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The Degradation of Gas-Fired Water Heaters

George F. Sushinsky

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U.S. DEPARTMENT OF COMMERCE

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1. INTRODUCTION

In a corner of the basement, in a closet, under a counter, or sometimes, in the way stands the lonely water heater. A forgotten object for the most part, the water heater continually works to provide hot water for laundry, bathing, and other household uses. Unlike the residential heating and cooling systems that are seasonally operated, the water heater presents a constant drain on the household energy budget as it consumes, on the average, 14 percent [1]* of the household energy used; it is second only to residential space heating at 56 percent [1] of household energy use. As such, water heaters fall under the jurisdiction of the "Energy Policy and Conservation Act" (Public Law 94-163) which mandated the implementation of an energy conservation program for consumer products. Under this law energy efficiency improvement targets for specified appliances (including water heaters) were prescribed.

Maximum feasible improvements in the energy efficiency of covered products were encouraged by P.L. 94-163. This concept extended not only to manufacturing capabilities but also to the necessity for any improvements to be "economically justified" as feasible. That is, the benefits of reduced energy use and operating costs over the estimated average life of the product must be greater than the added costs of the improvements plus any associated increased costs of operation. These anticipated savings in energy and operating costs may not be realized if the product efficiency degrades during the life of the product; thus, a consideration of energy efficiency degradation becomes important. A test program was initiated to study the energy efficiency degradation of one of the products covered by P.L. 94-163, the gas-fired water heater.

Water composition is the most important factor controlling water heater degradation. Of particular importance are highly mineralized (hard) waters that produce deposits in the forms of scale and sediment. The accumulation of these deposits can affect water heater performance, reduce water heater energy efficiency, increase service costs (e.g. electric water heater element burnout), and reduce the water heater's operating life. For the case of a gas-fired water heater, the accumulation of these deposits on the tank bottom (bottom head) and flue wall can affect the heat transfer from the flame and the hot flue gases to the water, resulting in a reduction in energy efficiency.

The primary purpose of the work covered in this report was to determine the significance of the energy efficiency degradation due to mineral deposit accumulation in typical gas-fired water heaters and to estimate the magnitude of the occurrence and geographical distribution of mineral deposit buildup. Water heaters using other fuels (oil, and electricity) were not specifically covered by the results presented in this report.

*Numbers in brackets refer to references on page 39.

Oil-fired water heaters with heat transfer systems comparable to those in gas-fired water heaters would be similarly affected by mineral deposit buildup; while electric water heaters do not suffer from these same effects.[a]

Used gas-fired water heaters were obtained from several known deposit-producing areas around the country for this study. These water heaters were inspected for deposit formation and then tested in both a recovery and standby mode of operation. In addition to energy efficiency degradation, three other forms of degradation were identified: lifetime, safety, and performance degradation. The causes and effects of each form of degradation are discussed in this report. The effects of these "aging processes" (degradation) of the water heater are considered in terms of the improvements to energy efficient operation that might be realized by proper maintenance and servicing of the water heater throughout its life.

This work was performed at the National Bureau of Standards in the Product Engineering Division of the Center for Consumer Product Technology, and was performed in conjunction with Federal Energy Administration sponsored work on water heater test method development [2] that was also performed at NBS. Sincere appreciation is extended to Robert Palla for his helpful contributions throughout this experimental program, and to Rose Massengill for manuscript preparation.

2. GAS-FIRED WATER HEATER CONSTRUCTION AND OPERATION

The residential gas water heater (Figure 1) is a relatively simple appliance in terms of construction and operation. Typically it consists of an insulated water storage tank (110 to 190 liter (30 to 50 gallon))[b] capacity), and a gas-fired burner (7.3 to 22 kW (25000 to 75000 Btu/h) firing rate). Cold water enters the tank from the cold water supply through a dip tube which carries the water to the bottom of the tank for heating. This incoming cold water pushes hot water upward through the tank outlet. A drain is provided about 5 cm above the edge of the convex tank bottom for the purpose of tank flushing, cleaning, or draining. The internal surfaces of the tank are usually protected from corrosive chemical attack by a glass lining and a sacrificial magnesium anode (not shown in Figure 1).

[a] Heavy deposit accumulations on electric water heating elements may reduce recovery rate (a performance penalty) but should not significantly affect the energy efficiency of the electric water heater. All of the energy from the heating element(s) will still be transferred to the water. However, heavy scale deposits on electric water heating elements will promote a reduction in operating lifetime through element burnout.

[b] S.I. units have been used throughout this report. Customary units have been included after the S.I. units for clarification in those cases where they are normally encountered in common usage (e.g. 110 liter (30 gallon water heater).

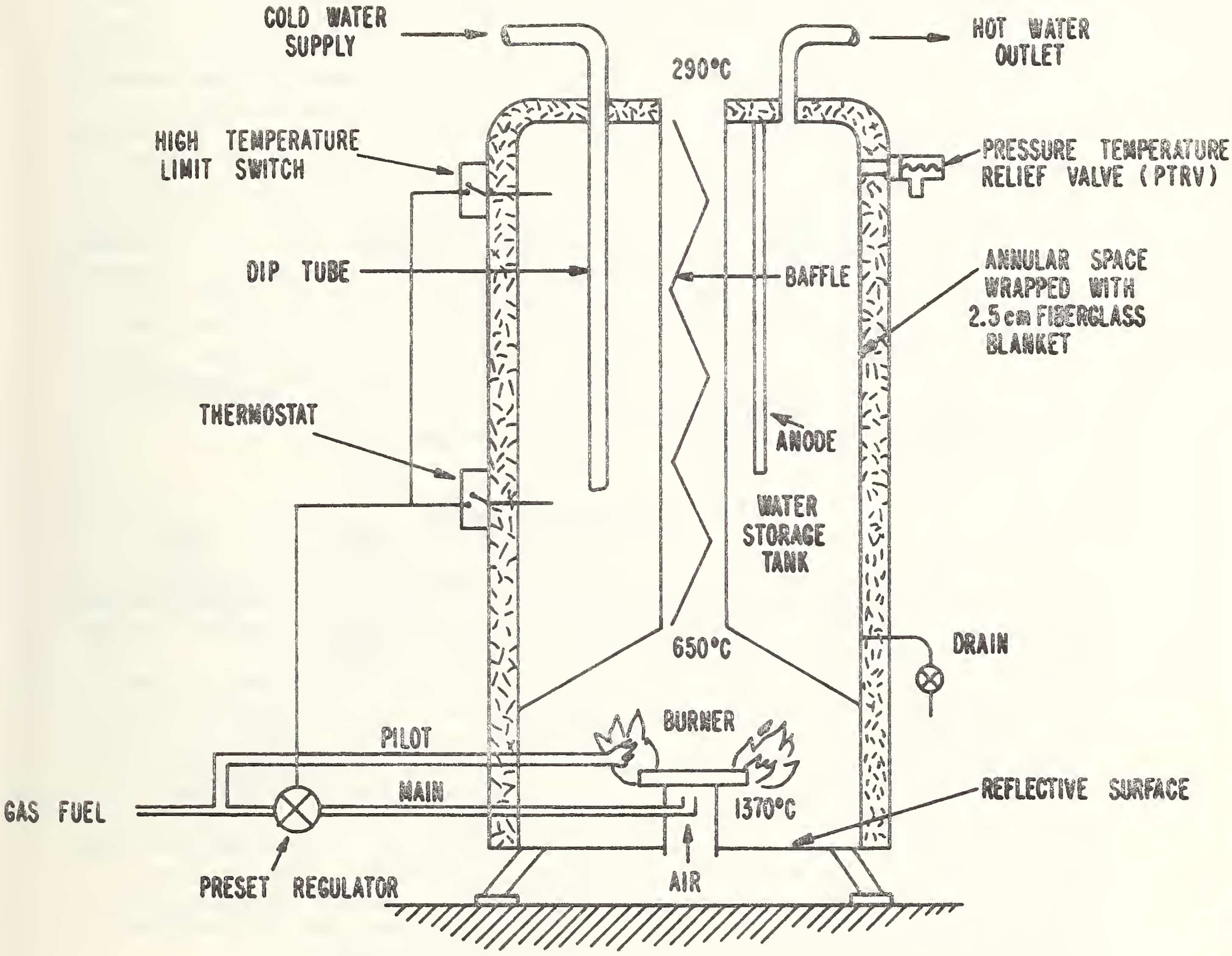

Figure 1 Schematic of a typical gas-fired water heater.

In operation the water heater is designed to (1) heat cold water to a desired temperature, (2) store the hot water near that temperature, and (3) deliver the hot water, in sufficient quantities to satisfy the users' demands. The operating mode of each of these functions is termed (1) recovery, (2) standby, and (3) performance[c]. A degradation in the energy efficiency operation of a gas-fired water heater would principally affect recovery.

In the recovery operation, gas enters the burner (Figure 2) from the main supply through an orifice opening. The gas is mixed with the primary air supply, ignited by the continuously burning pilot, and burned in the presence of secondary air at the burner head. The burner, located in the combustion chamber beneath the water tank, transfers energy to the water by passing hot combustion gases from the burner over the tank bottom and through the flue of the water heater. The transfer of heat is enhanced by baffling in the flue and other restrictions to the secondary air supply entering the combustion chamber. Current water heater designs provide baffling and air supplies that result in flue gas temperatures of 290°C at the flue exit with excess air levels (primary and secondary air in excess of that required for complete combustion) greater than 50 percent. Under these conditions, minimum recovery efficiencies of about 70 percent are obtained. A decrease in the recovery efficiency operation of the water heater is equivalent to a decrease in the heat transfer ability of the water heater. Such decreases can result from the presence of insulating layers of scale on the bottom and flue wall of a water heater or deterioration in burner operation or water heater baffling.

3. LITERATURE SURVEY

A literature survey was conducted to determine the existence of previously published information on the extent of a mineral deposit buildup problem in terms of geographical distribution and severity, and to relate this information to water heater energy efficiency degradation. Information pertaining to water heaters, water heater efficiency, water heater degradation, water quality, corrosion and scale, water treatment, etc. was sought. This survey included texts, magazines, technical society journals, published papers and reports, geological survey data, and abstract collections. In addition, two data bases available through the NBS Library computer retrieval systems (Lockheed DIALOG and ERDA/RECON) were searched for information in those subject areas. Collected data from these sources, were compared and refined with respect to each source in order to obtain an overall picture of the extent (numbers and geographical distribution) of a potential deposit build-up problem and its resultant effect on the energy efficiency of gas-fired water heaters.

[c] Water heater performance is closely related to the recovery mode of the water heater. As defined here, performance is also dependent on other factors including: heat transfer rate from the source to the stored water, the distribution of heated water in the tank, mixing of the incoming cold water, flow rate, and tank volume.

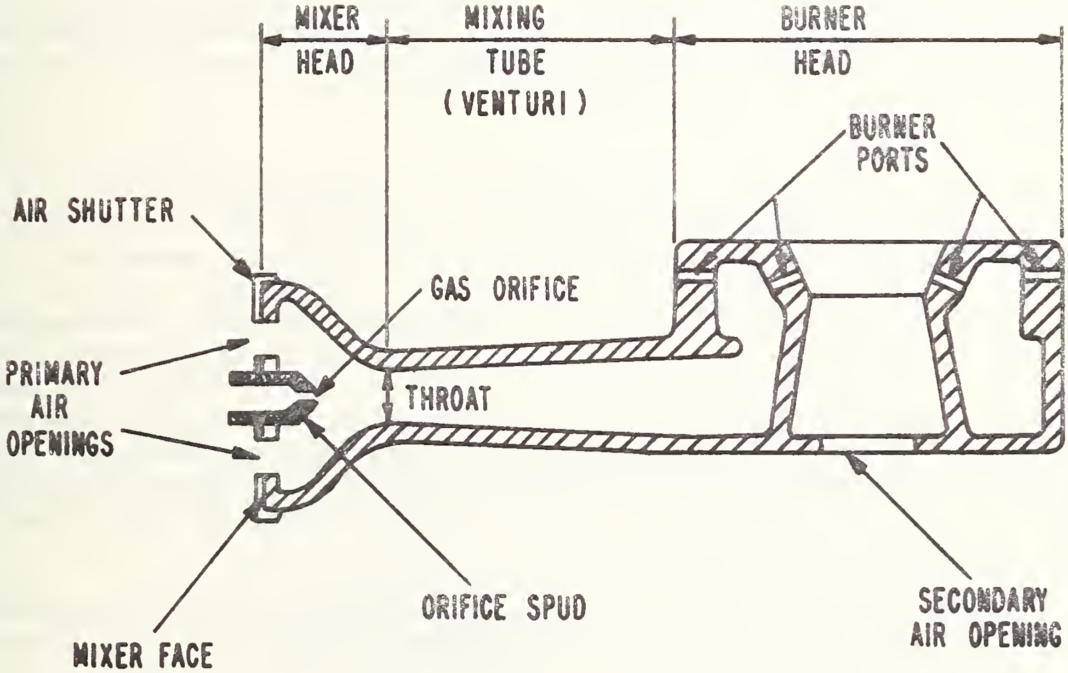

Figure 2 General design of an appliance gas burner.

