenser scale and presents the line equation slope resulting from the regressions. A negative slope indicates performance degradation; a positive slope indicates performance improvement; and a zero slope indicates no change. Also shown are the

correlation coefficients obtained for each unit regression. This coefficient measured the validity of the line regression of a number of points. The closer this coefficient is to +1 or -1, the more valid the calculated slope.

As Table 3.4 shows, the slopes range from -0.034 to +0.224 with an average slope of +0.012. Correlation coefficients were, for the most part, low indicating questionable validity for the analysis. When put into perspective, an average slope of +0.012 is unrealistic for it indicates that the performance of the average unit would improve with each month of operation. For example, if the unit COP were 1.9 the first month, its COP would be 1.912 the second month, 1.924 the third, 1.936 the fourth, etc. Since this result is not feasible, the only conclusion that can be reached is that no performance degradation is apparent as a result of the moderate condenser scaling observed.

This conclusion isn't totally surprising considering the fact that the HPWH condenser relies on free convective heat transfer. The most significant impediment to heat transfer in this situation is the water-to-condenser film boundary layer. Therefore, small changes in the condenser's thermal conductivity (caused by the insulating effects of scale deposits) would not be expected to signifcantly affect overall heat-transfer capabilities.

Table 3.4

MONTHLY PERFORMANCE REGRESSION
ANALYSIS OF SCALED CONDENSERS

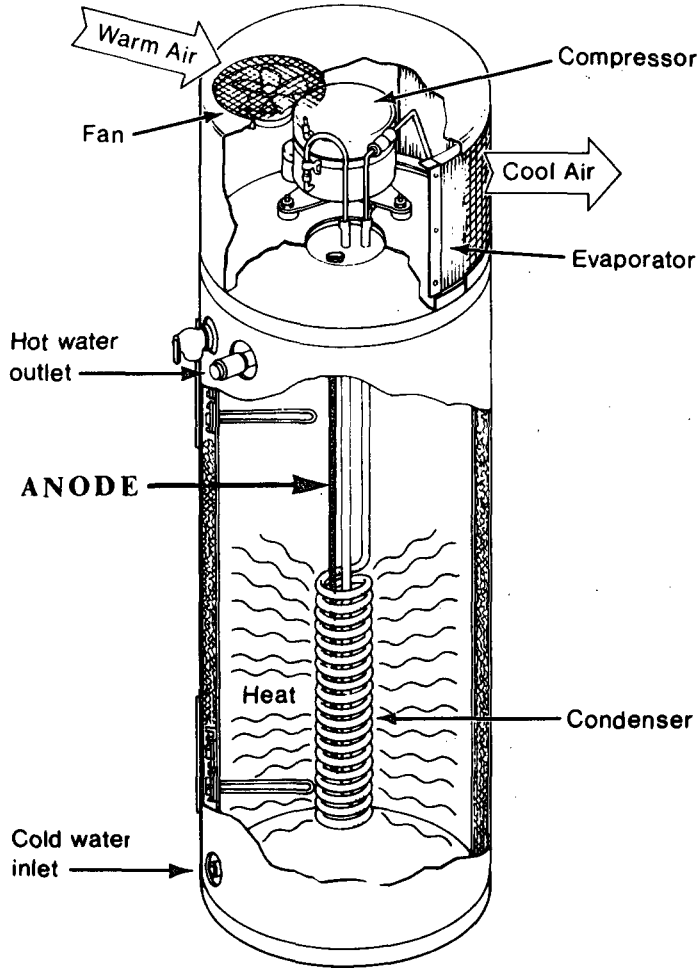
Utility/Unit	Regression Slope	Correlation Coefficient
Florida Power & Light		
Unit #1	-.023	-.33
Unit #2	-.018	-.17
Unit #3	+.046	+.46
Unit #4	+.033	+.25
Indianapolis Power & Light		
Unit #1	+.010	+.32
Unit #2	-.009	-.19
Unit #4	-.001	-.01
Kansas Gas & Electric		
Unit #1	-.034	-.41
Unit #2	-.027	-.32
Unit #3	+.017	+.26
Unit #4	+.032	+.30
Pacific Gas & Electric		
Unit #1	Insufficient Data	
Unit #3	-.021	-.13
Unit #4	+.224	+.78
Public Service of Indiana		
Unit #1	+.008	+.19
Unit #3	+.012	+.19
Unit #4	-.008	-.30
Somerset Rural Electric Coop*		
Unit #2	-.004	-.11
Unit #3	-.020	-.15
Average Slope	+.012	

*Unit #1 had no scale and, therefore, is not listed.

3.3 TANK AND ANODE CONDITIONS

The tanks used in the field-tested HPWHs were standard 82-gallon, glass-lined, mild steel, electric water heater tanks manufactured by Mor-Flo Industries. The primary inhibitor of galvanic corrosion (aside from the glass liner) is a sacrificial magnesium anode. The anode rod is centrally located in the tank; its lower portion extends down into the center of the condenser coils as shown in Figure 3.6.

Figure 3.6
LOCATION OF MAGNESIUM ANODE IN WATER TANK



As discussed in Section 3.1.2, the purpose of the sacrificial anode is to inhibit galvanic corrosion of the steel tank by providing a source of free electrons released by the slow breakdown of the less noble magnesium. Theoretically, galvanic corrosion should be inhibited as long as some of the magnesium anode remains. Exceptions to this include areas of the tank that are electrically "shaded" from the anode (i.e., portions within direct line of the anode hidden within the condenser).

Examination of the 20 units revealed that six of the 20 anodes were completely exhausted and four had lost 75% or more of their magnesium. In eight of the 20 units small amounts of tank rusting were detected. The other 12 units exhibited no rusting. Most rust was confined to areas where glass had chipped away from inlet fittings or where imperfections in the glass lining existed. (See Figures 3.7 and 3.8.)

Some reasonable conclusions can be made concerning anode deterioration, tank rusting, and use of water softeners. Seven test sites used water softeners. Five of the units from these sites had exhausted anodes; the remaining two units had only 31% and 22% of the original anode weight (26 oz.) remaining. Softeners replace calcium and magnesium ions with sodium ions which increase solution conductivity. This increased conductivity is believed to speed anode depletion, thereby shortening anode life and facilitating corrosion cell development. Conversations with a water-tank manufacturer indicate agreement that water softeners shorten tank life.

Some evidence of tank rusting was found in all but one of the units with water softeners. The one exception (Public Service of Indiana Unit #4) showed a relatively high level of calcium hardness in its water sample (150.7 mg/l $CaCO_3$) indicating that the water softener simply wasn't working well.

Of the 13 units without water softeners, only two showed any localized or spot rusting. One of these units (Somerset Rural Electric Coop Unit #2) had only 16% of the original anode material remaining and exhibited a calcium hardness level of only 2 mg/l $CaCO_3$. This site had extremely pure water which is naturally corrosive. The Langelier (-5.65) and Palin (6.31) indices and the pH (4.71) for the water used in this unit indicate highly corrosive water (see Section 3.1.2). The remaining unit exhibiting rust (Kansas Gas & Electric Unit #3 - see Figure 3.9) still had 20% of its anode material remaining. The pH level and Langelier and Palin indices for the water used in this unit would normally not be considered corrosive. The TDS content of this water was only 3 ppm. TDS is an indication of the conductivity of the water. This water sample showed the lowest conductivity of the whole test sample. Low conductivity reduces anode effectiveness, and this may allow local corrosion cells to develop despite the presence of anode material. Upon closer examination it was also found that the rusting in this tank was restricted to random spots on the tank walls which corresponded to imperfections in the glass lining. This could imply an excessively flawed tank.

The 12 units exhibiting no rusting had from 22 to 80% of the original anode material remaining. The average anode in this group had more than 40% of its original magnesium weight intact.

Placement of the lower anode rod within the condenser coil envelope definitely contributed to anode degradation. All anodes examined appeared to be more severely depleted on portions that had been located within the condenser (see Figure 3.10).

Figures 3.11 through 3.13 show anode rods with 0%, 47%, and 80% of their original magnesium intact. Table 3.5 summarizes test group findings on anode degradation, tank rusting, water chemistry, time of service, and water softener use.

Figure 3.7

RUST ON LOWER TANK
(Indianapolis Power & Light Unit #1)

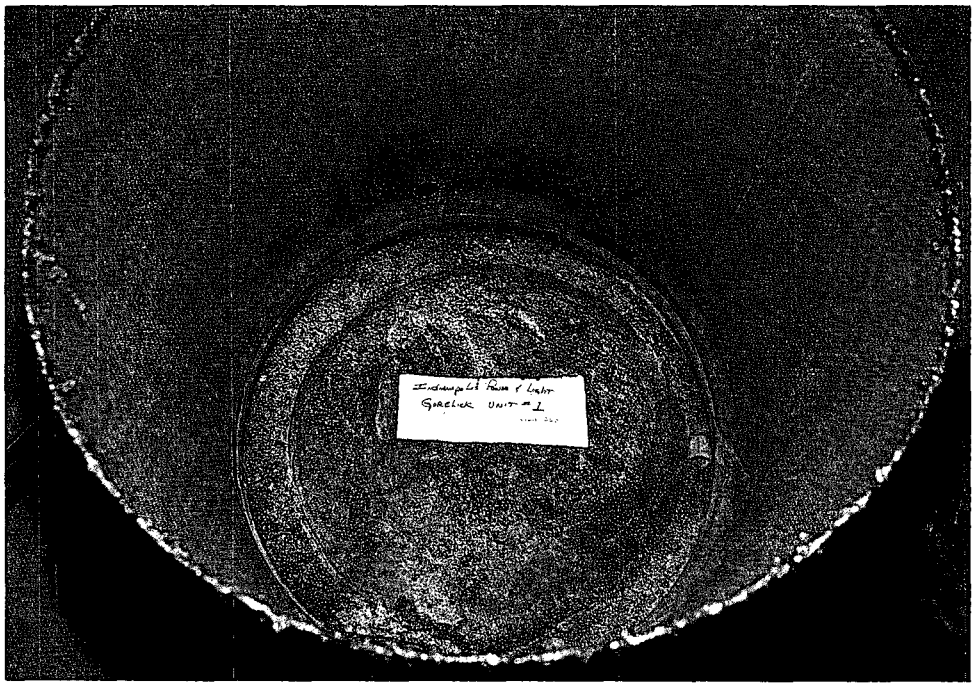


Figure 3.8

RUST AROUND INLET FITTING ON TANK
(Indianapolis Power & Light Unit #1)