3.1 Water Composition and Scale Formation Tendency

To some extent, all water heaters undergo an internal attack (either corrosive or scaling) that is caused by continuous contact with the water and controlled by the mineral content of the water. Two measures of the amount and nature of the mineral components in a water supply are the total dissolved solids (TDS) content and the hardness level.

The TDS content is a measure of the mineral constituent dissolved in the water. Typical values of TDS content in municipal water supplies range from 0 to more than 1000 ppm. According to the U.S. Public Health Service, water supplies with TDS levels greater than 500 ppm are undesirable for drinking purposes [4]. Water heater lifetimes tend to decrease with increasing dissolved solids levels [5,6].

Hardness is a more commonly recognized describer of water quality. Hardness is a measure of the calcium and magnesium in water and is commonly expressed as the equivalent amount of calcium carbonate (ppm) that can be formed from these minerals in solution. Water hardness levels (both low and high) are reported to effect plumbing system life [5,7,8] household economics [5,8,9,10] and human health [11,12].

Hardness levels in finished public water supplies range from 0 to more than 180 ppm. A hardness level of from 0 to 60 ppm is subjectively considered "soft", while hardness levels in excess of 120 ppm indicate "hard" water. Hard water is generally conducive to scale formation.

Any reasonable, qualitative measure of the scale-forming tendency of a water supply is dependent on other factors in addition to hardness. The Langelier Saturation Index [13] and the Ryznar Stability Index [14] each provide a semi-quantitative measure of the tendency of a given water to form scale. In the formulation of these indices both hardness and dissolved soilds levels are used along with other water parameters, the pH, alkalinity, and operating temperature, to provide an indication of the scale formation tendency of the water.

Both the Langelier and Ryznar indices are based on the calculation of the saturation pH (pH_s) of the water. A tabulated form for calculating the saturated pH of a water is given in Appendix A.

The Langelier Saturation Index (I_s) is given as the algebraic difference between the actual pH and saturation pH,

$$I_s = pH - pH_s. \qquad (2)$$

For positive values of I_s scale formation is predicted.

The Ryznar Stability Index is given by

$$\text{Stability Index} = 2\,pH_s - pH. \qquad (3)$$

Stability Index values less than 6 are scaling. From data in Reference 14 the stability index appears from field experience to predict not only scaling tendency but also the relative amount of scale formation.

Both the Langelier and Ryznar indices were used to evaluate the scale-forming tendencies of finished municipal water supplies in order to select areas from which scaled water heaters would most likely be obtained.

3.2 Extent and Effect of Scale Formation

Hard water is commonly cited as the chief cause of scaling problems in plumbing systems and appliances. In the absence of the other water quality parameters necessary for the calculation of both indices (equations 2 and 3), a hard water level of 120 ppm or greater was used to indicate scale formation tendency for municipal water supplies. Using this assumption, there are 20 states with a combined population of 94 million people (1970 census) that have, on an average statewide basis, hard and potentially scale forming public water supplies [15], Figure 3. This large population group has 24 million residential water heaters of which 17 million are gas-fired [16]. Eighteen percent of this group soften their water [5], therefore, 14 million water heaters are potentially subject to scale-produced problems.

The widespread deposition of scale is not in itself a serious problem since thin layers of scale can provide a beneficial buffer against plumbing system corrosion. But reports of water heaters 10 to 70 percent full of scale have been made [17,18]. Such large amounts of scale impose penalties in reduced water storage capability in addition to any energy efficiency degradation.

Estimated increases in fuel consumption (corresponding decrease in energy efficiency) of 20 to 50 percent have been attributed to large buildup of scale in boilers and water heaters [9,16,19,20,21]. For the gas-fired water heater this degradation is due to the preferential buildup, on the flue and the bottom head of the water heater, of an insulating layer of scale. (Scale as an insulator has a thermal conductivity value (k) approximately equivalent to firebrick [21]). For 14 million affected water heaters the extent, in terms of geographical distribution and severity of scale occurence, is more than significant. However, no quantitative experimental evidence relating scale accumulation to energy efficiency degradation was found in the literature survey.

4. SPECIMEN COLLECTION

Based on information obtained in the literature survey (particularly reference 22), 11 major metropolitan areas were identified as having treated municipal water supplies with scale-forming tendencies. The scale formation tendency of a given water supply was judged according to both the Langelier (L) and Ryznar (R) indices of those waters at 60°C as given by equations 1 through 3. A list of these 11 cities and the calculated indices of their municipal water supplies are given in Table 1.

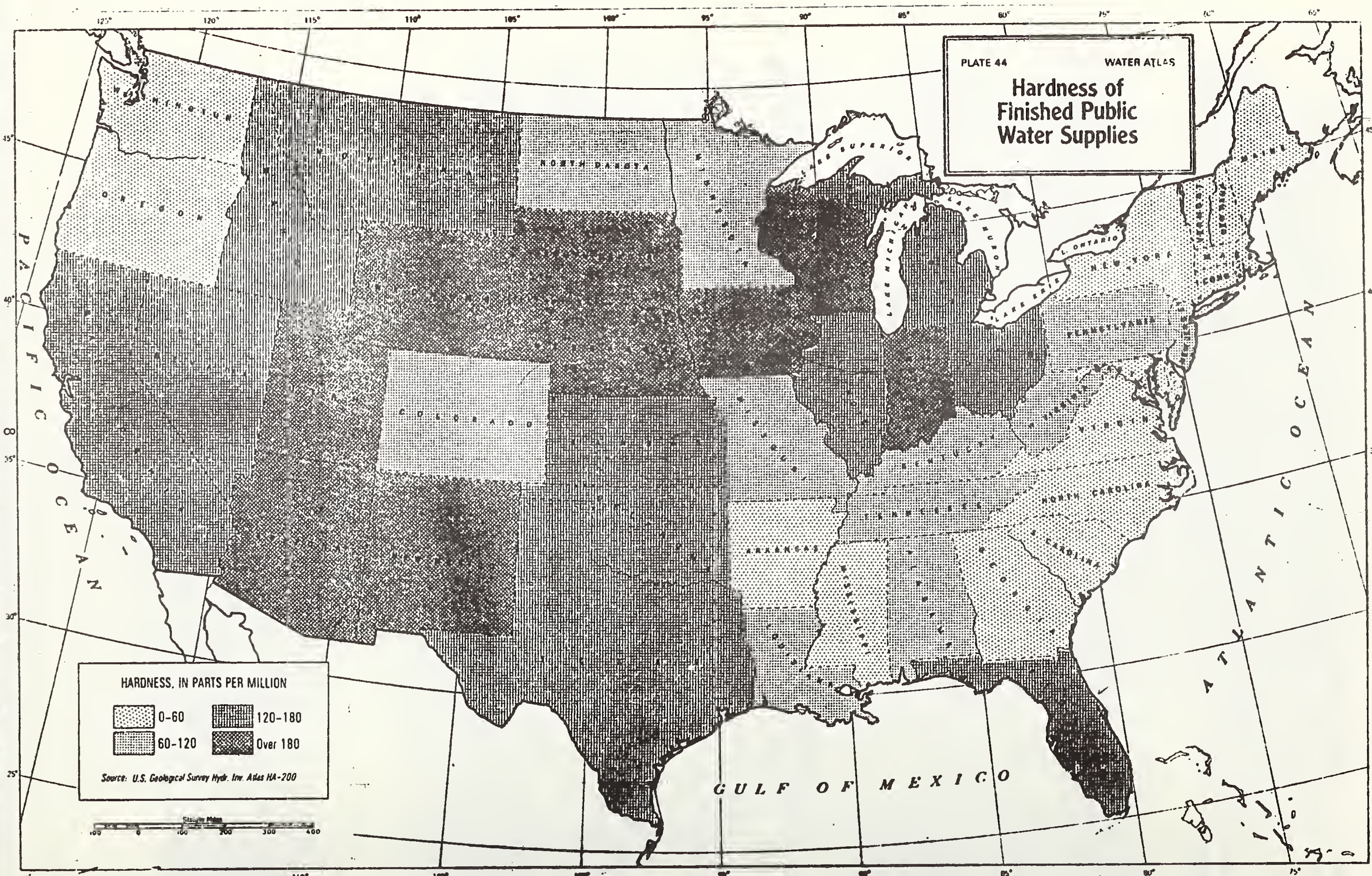

Figure 3 Hardness of Finished Public Water Supplies

Table 1 - Cities Supplying Water With Scale-Forming Tendencies (1962 Data)

City	State	L[a]	R[b]
San Diego	Calif.	1.7	5.3
San Jose	Calif.	1.6	5.0
Lubbock	Tex.	1.0	5.2
		1.0	5.1
		0.8	5.6
Amarillo	Tex.	0.9	5.5
		0.6	6.0
South Bend	Ind.	1.1	5.3
		0.9	5.5
		1.0	5.3
		1.3	4.7
Indianapolis	Ind.	0.6	6.0
		0.9	5.5
Rockford	Ill.	1.3	5.0
		1.3	4.9
Madison	Wis.	1.4	4.8
		1.5	4.8
		1.3	5.0
Kansas City	Kans.	0.9	5.9
Oklahoma City	Okla.	2.2	5.5
Lincoln	Nebr.	0.9	5.8

(a) Scale formation is predicted for L values positive - no quantititive estimation of scale formation is provided

(b) $R > 7$, plumbing system corrosion; $7>R>6$, neutral; $R<6$, scale formation; $R<5$, heavy scale

Efforts were made to obtain used water heaters from these and other locations. Plumbers, general contractors, municipal and private solid waste disposal personnel were asked to ship used water heaters containing scale for test purposes. Private sources from the metropolitan District of Columbia area and one of the two largest water heater manufacturers, State Industries, were also asked to provide specimens for use in the test program.

Twenty-six water heaters from various areas of the country were received for testing as a result of contacts in 4 of the 11 selected cities, State Industries cooperation, and private sources in the metropolitan District of Columbia area. One new 150 liter (40 gallon) water heater was also obtained in order to establish benchmark data on energy efficiency and energy efficiency degradation experiments.

This group of water heaters, ranging in age from less than 5 years to more than 20 years, included an external flue gas-fired water heater, an off-center flue gas-fired water heater, and one 24 year-old electric water heater with several features apparently designed for energy efficiency including an integral heat trap and a 7.5 cm thickness of insulation. None of these water heaters, however, contained other than slight amounts of sediment or loosened scale on the tank bottom.

Ten water heaters in this group were tested during this project. The main physical characteristics of these 10 water heaters are presented in Table 2.