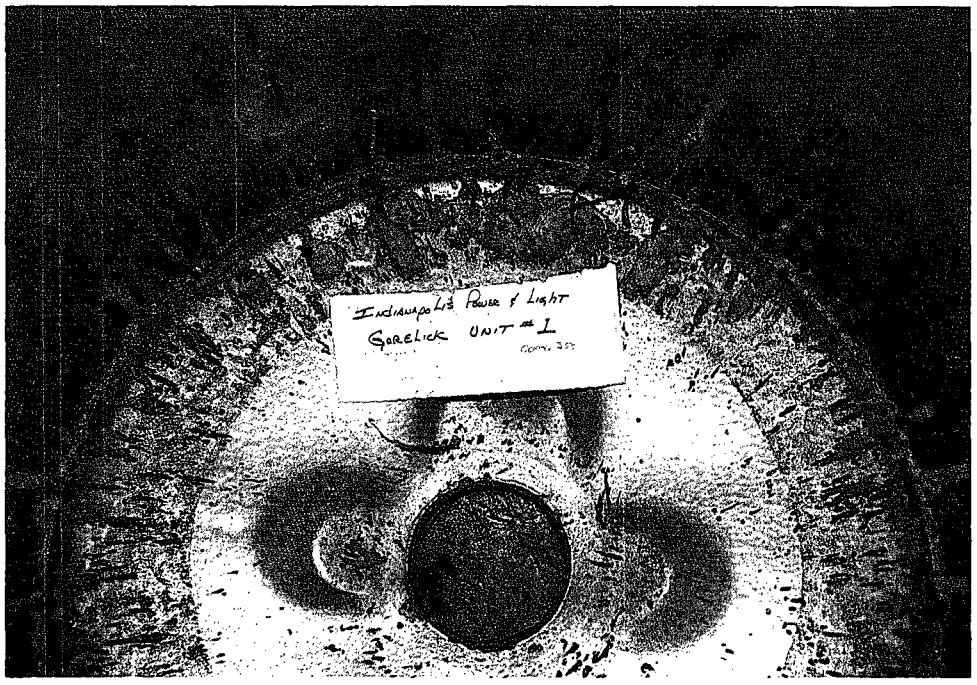


Figure 3.9

SPOT RUST ON TANK
(Kansas Gas & Electric Unit #3)

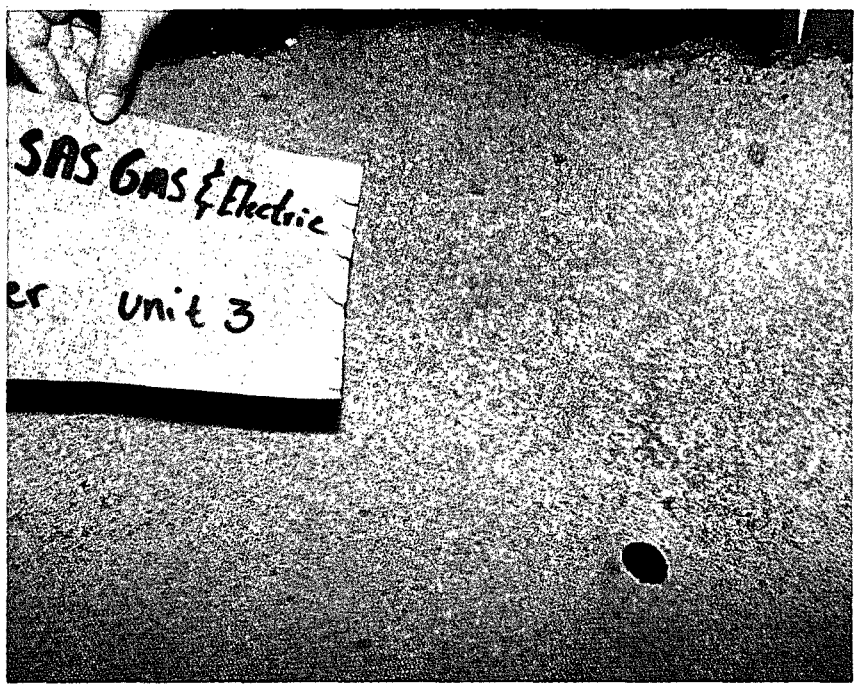


Figure 3.10

CONDENSER-SPECIFIC ANODE ROD DEGRADATION
(Somerset Rural Electric Coop Unit #3)

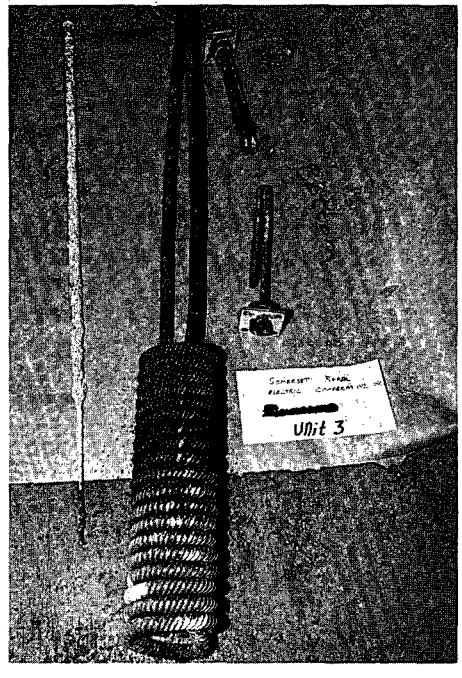


Figure 3.11

ANODE ROD WITH 0% OF ORIGINAL ANODIC MAGNESIUM INTACT
(Indianapolis Power & Light Unit #1)

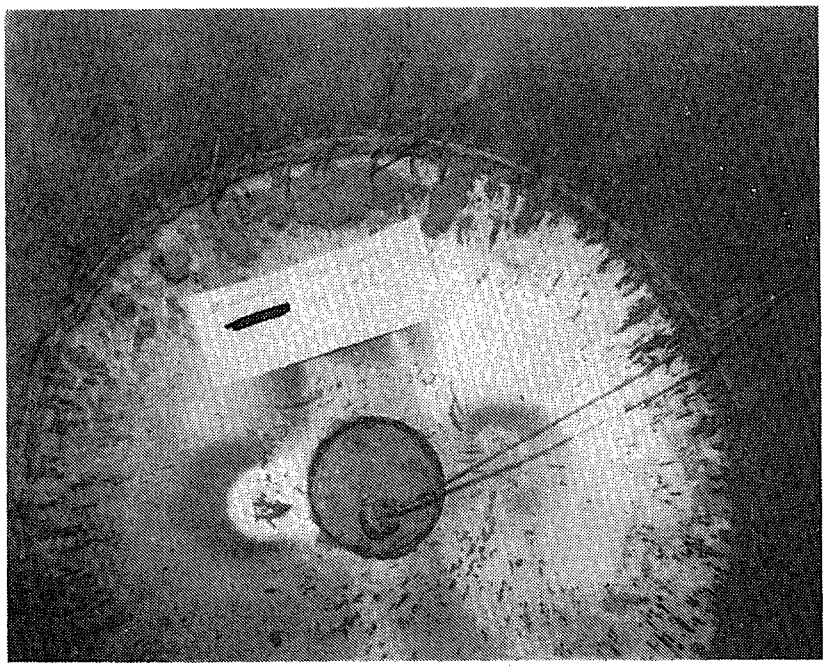


Figure 3.12

CONDENSER AND ANODE ROD WITH 47% OF ORIGINAL ANODIC MAGNESIUM INTACT
(Florida Power and Light Unit #2)

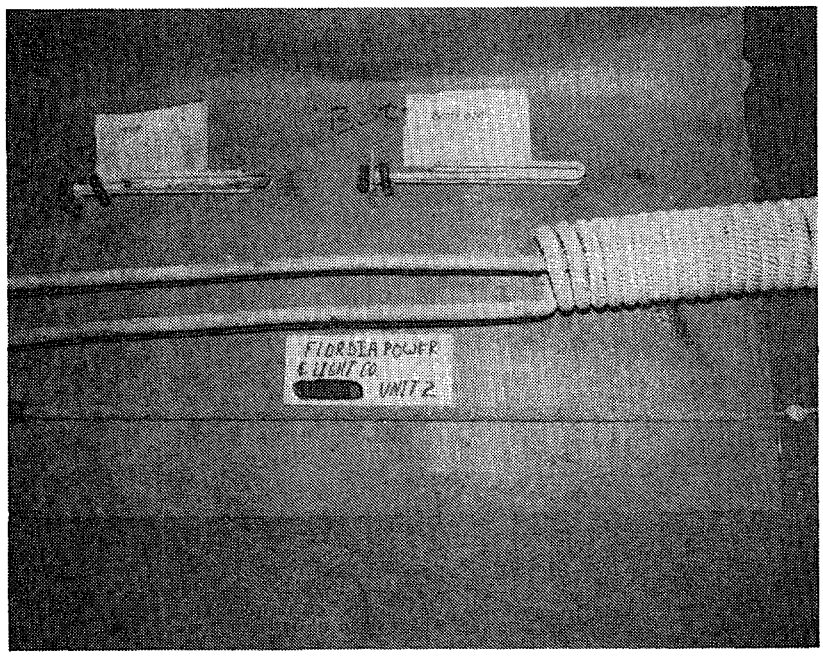


Figure 3.13

CONDENSER AND ANODE ROD WITH 80% OF ORIGINAL ANODIC MAGNESIUM INTACT
(Public Service of Indiana Unit #1)