5. LABORATORY FACILITIES

The test station established for the work on gas-fired water heater degradation is shown in Figure 4. The necessary equipment and utilities for testing one gas-fired water heater were available at this station. The equipment consisted of: (1) a precision wet-test gas meter (1.8 m^3/h capacity), (2) a multipoint temperature recorder with Type T or K thermocouple readout capability (0 to 100°C temperature range), (3) thermocouple probe(s), (4) a gas-pressure gage, (5) a gas-temperature thermometer, (6) a water-pressure gage, (7) a flue-temperature thermometer, and (8) an expansion tank, pump, and drain (not shown in the figure). The general building supply of hot and cold water and natural gas were available. Auxillary equipment needed for the test program, namely a gas calorimeter for continuously monitoring the incoming natural gas supply heating value, an infared-analyzer to measure CO and CO_2 levels in the flue gas, a portable oxygen analyzer to determine excess air, and an electronic barometer were readily accessible and were used when needed.

Table 2 - Water Heater Specimen Characteristics

Specimen	Origin	Age	Tank Volume		Main Burner Rate, q		Pilot Rate	
		Years	liter	gal	kW	Btu/h	W	Btu/h
1		New	144	38.1	14.6	$50x10^3$	230	800
2[a]	Wheaton, MD	7	143	37.8	10.3	$35x10^3$	290	980
3[b]	Arlington, VA	17	107	28.3	8.8	$30x10^3$	250	860
4	Rockville, MD	15	141	37.3	8.5	$29x10^3$	250	850
5	San Diego, CA	12	142	37.6	11.4	$39x10^3$	440	1500
6[c]	Madison, WI	20	104	27.6	6.7	$23x10^3$	230	790
7	Rockford, IL	-	105	27.8	9.7	$33x10^3$	-	-
8	Torrence, CA	5	142	37.6	14.1	$48x10^3$	210	700
9	Oceanside, CA	5	144	38.0	14.4	$49x10^3$	250	860
10	Huntington Beach, CA	7	185	49.0	15.8	$54x10^3$	350	1200

(a) collapsed flue

(b) off center flue

(c) external flue

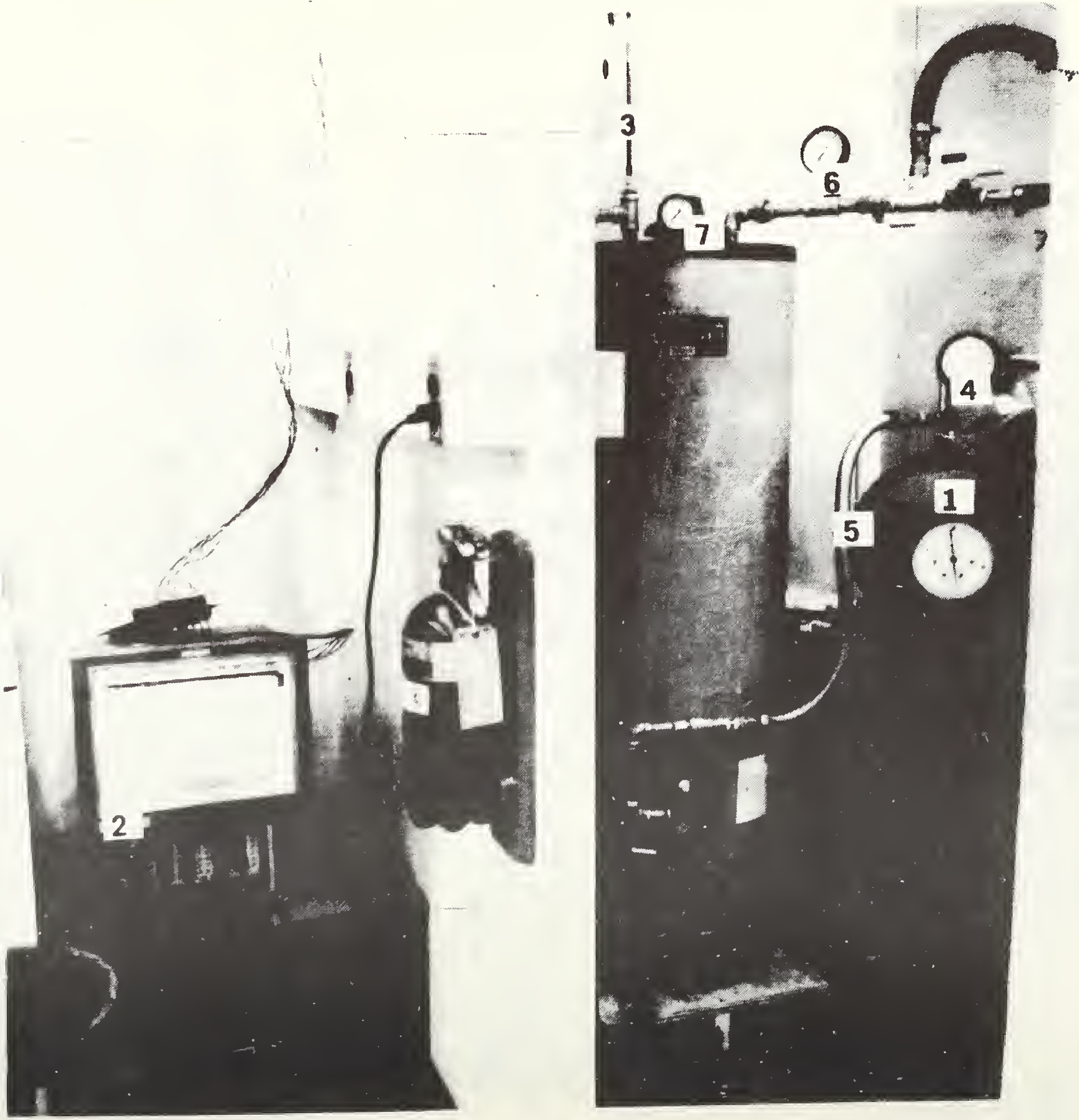

Figure 4 Water heater laboratory set-up.

6. TEST PROCEDURES

Recovery efficiency and standby loss tests were performed on used water heaters in accordance with the Department of Energy (DOE), prescribed test procedures that were developed at NBS [23]. A minor exception to the exact procedure for recovery efficiency involved the use of tap water in the range from 18 to 28°C due to seasonal variations in the incoming water supply. The effects of this procedural change were not significant for the large temperature differentials (ΔT in excess of 40°C) between the beginning and end of the recovery efficiency tests as shown in Figure 5. Reduced recovery efficiency values for temperature differentials less than 20°C are probably the result of short burner-on times.

According to the test procedure, recovery efficiency (E_r) is calculated by:

$$E_r = \frac{V\rho C_p(T_f-T_i)}{Q} \qquad (4)$$

where

E_r = recovery efficiency,

V = tank capacity (L)

ρ = density of water (0.989 kg/L),

C_p = specific heat of water (4180 J/kg°C),

T_f = final average tank water temperature (°C),

T_i = initial average tank water temperature (°C), and

Q = energy consumption (J).

Standby loss calculations are determined by:

$$S = \frac{\dfrac{V\rho C_p\ (T_1 - T_2)}{E_r} + Q}{tV\rho C_p\ (T_w - T_a)}, \qquad (5)$$

where

S = standby loss as a fraction of the stored energy lost per hour (h^{-1}),

Q = energy consumed during the standby loss test (J),

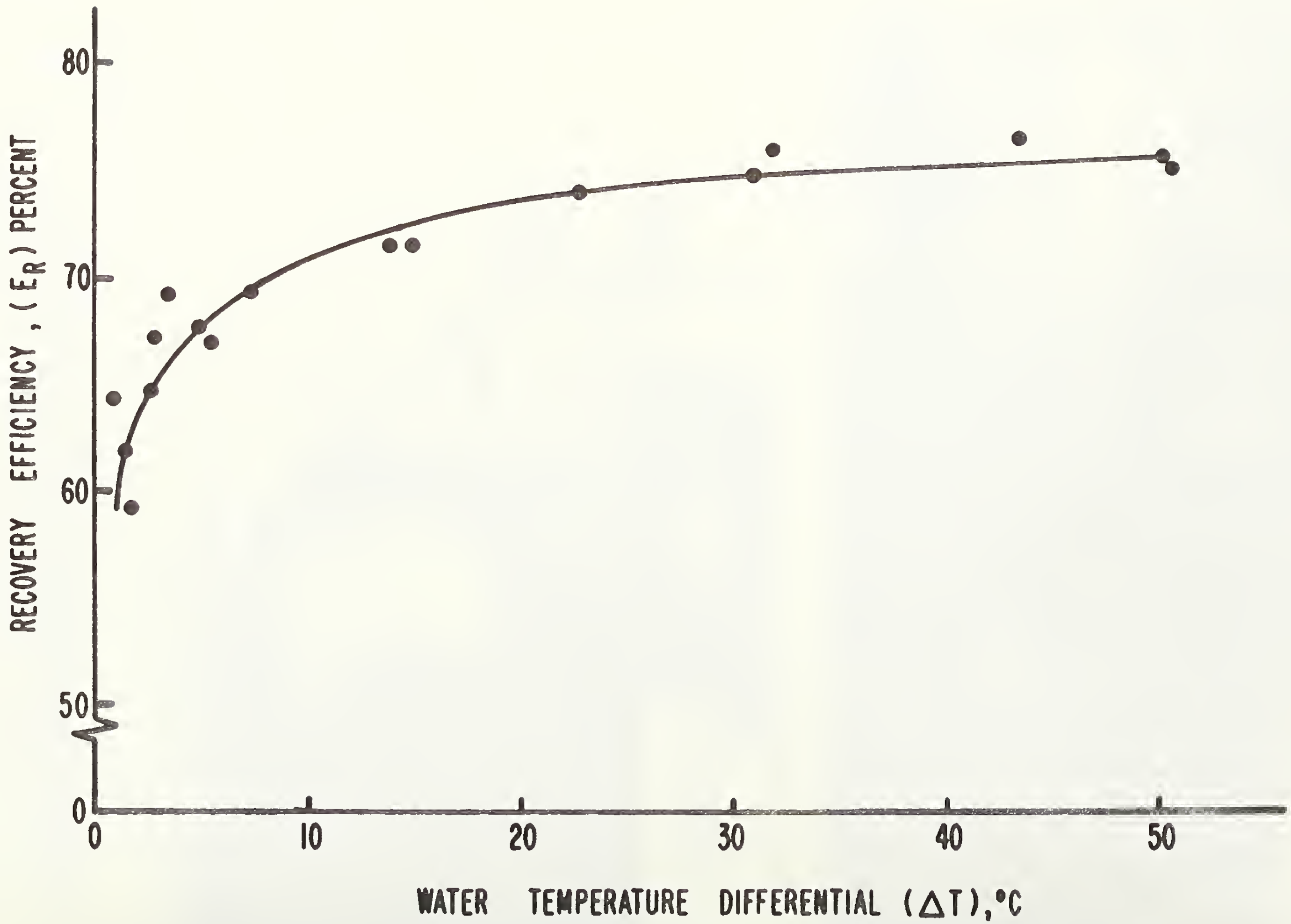

Figure 5 Effect of water temperature differential on gas-fired water heater recovery efficiency.

t = duration of standby test (h),

T_1 = average tank water temperature at start of test (^oC),

T_2 = average tank water temperature at end of test (^oC),

T_w = average tank water temperature during test (^oC) (arithmetic average of cut-on and cut-out temperatures), and

T_a = average ambient temperature during test (^oC).

V, ρ, C_p, and E_r are as defined previously for equation 4
A minimum standby period (t) of 48 hours with at least two complete thermostat cycles after an equilibrium period of approximately 24 hours was used for this test. (Note: Current DoE Test Procedure no longer requires an equilibrium period.)

For the purposes of estimating the percent increase or decrease in energy usage from water heater degradation or improvements, the daily energy consumption of the water heater was calculated from the equation:

Daily Energy Consumption = [Main burner input energy needed to raise U liters of water from inlet to outlet temperature] + [Energy required to maintain V liters of water at an average operating temperature above ambient for a 24 hour period] - [Main burner energy used during the 24 hour period to recover from hot water draws]

$$E = \frac{\rho C_p \ \Delta T_1 U}{E_r} + 24VS\rho C_p \ \Delta T_2 - \frac{\rho C_p U \Delta T_1 \ (\rho C_p \Delta T_2)VS}{qE_r}$$

where

E = energy consumption rate (J/day),

U = hot water usage rate (L/day),

ΔT_1 = temperature rise of incoming water (^oC),

ΔT_2 = average temperature of stored water above ambient during standby (^oC),

q = energy input rate (kW), and

V, ρ, C_p, E_r, and S are defined previously in equations 4 and 5. Equation 6 was originally developed by the American Gas Association [24].

Under the proposed test procedures for water heaters [23], an average usage rate, U, of 1700 liters per week, (243 liters per day) and temperature differentials, ΔT_1 and ΔT_2, of 50°C were prescribed. These selections were used in calculating the daily energy consumption, E, and to evaluate the magnitude of the energy degradation or improvements of the water heaters tested in this program.

The test procedures for recovery efficiency and standby loss are static or "steady state" tests that place no hot water delivery demand on the water heater. The ability to satisfy hot water delivery demand is dependent on the rate of heat transfer from the heat source to the stored and incoming water, the distribution of hot water in the tank and the mixing of incoming cold water. As such, the hot water delivery performance of a water heater is a usage or rate dependent attribute that is not necessarily measured by test methods for recovery efficiency or standby loss. In order to simulate use conditions and estimate the hot water delivery performance, a dynamic test using computer-controlled water draws was implemented. This method was used to calculate the effect of hot water delivery decline on water heaters with damaged dip tubes.

For these tests a draw schedule using 243 liters of hot water per day was established. The draw schedule consisted of simulated hot water usage for 2 showers, 1 dishwasher operation, 1 warm water clothes wash, and 12 sink uses. These events were spaced over a 24 hour period at intervals that could be representative of a hot water usage pattern. No heavy or continuous draw demand was placed on the water heater. This draw schedule is presented in Table 3.

A second draw schedule consisting of five 56.8-liter draws spaced every 600 seconds (water on for 300 seconds at 0.19 liters per second and off for 300 seconds) was used to deplete the supply of hot water in the tank. This would simulate an unusually heavy demand schedule, e.g. five showers taken sequentially.

Measurements of the energy content of delivered hot water were made using the draw schedules. The delivered energy content of the water was calculated by

$$E_D = \sum_{j=1}^{n} (V\rho C_p)_j \quad (T_{o_j} - T_{i_j}) \qquad (7)$$

$j = 1,2,3 \ldots n$ and

Table 3 - Simulated Daily Demand Draw Schedule

Time of Day	Rate of Draw L/s	Rate of Draw gpm	Duration of Draw seconds	Volume of Draw liter	Volume of Draw gal	Type[(a)] of Draw
0701	0.09	1.5	24	2.3	0.6	1
0705	0.19	3.0	300	56.8	15.0	2
0725	0.09	1.5	24	2.3	0.6	1
0800	0.09	1.5	24	2.3	0.6	1
1000	0.25	4.0	120	30.3	8.0	3
1022	0.25	4.0	60	15.1	4.0	3
1030	0.09	1.5	24	2.3	0.6	1
1200	0.09	1.5	24	2.3	0.6	1
1245	0.09	1.5	24	2.3	0.6	1
1600	0.09	1.5	24	2.3	0.6	1
1720	0.09	1.5	24	2.3	0.6	1
1800	0.09	1.5	24	2.3	0.6	1
1820	0.09	1.5	120	11.4	3.0	4
1828	0.09	1.5	120	11.4	3.0	4
1836	0.09	1.5	120	11.4	3.0	4
1844	0.09	1.5	120	11.4	3.0	4
1852	0.09	1.5	120	11.4	3.0	4
2200	0.09	1.5	24	2.3	0.6	1
2205	0.19	3.0	300	56.8	15.0	2
2225	0.09	1.5	24	2.3	0.6	1
2330	0.09	1.5	24	2.3	0.6	1

(a) Type of Draw

1. sink use
2. shower
3. warm water clothes wash
4. automatic dishwasher

n = number of draws

where:

E_D = energy content of the delivered water (J),

V = volume of draw (L),

ρ = average density of water at an average temperature $(T_{o_j} + T_{i_j})/2$ (kg/L),

C_p = specific heat of water (J/kg^{o}C),

T_{o_j} = outlet temperature of delivered water (^{o}C),

T_{i_j} = inlet temperature of cold water supply (^{o}C),

All of the water heaters tested using the recovery and standby procedures were visually inspected prior to testing. The general condition of each water heater was evaluated in terms of the amount of scale evident from the inspection, and the known history (age and reason for removal). When possible the more heavily scaled units were tested first.

The general test procedure consisted of testing the water heater in an "as received" condition for recovery efficiency and standby loss. Some scaled water heaters were cleaned and retested to note any changes in their operating characteristics. Adjustments to the primary air intake, the pilot rate, or baffle length and design were made on several water heaters to note their effects on water heater recovery efficiency and standby losses. Measurements of the levels of carbon dioxide, carbon monoxide, and excess air, as well as, flue gas temperature were routinely made to establish the range of operating values for these quantities in the used water heaters. Several specimens were dissected for closer internal inspection after the laboratory tests were completed.

7. RESULTS

The literature survey and experimental program combined to identify four interrelated forms of degradation that can exist in gas-fired water heaters. These forms have been labeled: (1) lifetime, (2) safety, (3) energy efficiency, and (4) performance degradation. The causes and resulting effects, for each form of degradation are discussed below.

7.1 Lifetime Degradation

The average operating life of a water heater has been estimated at approximately 8 to 10 years [25]. The range in operating lifetimes extends from less than 3 to more than 20 years. Lifetime degradation is the deterioration and ultimate failure of the water heater. Failure for the gas-fired water heater is typically a water heater tank leak. The primary normal failure mode is a corrosion induced leak.

Ignoring all other variables, the operating life (time to failure) of water heaters has been related to the total dissolved solids (TDS) content of a water supply [5,6]. Water heater lifetime as a function of TDS content is shown in Figure 6. But, for a given TDS level, the failure lifetime is basically temperature dependent. In the normal operating temperature range for water heaters, 49 to 82^{o}C the corrosion rate doubles for every 11^{o}C rise in temperature [26]. In this temperature range the rate of scale formation also rapidly increases [27]. In the gas-fired water heater any resultant accumulations of scale or sediment on the bottom head will significantly increase the water heater surface temperatures, [26] thus accelerating the corrosion process due to increased temperatures.

Most water heaters are initially protected against this corrosive attack on the tank through the use of a "glass" lining and a sacrificial magnesium anode. With use, the anode is preferentially attacked (Figure 7). The disintegration of the anode without replacement allows the corrosion process to attack the water heater tank through imperfections in the glass lining and accelerate the lifetime degradation of the tank. Most anodes in the water heaters tested were completely disintegrated. No laboratory work on measuring the parameters affecting the rate of failure or the lifetime phenomenon was undertaken in this program.

7.2 Safety Degradation

Properly installed, the gas-fired water heater is a reliable and safe appliance that will adequately perform throughout its lifetime. But occasionally safety related failures do occur.

Of the water heaters received for testing, two specimens (2 and 6) were found that had degraded in a manner that posed potential safety problems. Specimen 6 (see table 2), a 20 year old external-flue gas water heater, had been removed from service because of a thermostat malfunction that allowed the burner to remain on past the temperature cutout point. This malfunction produced excess water temperatures and pressures which activated the properly acting pressure-temperature relief valve (PTRV). The proper reaction of the PTRV to this situation prevented any serious safety problem. In addition to the PTRV many modern gas-fired water heaters are now equipped with high temperature limit switches to automatically shut off the gas supply in the presence of high water temperatures.

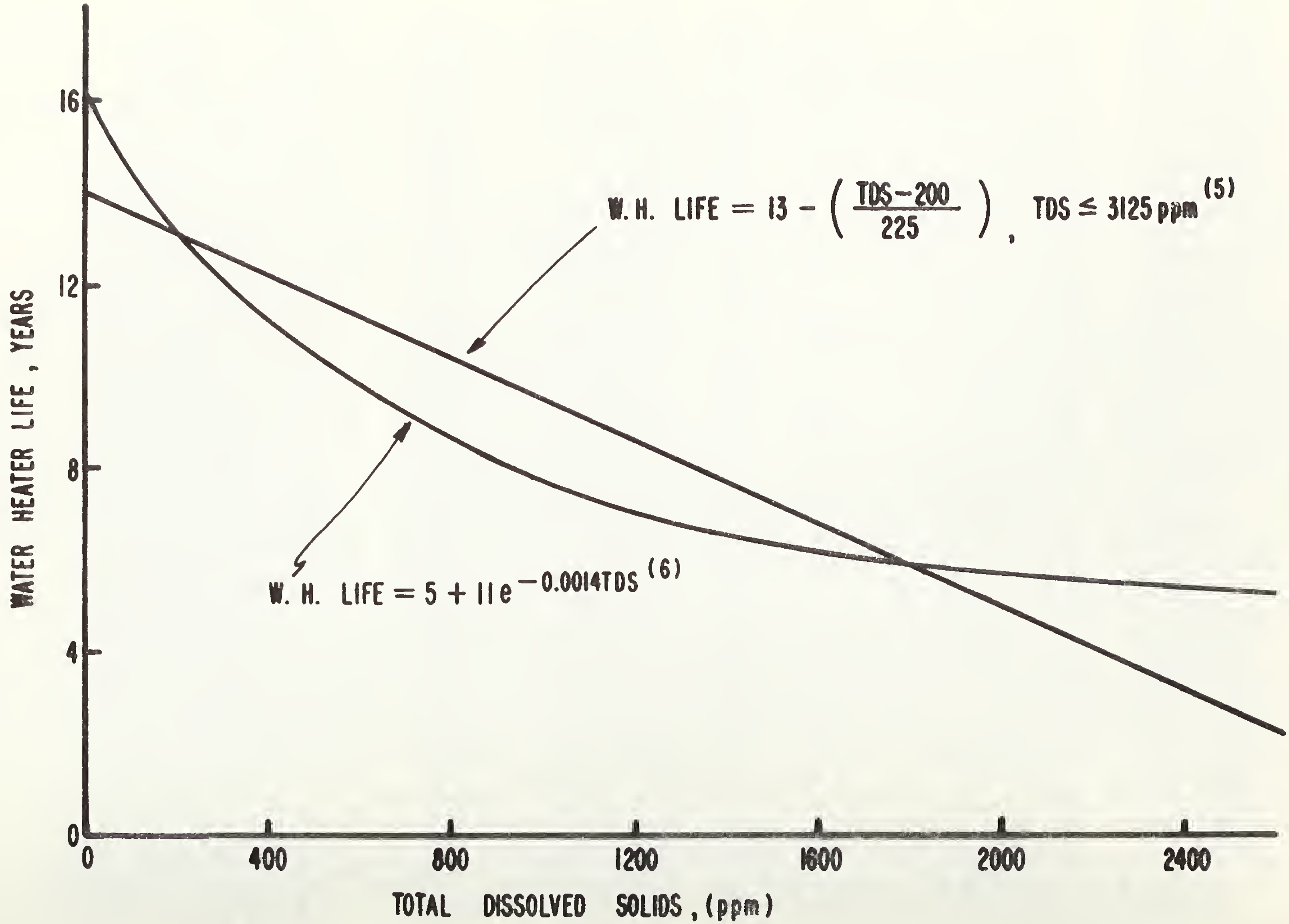

Figure 6 Water heater life as a function of the TDS level of the water supply.