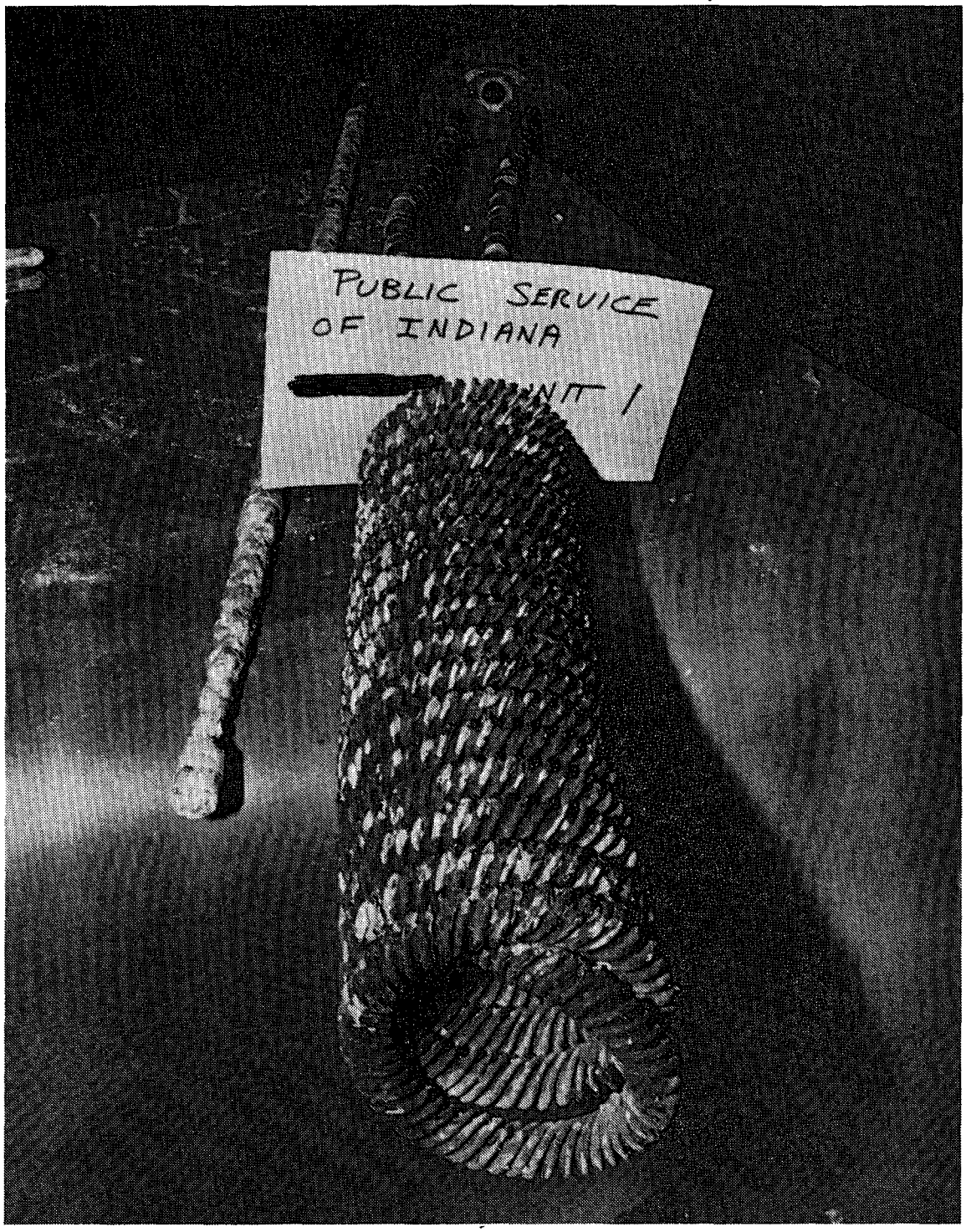


Table 3.5

TANK/ANODE EXAMINATION SUMMARY

Utility/Unit	Months of Service	pH	TDS (ppm)	Ca Hardness (mg/l $CaCO_3$)	Langelier Index @ 140°F	Palin Index @ 140°F	% Original Anode Weight Remaining	Minor Tank Rust Evident	Water Softener Used
Florida Power & Light									
Unit #1	23	7.72	184	52.3	-0.23	10.97	30	No	No
Unit #2	23	9.04	176	48.3	+0.77	12.17	47	No	No
Unit #3	23	8.19	360	59.3	+0.23	11.42	55	No	No
Unit #4	23	8.38	224	57.3	+0.64	11.78	0	No	No
Indianapolis Power & Light									
Unit #1	26	7.78	416	155.7[a]	+0.8	12.04	0	Yes	Yes[a]
Unit #2	26	7.84	708	0	-0.9	11.04	0	Yes	Yes
Unit #4	25	7.50	288	0	-1.6	10.37	0	Yes	Yes
Kansas Gas & Electric									
Unit #1	25	7.88	348	45.2	+0.16	11.36	25	No	No
Unit #2	25	7.76	436	62.2	+0.23	11.48	30	No	No
Unit #3	25	8.30	3	55.3	+0.63	11.86	20	Yes	No
Unit #4	25	7.30	576	249.2	+0.91	12.09	42	No	No
Pacific Gas & Electric									
Unit #1	25	7.24	288	55.2	-0.29	10.99	50	No	No
Unit #3	22	8.37	440	0	-0.4	11.57	0	Yes	Yes
Unit #4	21	7.31	364	130.0	+0.55	11.74	74	No	No
Public Service of Indiana									
Unit #1	28	7.48	412	194.9	+0.86	12.10	80	No	No
Unit #3	28	7.63	556	0	-1.2	10.78	0	Yes	Yes[a]
Unit #4	28	7.67	536	150.7[a]	+0.99	12.18	22	No	Yes[a]
Somerset Rural Electric Coop									
Unit #1	29	7.68	80	0	-1.51	10.42	31	Yes	Yes
Unit #2	29	4.71	24	2	-5.65	6.31	16	Yes	No
Unit #3	29	4.21	16	0	-6.08	5.81	42	No	No

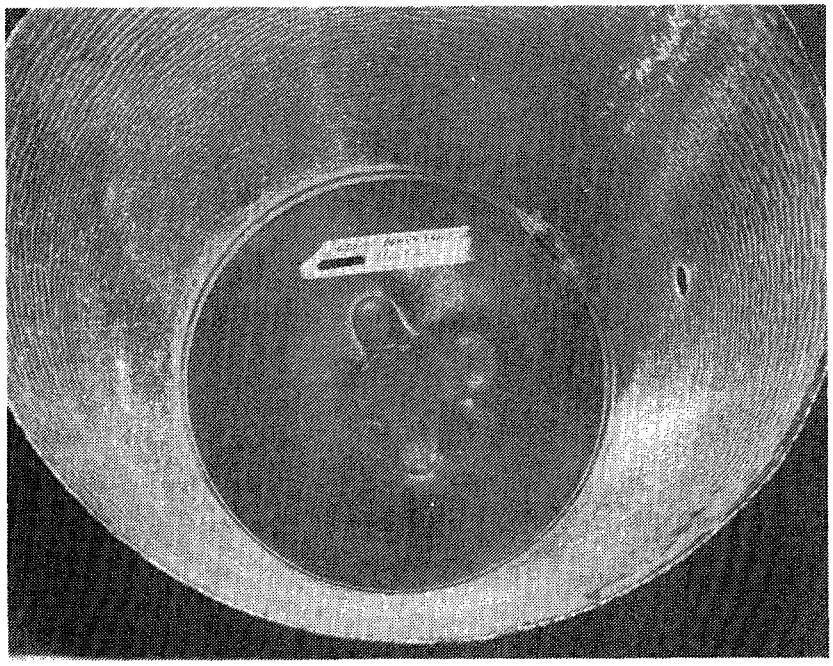
[a]Water softener evidently was ineffective when water sample was taken.

A major contributor to tank degradation appears to be the use of a water softener. It should be noted that none of the rusting observed was severe and that no pitting or measurable tank degradation was observed. No tanks suffered leaks. But visible corrosive cells and the absence of anodic protection for most units after an average of 26 months could imply limited tank life of perhaps five years or less. The units that were not exposed to softened water (or extremely corrosive water) showed no rusting and still had an average of more than 40% of their original anodic protection after average operation times of 25 months. Assuming anode degradation for these units would continue linearly, the expected average life of these anodes would exceed four years. Without anode replacement after four years of use, tanks in corrosive water would, however, begin to degrade. Total expected life for units using unsoftened water could be five to ten years. This expected lifespan falls within the expected range for electric water heater tanks. Design modifications that could extend tank life by slowing anode degradation are discussed in Section 4.