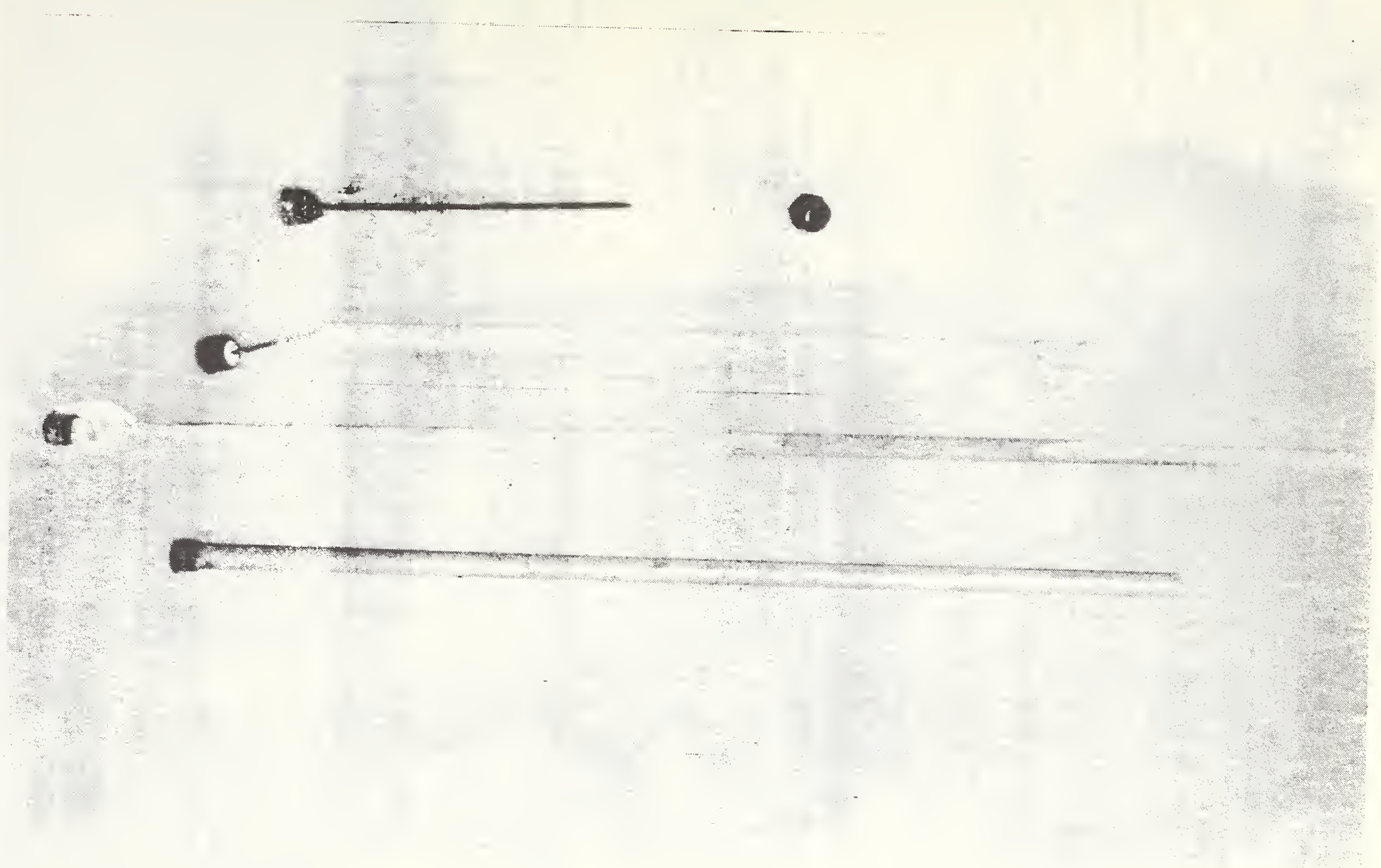

Figure 7 Stages of anode deterioration from new (bottom) to complete disintegration (upper right).

The other water heater (specimen 2) had been removed from service after only 7 years because of a "flue blockage". Initial tests showed a low recovery efficiency, long recovery time, evidence of occasional flame rollout (flames extending outside of the combustion chamber), and carbon monoxide (CO) levels in the flue gas in excess of 500 ppm. The exact cause of this deterioration, a collapsed flue (Figure 8), was not discovered until dissection. The collapse of the flue was apparently the result of the flue wall deterioration due to corrosive action of the hot flue gases on the flue of the water heater. (The flue wall thickness had decreased to about 25 percent of its original value.) This water heater without evidence of tank leakage, was fortunately replaced before the degraded operational characteristics, particularly CO concentration, produced any tragic results. Flue collapse can also result from temporarily high pressures produced by inoperable pressure-temperature relief valves.

Neither of these failures were typical of other service failures encountered in this investigation.

7.3 Energy Efficiency Degradation

Prior to 1975 gas-fired water heaters had a baseline recovery efficiency of approximately 70 percent[(d)] [28] with the remaining 30 percent lost to the surroundings, mainly through flue losses. Any reduction in the transfer of heat from the combustion gases to the water storage tank should reduce the operating efficiency of the water heater, increase the flue losses, and should be reflected directly in a lower recovery efficiency number. This reduction is "energy efficiency degradation".

The degradation in energy efficiency is primarily the result of reduced heat transfer capability arising from insulating layers of loose scale (sediment) on the tank bottom, insulating layers of adherent scale on the tank bottom and flue wall, burner malfunction or misadjustment, and a degradation in the heat transfer system (e.g. baffle deterioration, rust and soot accumulation in the flue, and flue blockage).

Nine of the 26 old water heaters and one new water heater were tested in accordance with the established procedures for recovery efficiency and, where possible, standby loss. The results of these tests are given in Table 4. Excluding specimens 1 and 2 (the new water heater and the water heater with the collapsed flue) the average recovery efficiency for these water heaters as received was 65 percent. This figure represents an average recovery efficiency degradation from a "new" condition of about 4 recovery efficiency percentage points. Efforts to determine the cause of this decrease were undertaken.

[(d)] This value for recovery efficiency is based on a recovery efficiency test method using a preheated tank according to standards in effect before 1977. The use of a cold start recovery efficiency test would decrease this baseline number by about one percent to 69 percent. The cold start recovery test method was used in this test program.

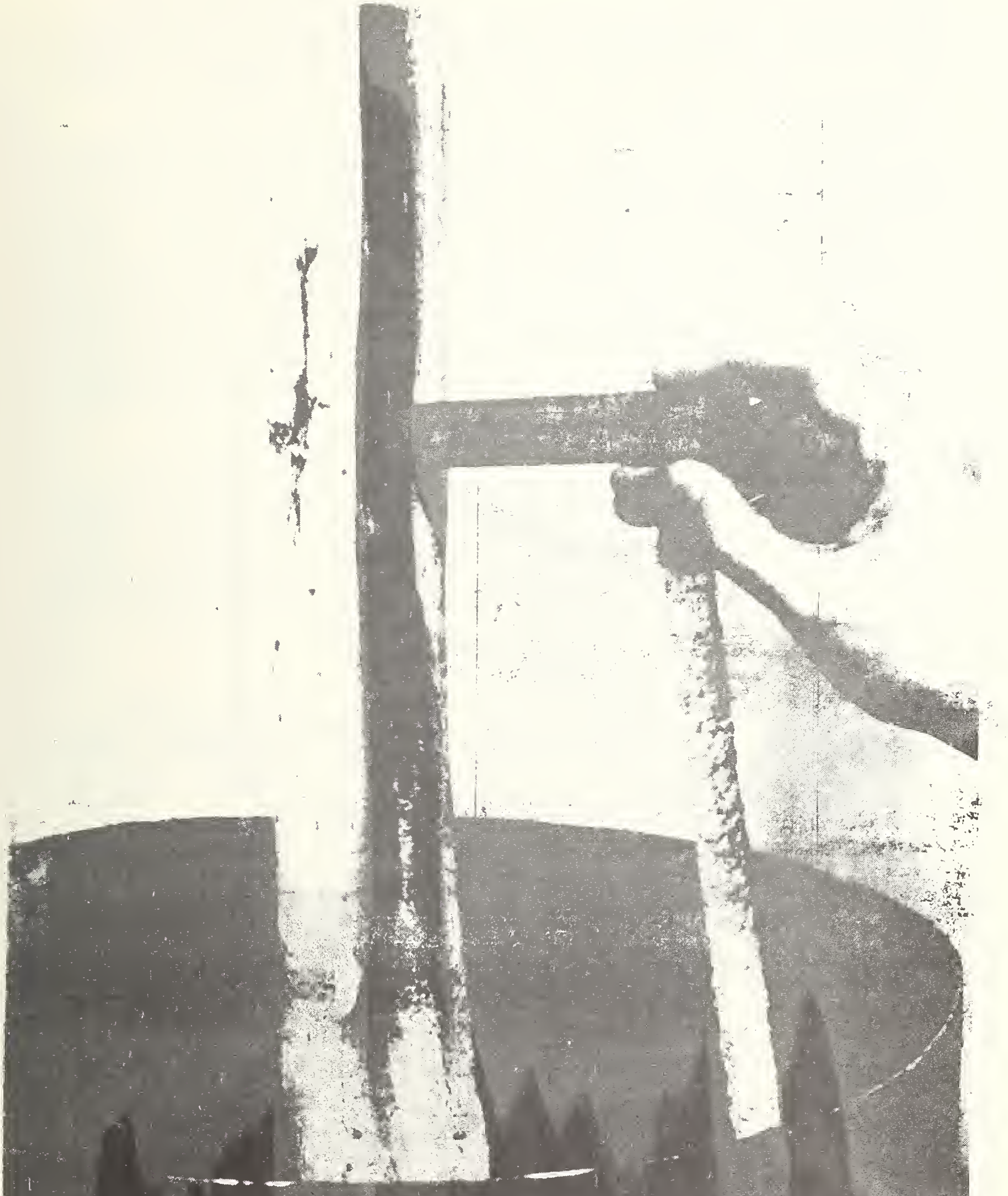

Figure 8 Collapsed flue of Specimen 2.

Table 4 - Energy Efficiency Degradation Results for Tests of Used Water Heater Specimens

Specimen	Origin	Age	Tank Volume(a)		Main Burner Rate, q	Pilot Rate	Recovery Efficiency E_r		Standby Loss S		CO_2		Daily Energy Consumption, E(b)		Sediment Accumulation	
							(c)	(d)	(c)	(d)	(c)	(d)	(c)	(d)		
		Years	gal	liter	kW	W	percent	percent	percent/h	percent/h	percent	percent	J /day	J /day	liter	kg
1		New	38.1	144	14.6	230	74	(e)	5.5	(c)	8.7	(e)	10.5×10^7	-	0.0	0.0
			35.5	134	14.6	230	69	(e)	4.9	(c)	-	(e)	10.3	-	9.9	14.5
2(e)	Wheaton, MD	7	37.8	143	10.3	290	40	45	-	8.0	-	-	17.4	16.1×10^7	-	-
3(g)	Arlington, VA	17	28.3	107	8.8	250	63	66	7.4	-	6.1	6.8	11.5	-	0.7	1.3
			28.6	108	8.8	250	-	66	-	8.6	6.6	-	-	11.8	0.2	0.4
			28.6	108	8.8	110	-	66	-	7.3	-	-	-	11.2	0.2	0.4
4	Rockville, MD	15	37.3	141	8.5	250	68	-	5.2	-	8.4	-	10.7	-	2.0	1.8
			37.9	143	8.5	250	(i)	-	-	-	-	-	-	-	0.0	0.0
5	San Diego, CA	12	37.6	142	11.4	440	65	(e)	7.3(h)	(e)	5.4	(e)	12.5	-	1.1	1.0
6(j)	Madison, WI	20	27.6	104	6.7	230	67	66	(k)	(k)	2.8	3.6	-	-	-	-
7	Rockford, IL	-	27.8	105	9.7	-	65	65	-	-	6.9	6.6	-	-	0.2	0.2
8	Torrence, CA	5	37.6	142	14.1	210	61	(e)	8.0	(e)	6.2	(e)	13.5	-	2.7	2.2
			38.2	144	14.1	210	62	(e)	7.3	(e)	-	(e)	13.0	-	0.5	0.5
9	Oceanside, CA	5	38.0	144	14.4	250	66	(e)	7.9	(e)	6.5	(e)	12.9	-	2.0	1.4
10	Huntington Beach, CA	7	49.0	185	15.8	350	68	(e)	6.4	(e)	6.6	(e)	13.0	-	-	-
			49.0	185	15.8	120	69	(e)	6.0	(e)	-	(e)	12.5	-	-	-

(a) tank volume as measured before and after sediment removal
(b) based on a water usage rate of 243 liters per day and temperature rises corresponding to prescribed values
(c) as received
(d) after primary air adjustment
(e) no primary air adjustment possible
(f) collapsed flue
(g) off center flue
(h) not measured by standard procedure - excess pilot rate
(i) leaked after cleaning
(j) external flue
(k) not measured - defective thermostat

7.3.1 Sediment and Scale Accumulation

Approximately 50 percent of the heat input to a gas-fired water heater is transferred through the tank bottom [29]. The accumulation of an insulating layer of scale or sediment should affect the heat transfer process and degrade the energy efficiency of the water heater.