Another factor related to tank corrosion is tank scaling. Scale, found on 14 of the 20 units examined, took three forms: a powdery film, small nodules, and a non-crystalline coating. The powdery film and the small nodules, which were the most common scale formation, were white to light yellow in color and of no appreciable thickness. Thickness of powdery film was estimated to be 0.01 to 0.04 inch; the nodules were in the same size range. Both appear to be deposits of calcium carbonate. (See Figure 3.14.) The non-crystalline coating (found on two Somerset Rural Electric Coop units) was blackish brown in color. The dome of one unit had very heavy deposits of this type. Based on discussions with tank manufacturers, this type of scale is most likely a metal sulfide which typically forms in areas with acidic water having a high sulfur content. Water samples from the two test units had pHs of 4.71 and 4.21 (indicating high acidity) and had operated in a high-sulfur coal producing area of the country.

Figure 3.14

TANK WALLS WITH POWDERY SCALE DEPOSITS
(Florida Power & Light Unit #2)



Scaling generally occurred on the upper one-third to one-half of the tank walls and thinned out toward the bottom. This type of scale distribution is perhaps due to higher water temperatures in the upper portion of the tank which decrease scale solubility and to greater water movement in the lower portion of the tank which tends to inhibit scale formation.

As noted in Section 3.1.2, water with scaling tendencies is usually non-corrosive. Although examinations of the 20 tanks generally supported this tendency (i.e., most of the scale deposits occurred on non-rusted tanks), exceptions were revealed. Of the eight tanks exhibiting rust, three had light scale formations on the tank walls. This scale generally took the form of either a very light, powdery film or a small number of white nodules and sparsely coated only one-third to one-half of the tank area. Such light scale deposits offer little protective coating to the tank wall. Only one tank with rust spots had heavy scale formation in the rusted areas (Kansas Gas & Electric

Unit #3). A rust-colored stalactite-like deposit was found in several other tanks with rust, but these deposits were not considered to be scale formations.

Sludge deposits, which form from scale, were found in all tank bottoms regardless of rust or scale formations elsewhere. Sludge deposits took various forms: white or yellow caked material, white to brown scale chips, sandy brown powder, and brownish-black viscous material.

Because the tank bottoms are shaped like concave domes, the sludge always settled in the crevice covering the seam weld joining the tank wall and bottom. Sludge accumulations were scraped away in order to check all seam welds for rust formation. No seam welds, however, were rusted. The sludge coating on the seam actually appears to protect the weld from corrosion.

3.4 HEAT PUMP SECTION OBSERVATIONS

As discussed in Section 2.2, numerous observations and measurements were made as each HPWH was disassembled. Those concerning the heat pump section are listed on the examination checklist in Appendix B. Table 3.6 summarizes the conditions found in each unit. Since no problems were found regarding electrical wiring or TXV bulb location and clamping, these conditions are not listed.

Another condition checked but not listed in Table 3.6 is the presence of compressor oil in other system components. If too much compressor oil is lost, the compressor will not be properly lubricated. However, only one unit (Florida Power & Light Unit #2) had any measurable amount of oil in the evaporator and it measured less than 1 ml. The heat pump condensers were also purged to check for trapped oil. None of the condensers had any measurable amount of oil.

Table 3.6

SUMMARY OF HEAT PUMP SECTION OBSERVATIONS

Utility/Unit	Dirt	Base Pan Rust	Condition of Fan Assembly	Approx. % Evaporator-Face Blockage	Blow-off Cap	Compressor Oil (oz.)	Compressor Mounting Condition	Other
Florida Power & Light								
Unit #1	Moderate	Heavy-Compr., Drip Tray	Good (Dirty)	Insignificant	In Place	15	Good	Note 1
Unit #2	Moderate	Heavy-Compr., Drip Tray	Good (Dirty)	5	In Place	15	Good	--
Unit #3	Light	Moderate-Compr.	Good	Insignificant	Missing	16	Good	Note 2
Unit #4	Moderate	Heavy-Compr., Drip Tray	Good (Dirty)	Insignificant	In Place	16	Good	--
Indianapolis Power & Light								
Unit #1	Light	Moderate-Compr.	Good (Dirty)	5	In Place	14	Good	--
Unit #2	Light	Heavy-Drip Tray	Good	Insignificant	In Place	16	Good	Note 3
Unit #4	Light	Light-Drip Tray	Good	Insignificant	In Place	13	Good	Note 4
Kansas Gas & Electric								
Unit #1	Very Light	Very Light-Compr.	Good	Insignificant	In Place	18	Good	--
Unit #2	Light	Light	Good	Insignificant	In Place	13 (Black)	Good	--
Unit #3	Moderate	Light-Drip Tray	Good (Dirty)	20	In Place	12	Good	Note 1
Unit #4	Light	Moderate	Bent Fan Guard Rings	Insignificant	In Place	17	Rust on Mounting bolts	--
Pacific Gas & Electric								
Unit #1	Heavy	Light-Spotty	Good (Dirty)	15	In Place	13	Good	Note 5
Unit #3	Moderate	Moderate-Drip Tray	Fan Guard Ring Weld Broken	5	Missing	16	Good	Note 6
Unit #4	Heavy	Moderate	Good (Dirty)	25	In Place	19	Good	--
Public Service of Indiana								
Unit #1	Moderate	Moderate-Drip Tray	Good (Dirty)	Insignificant	In Place	17	One mounting-foot split	--
Unit #3	Heavy	Heavy-Compr., Drip Tray	Good (Dirty)	Insignificant	In Place	16	Good	--
Unit #4	Moderate	Moderate-Compr., Drip Tray	Good (Dirty)	Insignificant	In Place	16	Good	--
Somerset Rural Electric Coop.								
Unit #1	Moderate	Light-Compr.	Good (Dirty)	50	In Place	17	Rust on Mounting bolts	--
Unit #2	Heavy	Moderate-Compr., Drip Tray	Good (Very Dirty)	25	In Place	16	Good	--
Unit #3	Heavy	Very Heavy	Good (Very Dirty)	5	In Place	14	Good	--

Note 1 Broken condenser inlet joint; no charge in system
Note 2 Corrosion on evaporator outlet joint
Note 3 Unusual odor in refrigerant
Note 4 Dust-clogged condensate drain tube
Note 5 Very little change in unit
Note 6 New drip tray cracked at drain fitting

The oil remaining in each compressor was also measured. As shown in Table 3.6, the amount of oil in five compressors varied more than 2 ounces from the 16-ounce (wt.) production charge. There is, apparently, a fairly wide tolerance on the initial oil charge, since one compressor contained 19 ounces and another contained 18 ounces. If the low-end oil-charge tolerance is the same as the high end (3 ounces), then only one compressor (Kansas Gas & Electric Unit #3) was significantly low on oil charge. This unit had lost its refrigerant charge because of a broken joint at the compressor discharge, and probably lost some oil as well.

The compressor, condenser, and evaporator oil measurements revealed no oil displacement problems. Thus this HPWH configuration has no oil traps to reduce compressor lubrication.

The condenser annulus blow-off cap was missing from two HPWHs. The purpose of this plastic cap is to seal the water-filled annulus between the refrigerant and water tubes in the condenser to prevent the water from evaporating and degrading heat transfer. In case of a leak, the annulus becomes sufficiently pressurized for the cap to blow off. Service records for the two units do not indicate condenser failures, and both condensers still had fluid in the annulus when the units were disassembled. Thus, the missing caps were probably dislodged during return shipment.

Nine HPWHs had significant levels of dirt clogging the evaporator fin surface. Five evaporators were estimated to be 15% or more blocked; one appeared to be 50% blocked. EUS laboratory tests have indicated that the HPWH evaporator is oversized compared to the rest of the refrigeration system. Although data are not sufficient to confirm this, a comparison of each unit's average field test performance with percentage of evaporator blockage, as shown in Table 3.7, indicates that at least seven of the nine units with significant blockages (5% or more) had COPs better than the field-test average

Table 3.7

EVAPORATOR BLOCKAGE AND FIELD-TEST PERFORMANCE

Utility/Unit	% Evaporator Face Blockage	Average Field-Test COP
Florida Power & Light		
Unit #1	<5	1.68
Unit #2	5	2.01
Unit #3	<5	1.95
Unit #4	<5	1.44
Indianapolis Power & Light		
Unit #1	5	1.97
Unit #2	<5	1.89
Unit #4	<5	1.98
Kansas Gas & Electric		
Unit #1	<5	1.79
Unit #2	<5	1.92
Unit #3	20	2.05
Unit #4	<5	1.96
Pacific Gas & Electric		
Unit #1	15	2.01
Unit #3	5	1.98
Unit #4	25	2.06
Public Service of Indiana		
Unit #1	<5	2.27
Unit #3	<5	2.07
Unit #4	<5	1.86
Somerset Rural Electric Coop.		
Unit #1	50	1.66
Unit #2	25	1.83
Unit #3	5	1.62

(1.93) or within 5% of this average. The remaining two blocked evaporators had low average COPs (1.62 and 1.66) even though one had very little air blockage (5%) and the other had very high air blockage (50%). It appears that, in general, the evaporator is large enough that even 20% airflow blockage has no noticeable effect on performance. This is an important consideration because, as Table 3.6 shows, 13 units were installed in areas where they collected at least moderate

amounts of dirt. Filters on the air inlet can reduce accumulations of evaporator dirt (current production models of the HPWH are offered with optional, cleanable filters); however, filters are only useful if checked regularly. Because water heaters are often overlooked by owners, the oversized evaporator appears to be a desirable feature to help minimize operating problems caused by dirt accumulation. Figure 3.15 shows one unit with typically dirty conditions and heavy evaporator clogging. Figure 3.16 shows the heat pump compartment of one of the cleaner units.

The fan assemblies of all but two units were in good condition. Two units had damaged fan guards: one had bent rings; the other had a broken spot-weld on one of its rings. The motor and blades had accumulated significant dirt in 13 units. Severe dirt buildup can increase the motor load slightly causing some increase in motor temperature; however, none of the units showed any signs of motor overheating.

All base pans had some rust. Fourteen units had moderate to heavy rust, although none showed any rusting through the metal. The most common rust locations were under the condensate drip tray and under the compressor. The original HPWH design incorporated a very shallow drip tray under the evaporator. During the field test, a number of units were reported to have condensate overflow; a new, deeper drip tray was designed and made available to those participants requesting one. Condensate overflow is the primary source of base pan rusting. Rusting under the compressor may be due in part to condensate spillage settling at a low point in the pan caused by the weight of the compressor. Another possible cause is compressor "sweating" resulting from excessive refrigerant charge and very high humidity. Sweating could have occurred in several units where the uninsulated suction line might have condensed moisture from the air. In most instances, however, the amount of moisture should not be heavy. In general, the pan rust should not be a problem for most units built after the field-tested units because of the enlarged condensate pan and drain.

Figure 3.15

HEAT PUMP COMPARTMENT OF UNIT WITH
DIRT ACCUMULATION AND EVAPORATOR CLOGGING
(Pacific Gas & Electric Unit #1)

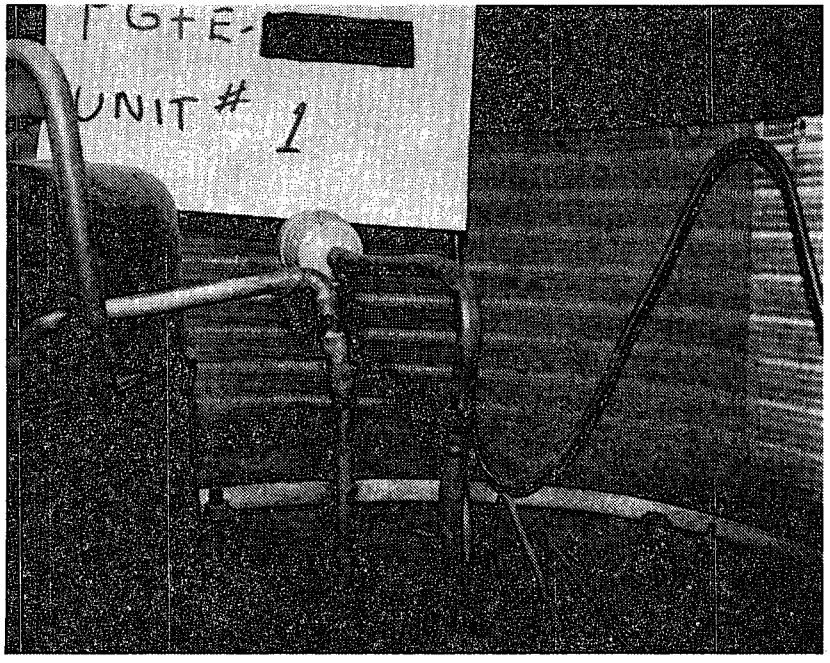
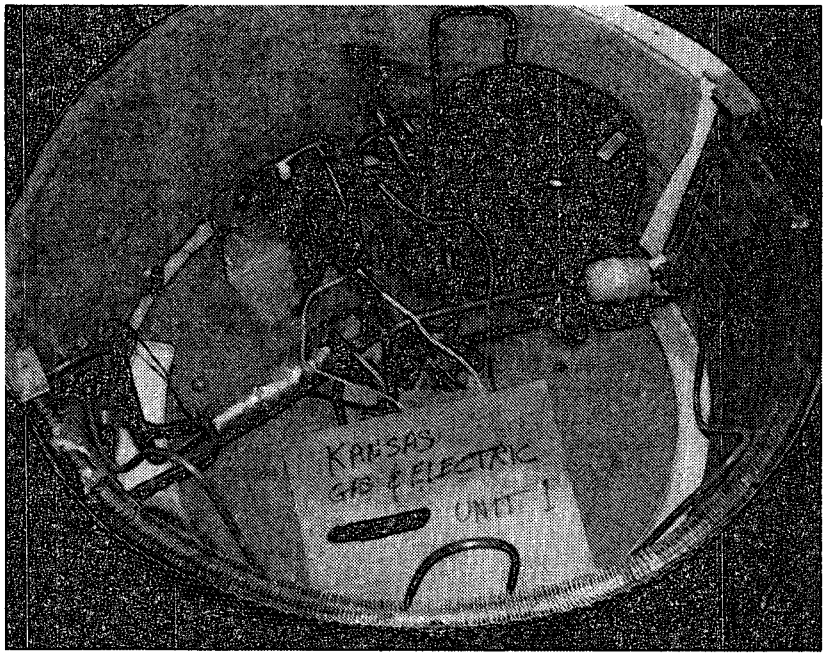


Figure 3.16

HEAT PUMP COMPARTMENT OF UNIT
WITH VERY LIGHT DIRT ACCUMULATION
(Kansas Gas & Electric Unit #1)



To summarize, examination of the heat pump section revealed no major reliability problem. No evidence was found of compressor oil collection in other parts of the HPWH. Large amounts of evaporator airflow blockage did not appear to significantly affect system performance. Significant amounts of dirt were found in several units; however, cleanable air filters are available to prevent dirt buildup. The redesigned condensate pan should eliminate most of the severe base pan rusting. In addition to these findings, a number of field-test experiences not discussed here led to HPWH design modifications on later units. These modifications, discussed in Section 2 of reference 4, include improved tube joint connection techniques, and vibration absorption loops in refrigeration system tubing. The current generation HPWH should, therefore, be more mechanically reliable.

3.5 COMPRESSOR EVALUATIONS

All 20 compressors were returned to the manufacturer (Copeland Corporation, Sidney, Ohio) for teardown and detailed inspection of all internal components. Two EUS personnel were present during these inspections.

The compressors used in the HPWH are Copeland Model JRL4-0100-PAV hermetically-sealed units rated at 11,000 Btu per hour using refrigerant 22 (R-22). The compressor rating drops to approximately 7500 Btu per hour with refrigerant 12 (R-12) as used in the HPWH. Nominal electrical ratings of the compressor are 5.3 amps at 230 VAC, 60 Hz.

The major steps in the compressor evaluations are listed in Appendix B. After the hermetically-sealed shell was cut in half, the motor was run to determine power consumption. Then dielectric tests were run at 2300 volts between the motor case and each of the three compressor input power leads to check for insulation failures.

The remaining inspections and measurements dealt primarily with the mechanical properties of the compressor components. The components were checked for signs of discoloration or other evidence of overheating, for wear on bearing surfaces and valves, for evidence of copper plating on the crankshaft and rod pin, and for corrosion on the inside of the compressor housing. Clearances in the motor and piston assemblies were measured to check for any significant wear or distortion. Figure 3.17 shows the disassembly area with several of the units being inspected.

A qualitative summary of significant results of the compressor inspections is shown in Table 3.8. Only one compressor showed significant wear. One other compressor had been assembled with the wrong piston. The only other abnormalities found were small distortions in the air gap between the rotor and stator coils of the motor, and light copper plating on some of the crankshafts and piston rod pins.

Figure 3.17
COMPRESSOR DISASSEMBLY AREA

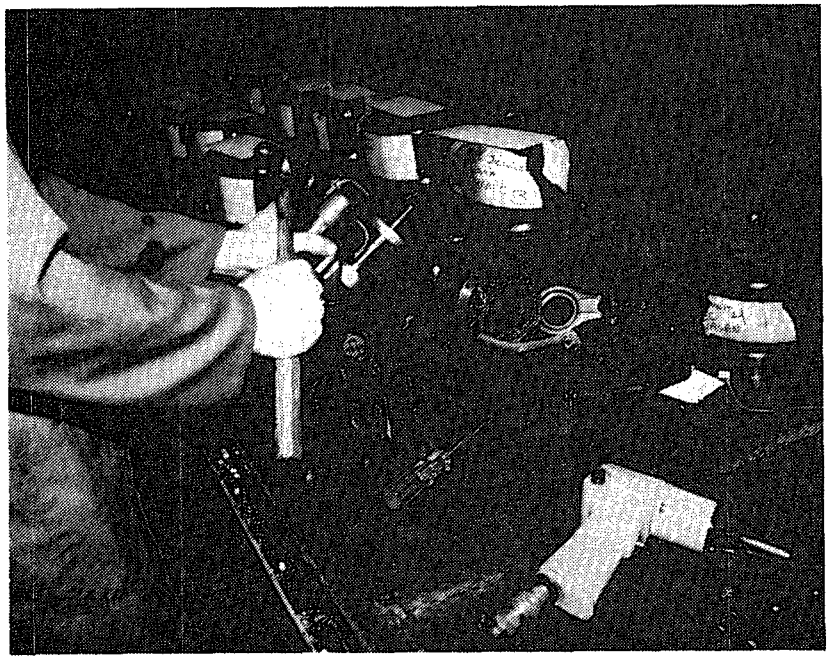


Table 3.8

COMPRESSOR INSPECTION RESULTS SUMMARY

Utility/Unit	Inspection Results
Florida Power & Light	
Unit #1	Oil clean; no abnormalities
Unit #2	Motor rotor air gap slightly off; nothing else wrong
Unit #3	Oil clean; no abnormalities
Unit #4	Oil clean; no abnormalities
Indianapolis Power & Light	
Unit #1	Oil clean; motor rotor air gap slightly off; light copper plating on crankshaft and rod pin
Unit #2	Oil clean; light copper plating on crankshaft and rod pin
Unit #4	Oil clean; motor rotor air gap slightly off; light copper plating on crankshaft and rod pin
Kansas Gas & Electric	
Unit #1	Oil clean; no abnormalities
Unit #2	Oil black; excessive rod and piston wear
Unit #3	Oil clean; light copper plating on crankshaft and rod pin
Unit #4	Motor rotor air gap slightly off; nothing else wrong
Pacific Gas & Electric	
Unit #1	Oil clean; no abnormalities
Unit #3	Oil clean; no abnormalities
Unit #4	Oil clean; no abnormalities
Public Service of Indiana	
Unit #1	Oil clean; no abnormalities
Unit #3	Oil clean; no abnormalities
Unit #4	Oil clean; light copper plating on crankshaft and rod pin; assembly error*
Somerset Rural Electric Coop	
Unit #1	Oil clean; no abnormalities
Unit #2	Oil clean; light copper plating on crankshaft and rod pin
Unit #3	Oil clean; no abnormalities