The effect of loose sediment on the recovery efficiency of a gas-fired water heater was demonstrated in tests on a new water heater to which sand was added. Recovery efficiency dropped linearily from 74 to 69 percent as 9.9 liters of sand (an average depth of about 10 cm) were deposited in the tank, Figure 9. Relatively little degradation in energy efficiency was noted in agreement with Reference 29. This volume of sand was at least five times the accumulation of sediment (loose scale) found in any of the 26 water heaters received for testing. Removal of the sand restored this water heater's recovery efficiency to its original value, but the removal of sand was a laborious and probably not cost effective task. The recommended practice of draining the tank "until the water runs clear" is ineffective because it does not remove large amounts of sand and sediment in the tank.

In addition to specimen 1, repeat tests for recovery efficiency and standby loss were also made on specimens 3, and 8 after sediment removal. Recovery efficiencies improved slightly for these specimens, while standby losses increased for specimens 1 and 3 after removal of the insulating layer of sediment. The overall effect of sediment removal for specimens 1 and 3 would increase the energy consumption of the water heater due to the increased standby losses, according to equation 6.

7.3.2 Burner System Adjustments

Water is heated in the typical gas-fired water heater by passing hot combustion gases from the burner over the tank bottom and through the water heater flueway. The transfer of heat is enhanced by baffling in the flue and other restrictions to the air supply traveling through the flue. A degradation in the heat transfer capability of the burner, combustion, and flue system would result in an energy efficiency degradation for a water heater. The degree of improvement in water heating efficiency obtained through servicing or minor adjustments to the burner-combination system of old, in-service water heaters can provide an estimate of energy efficiency degradation as a result of burner-combustion system misadjustment. Such improvements require either an increase in heat transfer capability or a reduction in energy consumption without a corresponding reduction in water heating performance.

The burner, Figure 2, is the most conspicuous part of the burner system. In the typical burner primary air is premixed with the gas supply in the mixing tube and burned in the presence of secondary air at the ports in the burner head. Other parts of the burner system include the continuous pilot, used primarily for main burner ignition, the orifice spud

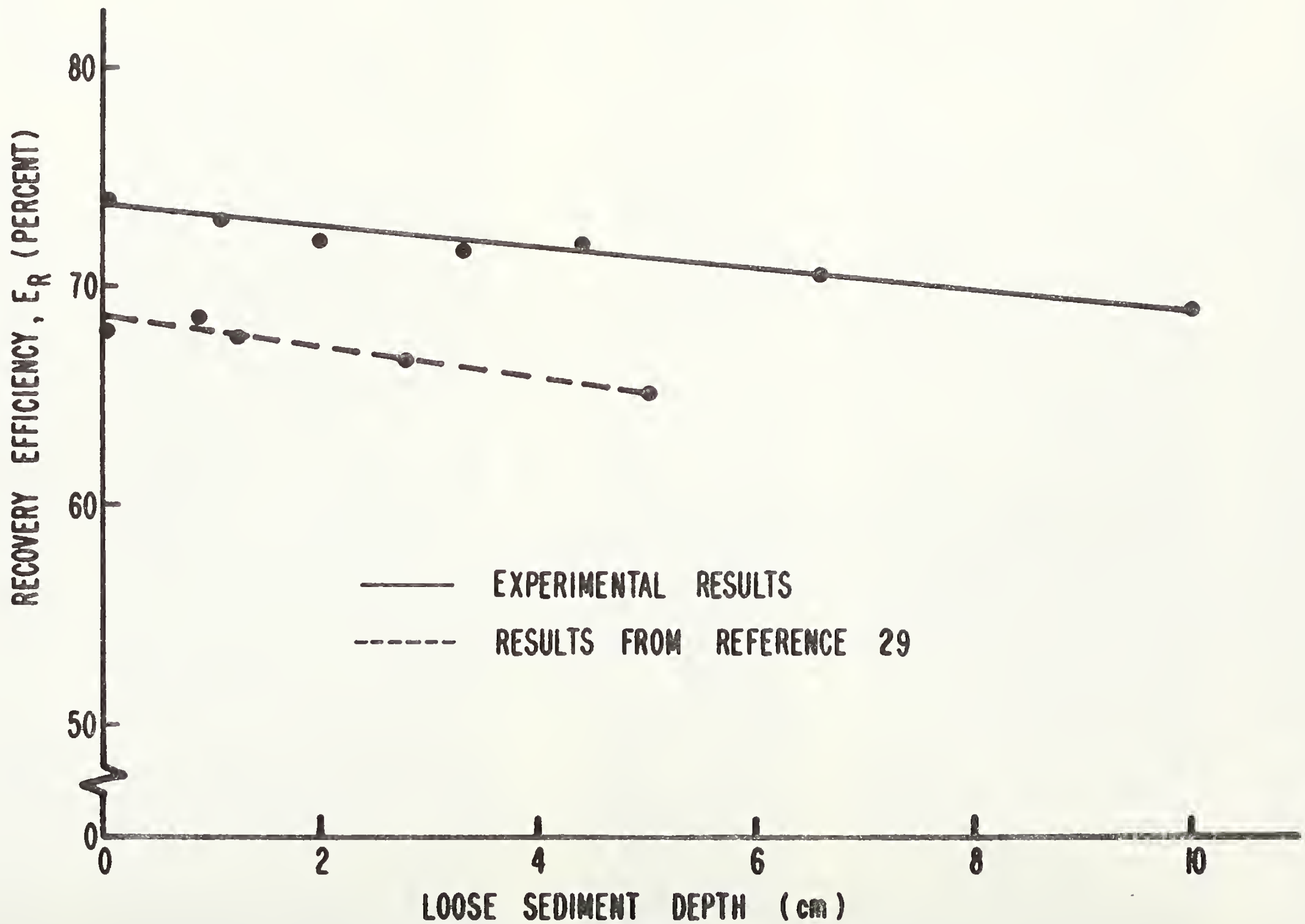

Figure 9 Effect of sediment accumulation, on the bottom of gas-fired water heaters, on water heater recovery efficiency.

and pressure regulator, which determine the gas flow rate, the thermostat valve, which controls the burner on-off operation according to sensed water temperature, and manual on-off switch. The pressure regulator, thermostat valve, and on-off switch are generally physically located together in a packaged "thermostat" control (not shown in Figure 2).

In this relatively simple system, adjustments are limited to the (a) primary air supply, (b) secondary air supply, (c) pilot rate, and (d) main burner rate. The effects of adjusting the primary air supply and pilot rate on several water heaters were determined.

(a) Primary Air Supply

Primary air is the air that is premixed with the gas before it enters the burner head. This air supply is adjustable within limits by means of an air shutter at the burner mixer face on older water heaters. The primary air supply was adjusted on specimens 2,3,6, and 7 in an effort to improve the recovery efficiencies of these water heaters. Recovery efficiency changes of 5 and 3 percentage points were recorded for specimens 2 and 3 while no beneficial effects were observed from the primary air adjustments to specimens 6 and 7. Under normal use conditions, once properly installed and adjusted, adjustments to the primary air supply are generally unnecessary. Current industry trend is to produce burners with preset non-adjustable primary air supplies.

(b) Pilot Rate

The continuous pilot in a gas appliance is a major consumer of energy. In the water heater it contributes heavily to the standby loss. The effect of pilot-rate on the standby loss was demonstrated on specimens 3 and 10.

Specimen 3, a nominal, 114 liter (30 gallon) water heater with an off-center flue was tested in a standby mode with pilot rates of 250 (as received) and 110 W (800 and 360 Btu per hour). The corresponding standby losses were 8.6 and 7.3 percent per hour. Using equation 6 and the estimated average use conditions this reduction in pilot rate produced a five percent reduction in total energy consumption for the water heater.

Specimen 10, a conventional water heater with a nominal capacity of 189 liters (50 gallons) was tested in a standby mode with pilot rates of 350 (as received) and 120 W (1200 and 400 Btu per hour). The standby loss rates for these tests were 6.4 and 6.0 percent per hour. Using equation 6 and the average use conditions, a 3 percent savings in total energy usage was predicted for this pilot rate reduction.

The results for specimens 3 and 10 are given in Table 4. These results are in general agreement with other pilot-rate reduction tests run at NBS on new water heaters [30] and with other reported estimates of a 2 percent energy savings that can be obtained through pilot rate reduction on a typical 151 liter (40 gallon) water heater [16].

7.3.3 Flue Baffle Effect

The burner does not work alone in the process of heating water. The combustion chamber, flue, and flue baffle provide the path for the hot combustion gases and promote the transfer of heat from the gases to the water. Current gas-fired water heater designs provide baffling, and primary and secondary air supplies which result in flue gas temperatures of about 290°C, at the diverter, and excess air levels (i.e., primary and secondary air in excess of the air required for complete combustion) greater than 50 percent. Both the exit flue temperature and excess air level are higher than required for safe and proper combustion; reductions in each of these parameters would result in an increase in water heater efficiency (heat transfer capability) and a corresponding reduction in flue loss. Safe lower limits for these parameters are a 220°C flue gas exit temperature and 25 percent excess air. The net effect of reduction to this lower flue temperature and excess air level is a decrease in flue loss from 24 to 18 percent, as shown on the nomograph, Figure 10.

Flue baffling can be increased through length increases, added air flow restrictions, or baffle pattern redesign. However, the harsh environment of the flue of the gas-fired water heater is capable of destroying the baffle's lower end, effectively decreasing the baffle length and eliminating any added air flow restrictions at that point. The net result of this destruction would be a decrease in water heater recovery efficiency -- energy efficiency degradation.

The effect of baffle length on water heater recovery efficiency was demonstrated by tests on specimen 3 in which several baffles of various lengths and configurations were installed in place of the original baffle. The results of these tests are presented in Table 5 and Figure 11. For this off-center flue water heater, recovery efficiency appears to be a linear function of baffle length, independent of the baffle pattern, Figure 12. In all of the specimens examined during this project baffle length destruction was limited to the bottom 3 cm of the baffle. Based on Figure 11 a decrease in baffle length of 3 cm produces less than a 1 percentage point degradation in water heater recovery efficiency.