*Wrong piston used during compressor manufacture

The compressor with severe wear and black oil was Kansas Gas and Electric Unit #2. Figures 3.18 and 3.19 show the distortion of the piston rod and pin from this unit and the darkened motor coil windings (a normal coil can be seen in Figure 3.17). These abnormalities all indicate severe overheating. Field-test records and the participant survey for this unit showed that the unit had lost refrigerant charge twice and had been operating with a high (145°F) tank thermostat setting. Because several of the other returned units had also lost charge but did not exhibit such wear, it is likely that this unit had operated for an extended period of time at low charge. This assumption is partially confirmed by the fact that the participating homeowner reported occasional hammering sounds from the unit during operation. Based on the clean condition of the other 19 units, Copeland concluded that this case represented an individual failure and was not indicative of a generic problem resulting from HPWH operation.

Field-test data for the unit with the incorrectly assembled compressor (Public Service of Indiana Unit #4) revealed an average COP about 4% lower than the test unit average. This difference is not significant enough to indicate that the incorrect compressor piston caused a problem, especially since no other evidence of abnormal wear was found in this unit.

The motor coil air gap variances in four units were not considered significant by Copeland. The motors might, in fact, have been assembled with these same tolerances. As the field-test performance data show, these four units all had slightly (2 to 4%) higher than average COPs (see Section 6 and Appendix C of reference 4).

Copper plating on bearing surfaces was found in six compressors. Copper plating is a relatively common and harmless condition in refrigeration systems where water vapor is present. It is caused by the water chemically reacting with oil and refrigerant, becoming acidic, and

Figure 3.18

COMPRESSOR WITH
DISTORTED PISTON ROD AND PIN
(Kansas Gas & Electric Unit #2)

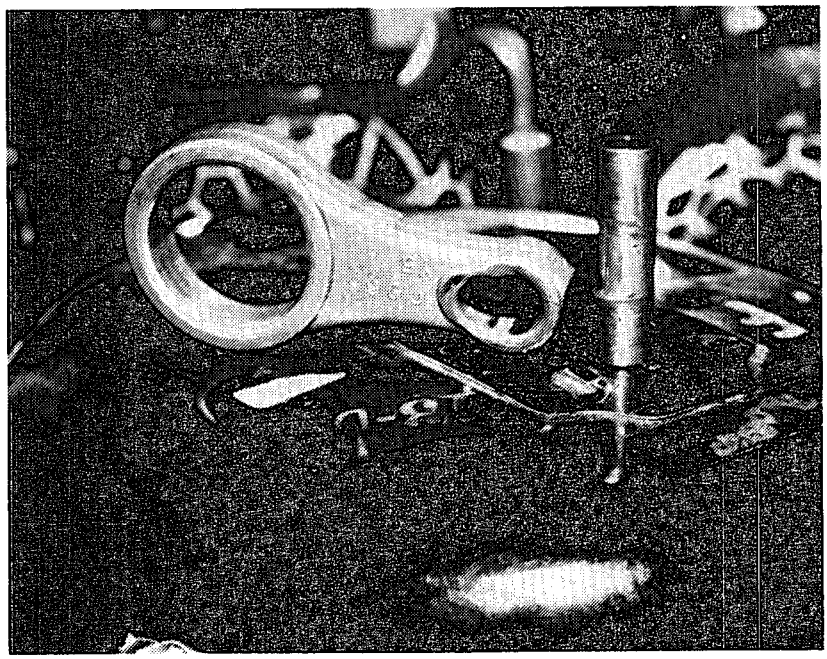
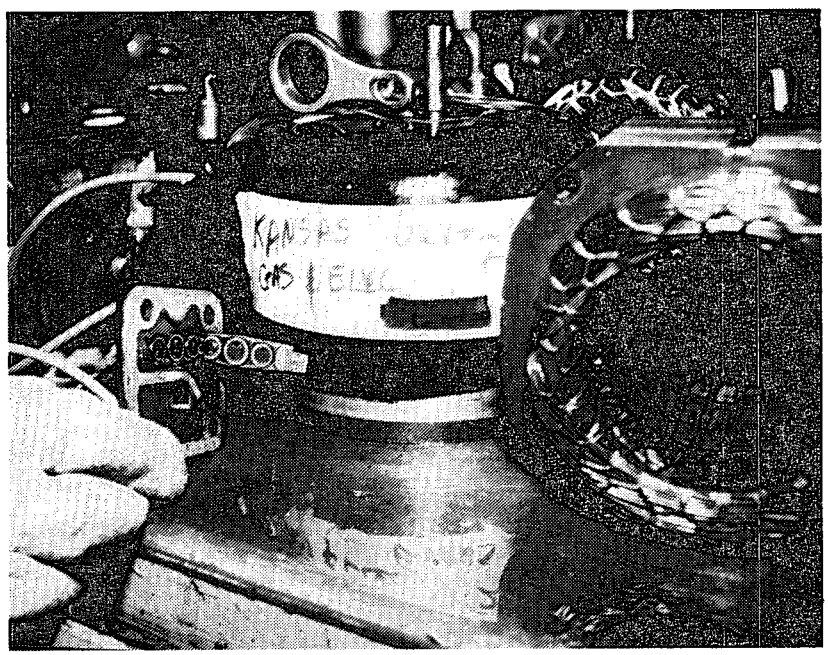


Figure 3.19

COMPRESSOR WITH DARKENED
MOTOR COIL WINDINGS AND DISCOLORED VALVE FLAPPER
(Kansas Gas & Electric Unit #2)



subsequently transferring copper to the hotter bearing surfaces. As Copeland engineering personnel indicated, such copper plating virtually never leads to compressor failure. Since only one of the six compressors had been serviced, the copper plating was most likely caused by insufficient system evacuation during production. Current production methods, however, achieve a more thorough system evacuation. Copper plating is not expected to be a problem with newer units.

Copeland engineering personnel were pleased with the evaluation results. They anticipated no significant reliability problems for their compressors in this HPWH application using R-12. Copeland considered wear to be minimal and saw nothing to prevent a compressor life expectancy of 10 years.

3.6 SUMMARY OF FINDINGS

Since the economics of major component repair and replacement determine a unit's useful life, assessment of the expected life of the major components is critical. For the HPWH the four major components in terms of both initial and replacement costs are the compressor, the water tank, the condenser, and the evaporator.

None of the compressors showed significant wear and, with only one exception, none showed signs of premature failure. One compressor did show severe valve overheating and connecting-rod deformation. Copeland, the compressor manufacturer, attributed these problems to abnormal service conditions such as sustained operation with low charge or loss of charge. The participant questionnaire and operating records verified that the unit had sustained loss of charge when initially installed. Based on the compressor examination results, Copeland engineering personnel consider a 10-year life realistic for this HPWH application using R-12 refrigerant.

Despite an average of 25 months of service, none of the 20 tanks examined showed any signs of severe corrosion. Twelve tanks were free of rust; eight showed some rust. Rust formations were found in three tank areas: around the water inlet and outlet openings where the glass lining was chipped or eroded; around the sharp edge of the tank dome at the tank cylinder (an area difficult to cover with glass lining); and on the tank walls where lining imperfections allowed spot rusting. In none of the cases was depth of rust measurable. All deposits wiped clean indicating no major breach of the glass lining.

Examination results did, however, show a strong correlation between accelerated magnesium anode depletion-tank rusting and water softener use. When water softeners are not used, tank life is expected to equal that of a standard electric water heater. Recommended design changes to prolong tank life by improving anodic protection are presented in Section 4.

The 20 condensers examined showed no corrosion. Scale, found on all but one of the condensers, varied in type and thickness. These deposits did not, however, affect overall heat transfer capabilities. Consequently, no performance degradation occurred as a result of scale accumulations on the condenser.

Some minor problems found with less critical components have already been addressed. Evaporator clogging should be alleviated by the optional filters available with current production HPWHs. And the rusting caused by condensate pan overflow should be eliminated with the new, larger condensate pan and drain incorporated on newer units.

4 RECOMMENDED DESIGN MODIFICATIONS

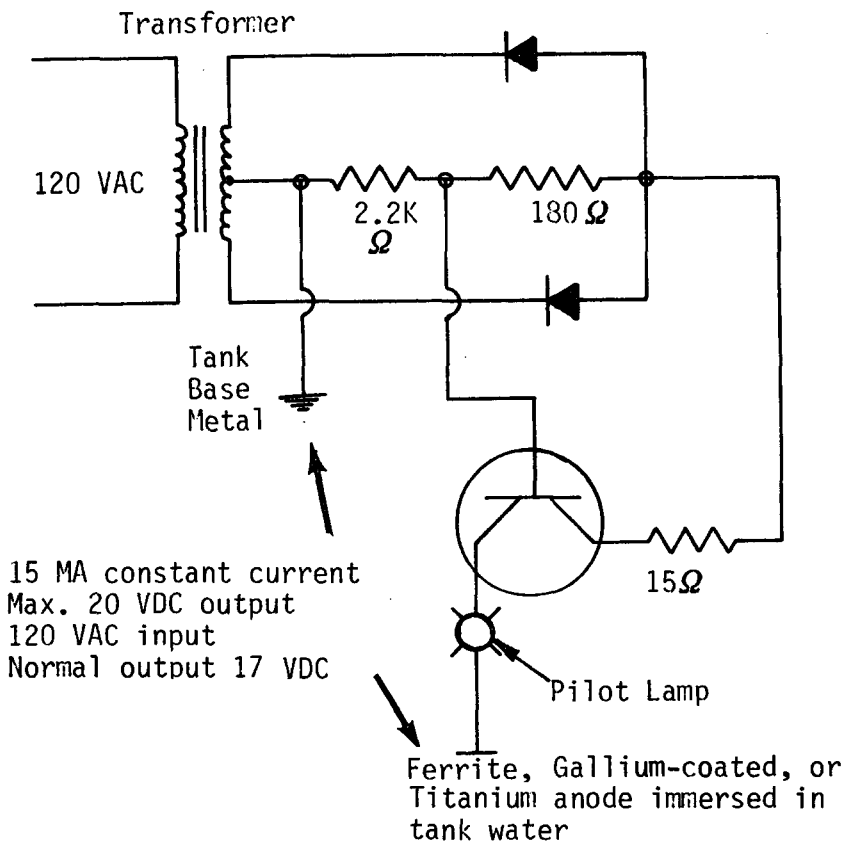
Results of the HPWH teardowns and evaluations indicate that the heat pump portion should be capable of performing properly for at least 10 years. The reliability and useful life of the system can, however, be jeopardized by certain operating conditions. The component most susceptible to premature failure is the water tank. As indicated in Section 3.3, the use of water softeners on HPWH supply water appears to significantly increase the rate of anode degradation and the formation of corrosion cells. Improved anodic protection is required to prolong tank life--at least for those units installed with water softeners. Periodic replacement of the anode rod could significantly extend tank life. But this solution is not cost-effective to the customer because of labor costs involved with replacing the 43-inch-long anode in locations with minimum clearance above the HPWH.

Several design modifications can be made to improve anodic protection. Some of these modifications have, in fact, already been made on current production HPWHs. In the original field-test units, for example, the anode rod extended through the center of the condenser. As a result, that portion of the anode inside the condenser was found to have plated onto the center of the condenser loop rather than onto the tank. In current production HPWHs the anode rod is located outside the condenser coil to minimize plating to the condenser.

Another means of improving anodic protection is to install two anodes in the tank. For most tanks installed in houses without water softeners, this would essentially ensure a 10-year tank life based on the evaluation presented in Section 3.3. Whether the improvement would be sufficient with a water softener installed is not, however, clear because most units used with softeners had completely depleted anodes after an average of only 26 months of service.

Using non-depleting, powered anodes may be a more practical solution to the problem with softened water. These devices induce a small, low-voltage direct current (typically less than 1/3 watt) through the tank water to counter the current of the galvanic corrosion cell. Power is obtained from a small power supply driven by the water heater's electrical source. A schematic of the system is shown in Figure 4.1. Because the powered anode is non-depleting, it can protect the tank for an indefinite period. The non-depleting anode does, however, have disadvantages. A powered anode increases the initial cost of the HPWH and, based on its size, can only protect a finite area of exposed metal (either tank wall or condenser coil).

Figure 4.1
ELECTRIC ANODE SCHEMATIC



The large condenser metal mass in the HPWH represents an electrical current "sink" that must be electrically insulated so that the anode's protective current capacity is not exceeded. One relatively simple method of insulating involves coating the condenser with an organic material such as nylon. The organic coating can be applied, using a fluidized-bed process, in the form of very small particles and then baked on.

Tests by the HPWH manufacturer using such a coated condenser in a standard 82-gallon unit show only a small (several psi) rise in refrigerant system pressures, indicating that the coating does not represent a significant thermal resistance compared to the natural convective boundary layer.

The organic coating could be used with a sacrificial anode instead of a powered anode. The coating would extend the useful life of the sacrificial anode by eliminating plating onto the condenser. Although this modification should result in a tank life expectancy identical to a standard electric water heater, it does not resolve the corrosion problems if softened water is used.

Further testing is needed to ensure that no significant electrical "blockage" of tank areas occurs because of the insulated condenser and that the powered anode current is sufficient when used in HPWHs with softeners. The powered anode and condenser coating concepts do, however, appear to be viable solutions to the tank corrosion problem, and are being pursued by the HPWH manufacturer.

The only recommendation regarding the heat pump section is the addition of an air filter for units that will be installed in areas with large amounts of dirt or dust. A filter would reduce the possibility of severe evaporator clogging. Homeowners would, of course, have to clean the filters periodically to prevent airflow restrictions, but cleaning a filter is much simpler than cleaning an evaporator. Because the air inlet opening is relatively small (10½-inch diameter), a domed filter

provides more surface area and less flow resistance. A dome-shaped filter, made of expanded metal (like that used on range hood filters), is offered by several filter manufacturers, and can easily be mounted atop the HPWH.

Other modifications have already been made as a result of early field-test experience. These are described in reference 4.

Condenser scaling caused by hard water does not appear to be a significant problem in most cases. Although there are likely to be locations with extremely high hardness levels where scaling could become a problem, no design modification appears to be required to compensate for scaling.

With the incorporation of the modifications recommended here, the HPWH, which already appears to be a reliable device in many applications, should perform properly for periods approaching or exceeding 10 years.

REFERENCES

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5. Langelier, W. F. "Chemical Equilibria in Water Treatment," J. Am. Water Works Assoc., 38 No. 2, 169 (February 1946)

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8. ASHRAE 1980 Systems Handbook, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1980.

APPENDIX A

QUESTIONNAIRES

Water Sample Questionnaire A-1
Participant Questionnaire A-2

Bottle ID# _____

WATER SAMPLE QUESTIONNAIRE

(Return this Form with Bottle)

Name: _____

Location of Unit: _____

Date: _____

1. a. Source of water: (well, spring, municipal, utility, etc.)

   b. If utility, name of water supplier:

2. a. Is any water softener or conditioner in your supply line to the TEMCOR? Yes/No

   b. If so, what type, brand name?

3. a. Has there been any change in the quality or source of supply water since the TEMCOR was installed? Yes/No

   b. If so, please describe:

INSTRUCTIONS FOR SAMPLING

1. Take sample from any cold water spigot in the house. However, where water softeners or conditioners are used the water sample must be taken from softened or conditioned cold water.

2. Do not contaminate bottle or use any transfer container between supply and bottle.

3. Run water for approximately 1/2 to 1 minute before sampling. Rinse the bottom by filling two to three times before taking sample.

4. Seal sample bottle and return with this form completed.

Utility name _____

TEMCOR location _____

Participant Questionnaire

Please answer the following questions regarding the operation of your field test unit up to the time of replacement.

1. When draining the unit was there any significant sludge? yes no

   Color? rust black white

2. What temperature was the unit thermostat setting? 110 120 130 140

3. Has the thermostat setting been changed? yes no

   If yes, how many times? _____

4. Has the unit ever required services? yes no

   If yes, how many times? _____

5. Has unit noise level changed over time periods during operation?

   yes no

   _____ louder _____ softer

6. Has the unit condensation been excessive or required special service?

   yes no

7. General comments/specific problems:

APPENDIX B

TEARDOWN PROCEDURES AND CHECKLISTS

Procedure for Field Test Unit Disassembly and Examination B-1

Examination Checklist for Field Test Units B-3

Compressor Teardown Procedure B-9

PROCEDURE FOR FIELD TEST UNIT DISASSEMBLY AND EXAMINATION

The following procedure and attached checklist are to be used in the examination of each of the 20 field test units by EUS, Inc., Pittsburgh. A checklist will be completed and filed with each unit's photographs as the examinations are completed.

1. Upon receipt of each crated unit at EUS, Pittsburgh, inspect packaging for shipping damage such as punctures, broken crating, etc., and photograph any damage found.

2. Uncrate the unit and attach a 1-1/2" x 3" (approximate size) adhesive label on top of the heat pump cabinet to identify unit number, date, and field location (name of participant).

3. Complete inspection and photograph all damage or unusual conditions.

4. Examine and disassemble the unit in the following order using the attached checklist for completeness and records of observations. For every item on the checklist, enter a positive record of observation (e.g. O.K., none, etc.) or describe the condition found in the 'Notes' section of checklist. Refer to the Service Manual for detailed instructions when necessary. Prepare a small identification sign to be used for all photography.

   A. Remove the heat pump cabinet top cover and inspect and photograph per checklist.

   B. Cut two condenser refrigerant lines, dismount and remove the heat pump cabinet from the tank.

   C. Dismantle the heat pump cabinet by removing wiring, unbolting the wrapper and insulation, and cutting copper tubing to permit removal of the compressor, evaporator, and TXV valve.

   D. Purge the evaporator with dry nitrogen. Collect any compressor oil, measure using graduated cylinder (1 ml. increments), and note on checklist.

   E. Remove compressor unit and set aside.

F. Remove the access covers, thermostats, and upper and lower resistance heating elements, taking care not to disturb any scale formation. Using a micrometer, measure the scale thickness in three locations, record, note location, and photograph per checklist.