The off-center flue design of specimen 3 is not typical of most gas-fired water heaters. However, a design of this type is more efficient in transferring heat from the burner to the water [29] and, as a result, use of the original baffle (No. 2), which was 40 cm shorter than the flue, resulted in the commonly encountered flue temperature and excess air level. For specimen 3 significant improvements to the water heater recovery efficiency were made by increasing baffle length alone. In the center-flue water heaters tested (8,9, and 10) typical baffle lengths were

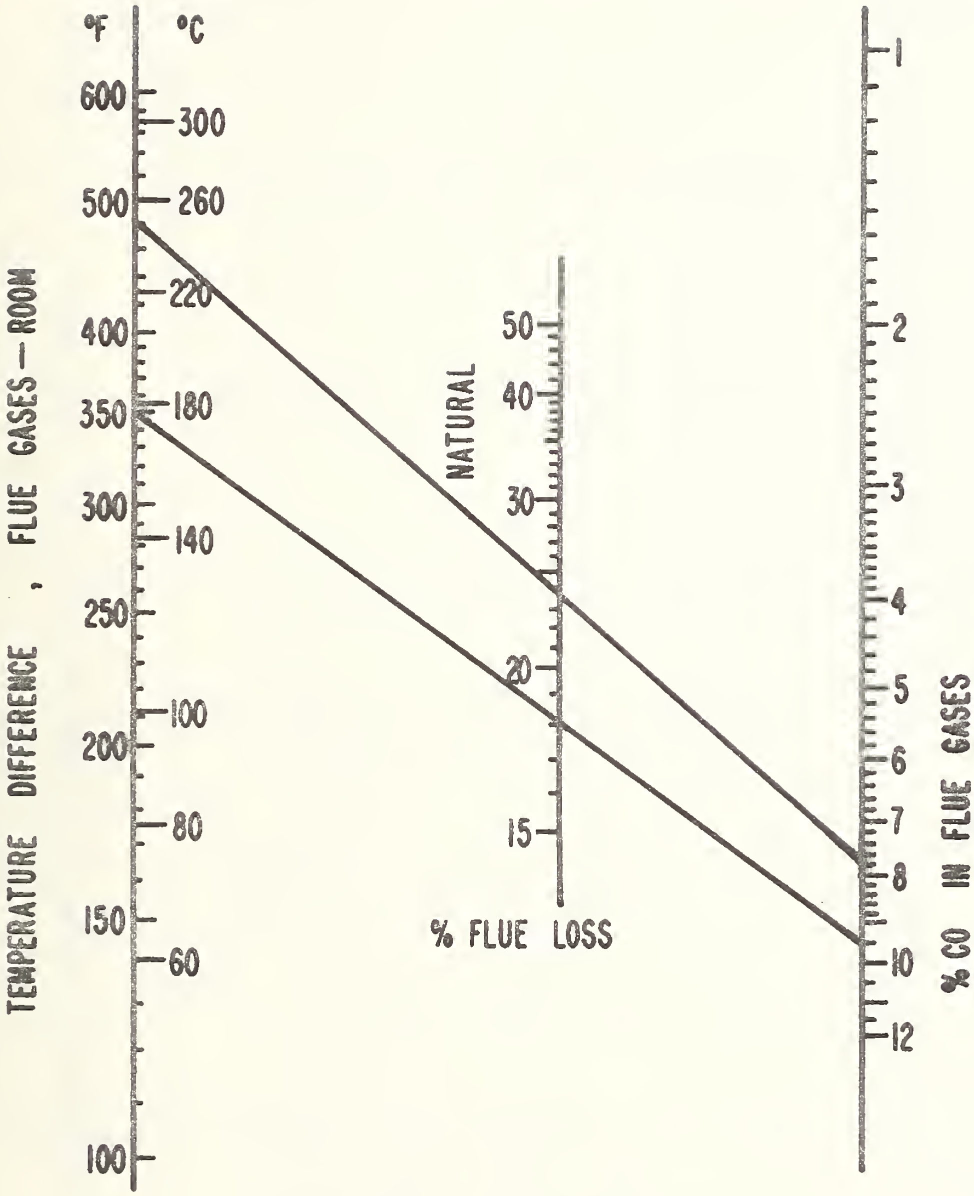

Figure 10 Flue loss alinement nomograph(31)

Table 5 - Effect of Baffle on Water Heater Recovery Efficiency

Specimen No.	Volume	Flue Length	Flue Diameter	Baffle No.	Baffle Length	Baffle Width	Recovery Efficiency	Flue Temperature	CO_2 Level
	Liter	cm	cm		cm	cm	(percent)	°C	(percent)
3	107	121	8	1	43	6.3	60	---	---
				2(a)	81	6.3	66	270	6.4
				3	61	6.3	64	290	5.7
				4	97	6.3	68	250	---
				5	107	6.7	70	230	7.3
8	142	126	10	6(a)	117	9.7	61	370	6.2
				7	117	9.7	70	290	8.3
9	150	126	10	6	117	9.7	65	---	---
				7	117	9.7	73	---	7.9
				8(a)	114	9.7	66	350	6.5
10	190	126	10	6	117	9.7	64	---	---
				7	117	9.7	71	280	7.7
				8	114	9.7	64	---	---
				9(b)	114	9.7	70	270	8.2
				10(a)	114	9.7	68	330	6.6
				11	112	9.7	70	---	---

(a) Original baffle

(b) Baffle 8 with a rectangular (5.8 x 6.3 cm) flow restricting tab attached at the baffle end.

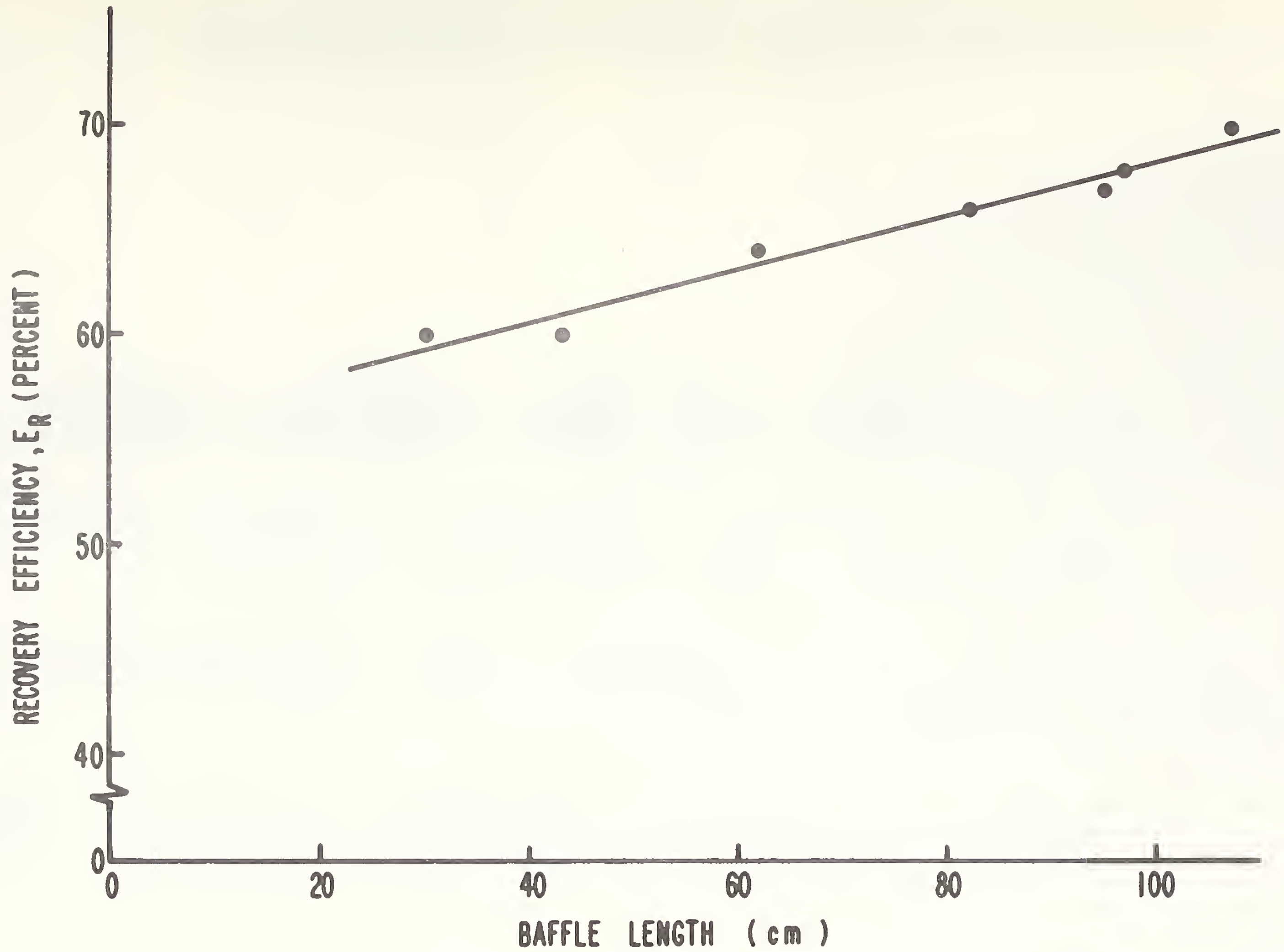

Figure 11 Effect of baffle length on the recovery efficiency of a gas-fired water heater with an 8-cm diameter, off-center flue.

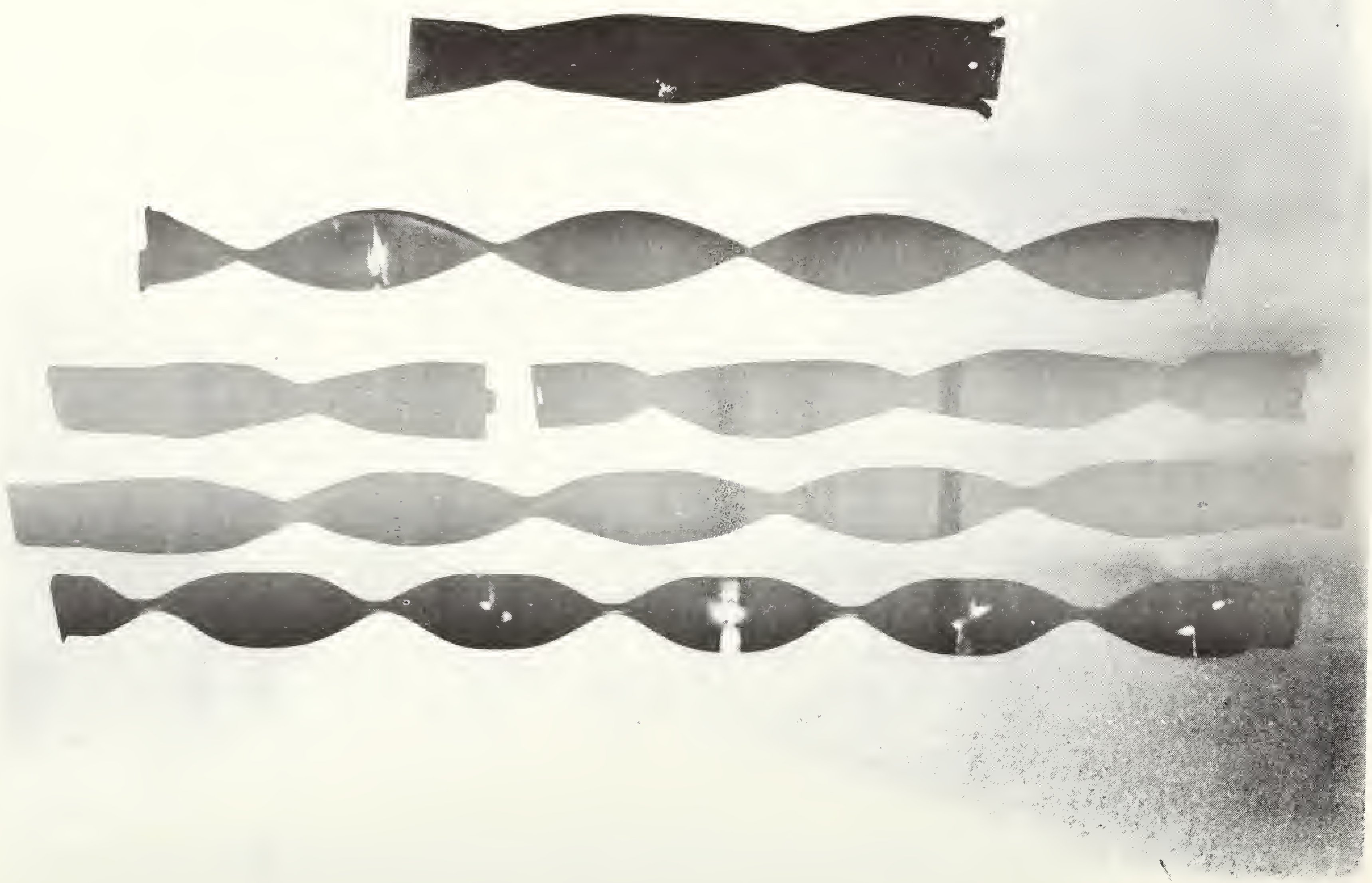

Figure 12 Baffles used to assess effect of baffle length on water heater Recovery Efficiency.

within 15 cm of the flue column length and significant improvements in recovery efficiency were brought about by baffle modifications other than increased baffle length.