G. Remove the magnesium anode located in the center of the condenser coil. Weigh the anode ($\pm$ .5 oz.) and record shape and condition per checklist. Calibrate scale using weights with known accuracy of $\pm$ .25 oz.

H. Remove six-condenser flange mounting bolts and carefully remove condenser from tank and tag it consistent with Step 2. Measure scale thickness on the inside and outside surfaces of coil. Photograph and record all observations per checklist.

I. Purge condenser with dry nitrogen. Collect any compressor oil in graduated cylinder (1 ml. increments), measure, and record per checklist.

J. Measure and record amount of oil in the compressor using 1 ml. graduated cylinder. Return all oil collected from the condenser or evaporator to the compressor inlet and seal both suction and discharge ports using rubber stoppers.

K. Label the compressor, marking the unit number and field test location; package the compressor, and ship to the manufacturer for life test evaluation.

L. Remove the T & P valve, drain valve, and hot and cold water fittings from the tank.

M. Remove the tank sheath and insulation, and photograph unusual conditions.

N. Attach a small hoist to the tank flange and lift the tank approximately 1 inch above the floor. Place a wood board underneath for cushioning. Flame cut the tank in half, circumferentially, approximately 2 feet above its bottom.

O. Examine tank sides, seam weld, and top for corrosion sites and damaged threads in pipe joints. Photograph any unusual conditions.

P. Examine the tank bottom for sediment or sludge noting color, consistency, and depth. Record observations and photograph.

Unit I.D. _____

Date _____

Technician _____

Engineer _____

Date Compressor Shipped to Mfgr. _____

Total Hours Spent _____

EXAMINATION CHECKLIST FOR FIELD TEST UNITS

ıeck
ch item
ımpleted

Receipt Inspection

_____Label unit, mark field location and date on top of heat pump cabinet

_____Photograph damage

_____Make up photographic identification sign

TES:

Condition of Heat Pump Section

_____Cabinet wrapper-insulation, water damage (photograph)

_____Fan blades - looseness, dirt

_____Fan motor - overheating, dirt, insulation

_____Evaporator coil air passage, blockage ___% of face area blocked

_____Rust on base plate, condensation evidence

_____Brazed joint corrosion, seepage

_____Drip tray/tube - staining, leakage

_____Condenser blow-off cap-sealed

_____TXV valve-bulb attachment integrity

_____Wiring insulation, connections

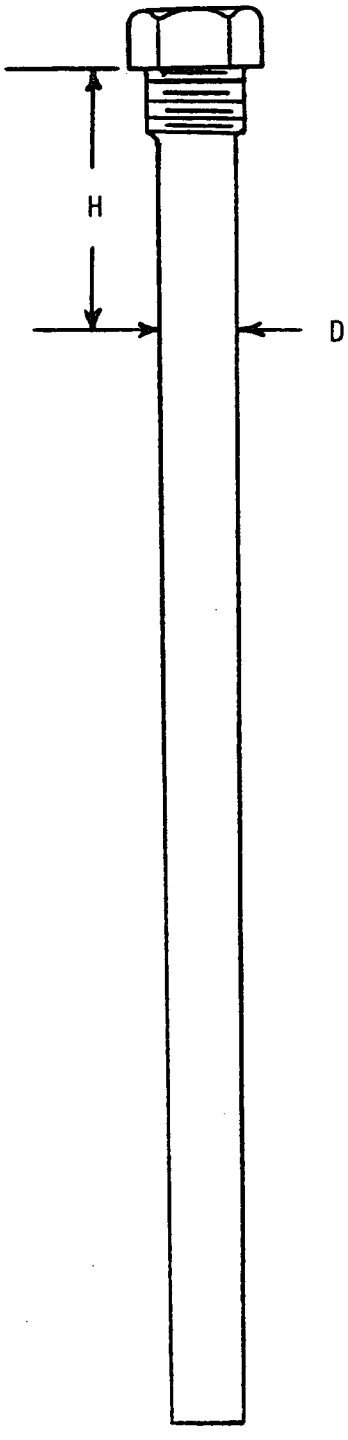
_____Carefully purge evaporator with dry nitrogen, collect and measure any accumulated compressor oil ____ml.

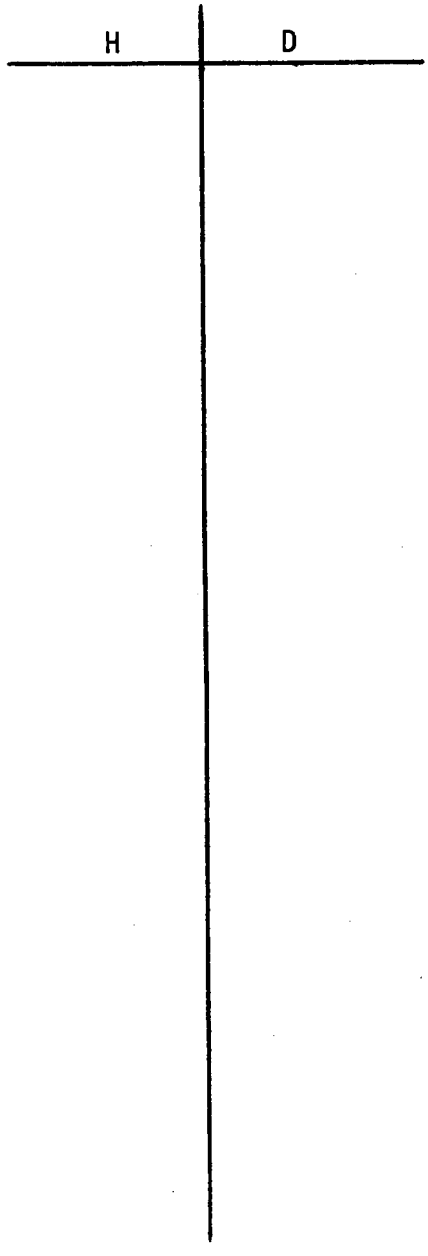
TES:

Condition of Anode

_____ Weight of Anode: _____lb. _____oz. (±.5 oz.)

_____ Record shape by measuring diameter at various heights and recording below





Condition of Resistance Heating Elements

_____ Heating surface - scaling, deposits, uniformity, depth _____inch

_____ Electrical connections - corrosion, evidence of arcing, frayed insulation

_____ Mechanical condition - integrity, fasteners, threads, etc.

_____ Thermostats - safety reset button depresses, contacts open

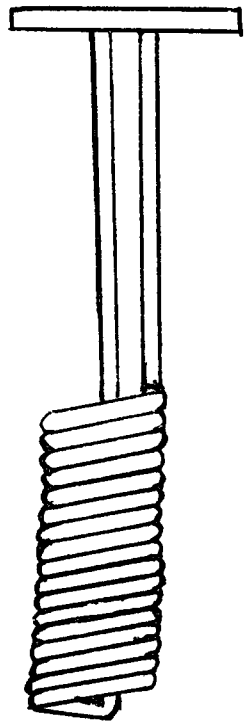
)TES:

Condition of Condenser

_____ Flange bolt corrosion
_____ Flange gasket seal - condition, hardness, amount of sealant used
_____ Brazed connections to flange - cracks, plating condition
_____ Inside of coil tubing - general surface condition
_____ Red fluid in the annulus - leakage, cap condition
_____ Coil rubbing marks (photograph)
_____ Purge with dry nitrogen, collect and measure any compressor oil _____ml.
_____ Scaling - local or general, color, thickness (photograph)
_____ Measure scale and show location below

_____ inch thick

_____ inch thick



NOTES:

Condition of Tank Fixtures and Covering

_____ T & P valve, manufacturer_____, rating_____
corrosion, scale, cracks, etc.

_____ Drain valve

_____ Cold water inlet

_____ Hot water outlet

_____ Tank jacket - paint blistering, corrosion, seam weld integrity, stains

_____ Insulation - uniformity, evidence of wetting

OTES:

Condition of Tank

_____ Sludge depth _____inch (photograph)

_____ Corrosion _____% of surface area, locations, uniformity

_____ Tank seam weld - corrosion, weld quality

_____ Thread of pipe joints - rusting, incomplete engagement, overtightening

OTES:

:her Observations:

Condition of Compressor

_____ Measured amount of oil remaining in compressor _____oz.

_____ Brazed connections - joint integrity, corrosion

_____ Wiring - water tightness of junction box, connection integrity, insulation condition

_____ Mounting - hardness of rubber, cracking, degradation, etc.

_____ Casing - evidence of heat, corrosion, paint blistering, etc.

_____ Label compressor and mark unit number and field test location

_____ Ship compressor to manufacturer, _____ date shipped

COMPRESSOR TEARDOWN PROCEDURE

Copeland Laboratory technicians performed the following teardown/inspection steps on each of the 20 compressors in their Sidney, Ohio, compressor rebuild plant labs:

1. Separate hermetic can into halves using can-cutting machine.

2. Energize motor briefly as an operational check, monitoring volts, amps, and watts.

3. Perform dielectric test at 2300 volts between each of the three electric leads and ground (motor can).

4. Remove the can and examine oil for discoloration and insulation for hot spots.

5. Examine inside of can for rubbing, corrosion, etc.

6. Check the air gap between rotor and stator winding using feed gage.

7. Disassemble motor head, valves, crank, etc.

8. Examine suction and discharge valves, flappers, and seats for wear, copper plating, and evidence of overheating.

9. Remove rotor from stator and examine laminated surfaces.

10. Examine all bearing surfaces on crankshaft and crank pin and connecting rods for copper plating and wear. Check looseness of crank pin in the connecting-rod bore.

11. Inspect piston and teflon ring for evidence of wear/overheating.