Recovery efficiency tests were run on specimens 8, 9, and 10 using two to six similar baffles, Figure 13. Baffle length, width, and pattern were all similar; the major difference between baffles was the presence of a flow restricting disk or plate normal to the flue column axis at the bottom edge of baffles 7 and 9, and the use of a disk at the bottom edge, plus a tab located 30 cm from the bottom tip of baffle 11. The results of these tests are also presented in Table 5. The use of restrictions on the bottom edge of a baffle produced recovery efficiency improvements from 6 to 9 percentage points. Based on recorded flue temperatures, even higher recovery efficiency improvements are attainable through further baffle modifications. The resultant increases in heat transfer from the combustion gases to the water offer a significant energy savings at a relatively small price.

The inclusion of air flow restrictions at the baffle end do not insure increased operating efficiency throughout the water heater's operating life. Loss of such restrictions from environmental factors would suddenly and significantly degrade the water heater's energy efficient operation.

7.4 Performance Degradation

The fourth form of degradation is in the area of performance. Water heater performance is closely related to the operating efficiency of the water heater; a degradation in energy efficiency generally results in a degradation in performance. Performance deterioration is specifically defined here as a decrease in the ability of the water heater to deliver a desired quantity of water at a desired temperature. The ability to satisfy hot water demand is dependent on the rate of heat transfer from the heat source to the stored water, the distribution of hot water in the tank, mixing of the incoming cold water, hot water flow rate, and the tank volume. As such, performance is a usage or rate dependent attribute that is not readily measured or determined by a test method for recovery efficiency or standby loss.

The deterioration in performance can be qualitatively observed by the water heater user as a decline (either sudden or gradual) in the quantity of hot water available for large draws.

One cause of such performance degradation is the broken or damaged dip tube, Figure 14. A water heater with a damaged dip tube introduces cold water near the top of the tank. This cold water mixes with and tempers the stored hot water already present in the tank. This mixing prevents the exit flow of large quantities of hot water to the point of use. Using the two draw schedules outlined in Section 6, Test Procedures, the performance of a 200 liter (52 gallon) electric water heater[e] was measured using both its original dip tube and the broken dip tube identified in Figure 14.

[e] An electric water heater was used for this test for convenience because it was already being monitored on computer control. The effect of dip tube deterioration is similar to that for gas water heaters (see later).

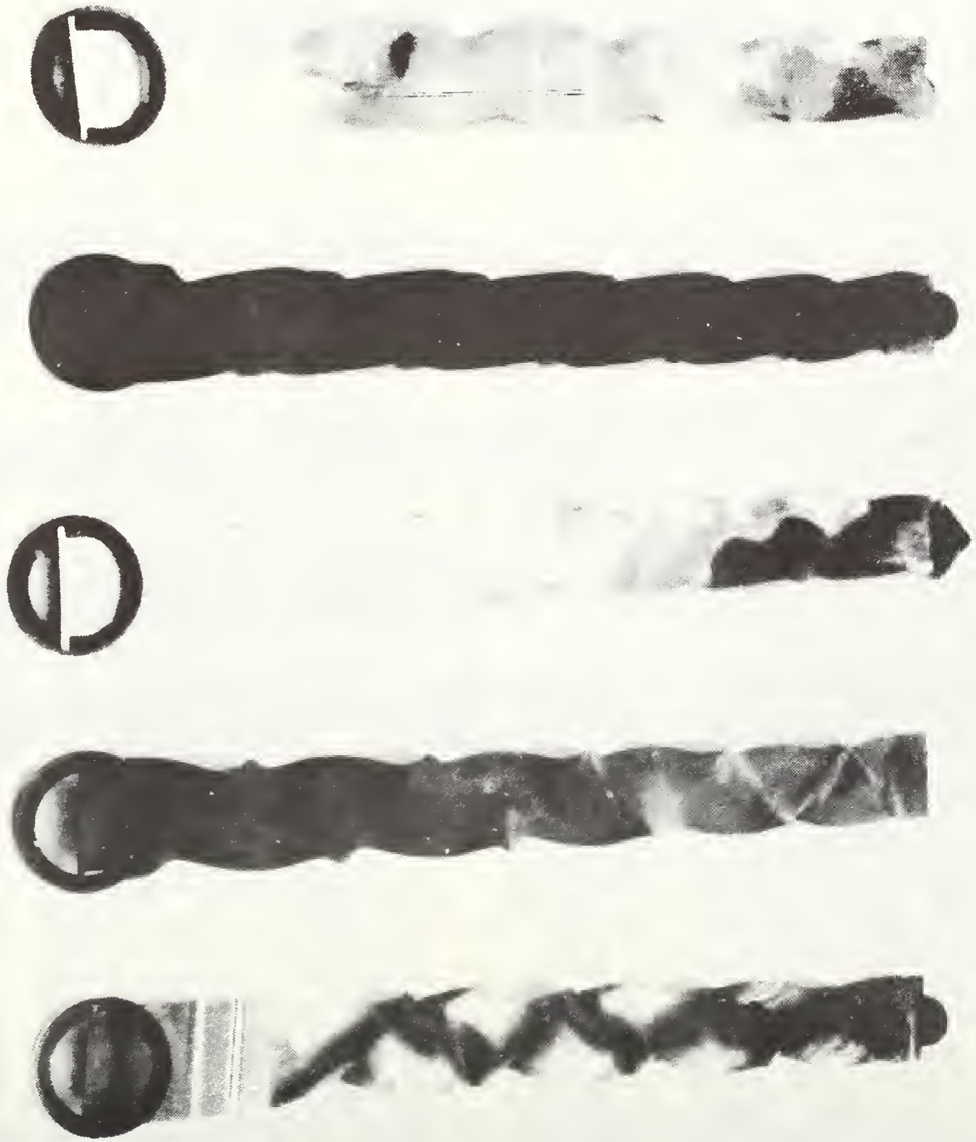

Figure 13 Baffles used to assess the effect of minor baffle modifications on water heater recovery efficiency.

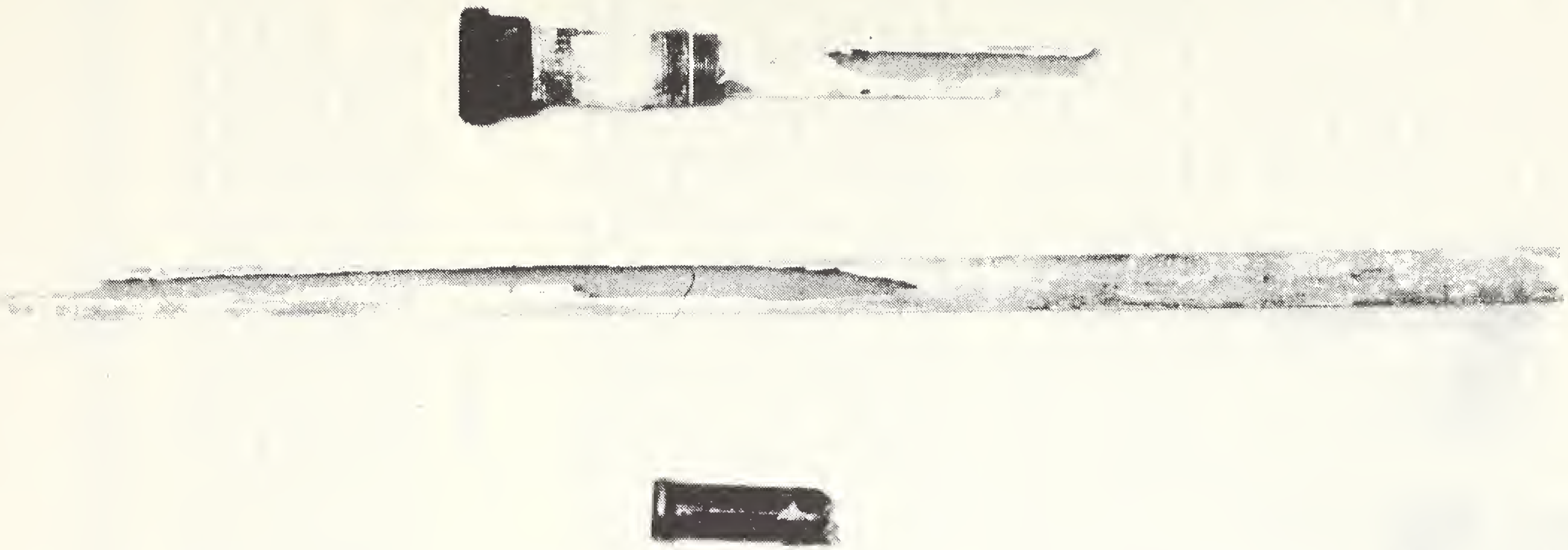

Figure 14 Deteriorated dip-tubes. Upper dip tube piece was used in simulated draw tests.

Specimen 1 was tested under the normal draw schedule with and without a dip tube (limiting case of a broken dip tube).

Under the normal draw schedule, a 7 percent reduction in delivered energy content for the electric water heater and 21 percent reduction in delivered energy content for the gas water heater (specimen 1), were observed in test comparisons between good and broken dip tubes. Under the heavy demand draw schedule a 12 percent decrease in delivered hot water energy content from the electric water heater was measured with the broken dip tube. These reductions signify water heater performance degradation.

The reduction in energy content in the delivered hot water is a result of mixing incoming cold water throughout the tank volume and delivering tempered hot water. No thermal stratification was observed in the water heater tests with the broken dip tube shown in Figure 14. The use of a good dip tube promotes stratification between the incoming cold water and the delivered hot water. Mixing occurs primarily at the boundary of these The stored hot water is essentially pushed, with little mixing, from the tank bottom to the top through the hot water outlet.

With the assumption of a constant daily water usage (243 liters per day), the energy consumption of the water heater decreases because of the broken dip tube. But hot water demands are not solely made on a constant volume basis. Personal use demands showers, baths, and sink uses, are usually based on the delivered energy content of the water. Thus, under the normal-use draw schedule, the broken dip tube test requires a 7 percent increase in delivered energy content to satisfy the personal use (energy content demands) for hot water. This is accomplished by either increasing the volume of heated water delivered or increasing stored water temperature; either action would increase energy consumption. For constant-volume demands (clothes and automatic dish washing) the reduction in energy content from the broken dip tube could affect the operational performance of the clothes or dishwasher and produce unsatisfactory results.

8. CONCLUSIONS

The aim of this project was to estimate the magnitude of the energy-efficiency degradation of gas-fired water heaters caused by the accumulation of mineral deposits, and the operating efficiency improvements that can be made by proper adjustments or maintenance. The typical used water heater tested at NBS contained a small amount of sediment and possibly service related deterioration to the burner and baffle. The average degradation in recovery efficiency performance (as measured by water heater recovery efficiency) was 4 percentage points from an assumed value, as new, of 69 percent.

The comparison of recovery efficiency results for used water heaters tested before and after sediment removal indicated that in the amounts present, loose mineral deposits (sediment) on the tank bottom have relatively little effect on water heater recovery efficiency. Larger sediment amounts and insulating layers of adherent scale on water heater flue walls should produce significant decreases in water heater recovery efficiency. These conclusions are in general agreement with the results of simulated tests in Reference 29. No water heaters containing large quantities of mineral deposits or adherent scale were received for testing.

In general, the operating efficiency of the used water heaters tested did not suffer from the lack of proper burner maintenance either. Adjustments to the burner that could improve the efficiency or performance of a water heater were not dependent on degraded water heater performance but were applicable to most existing gas-fired water heaters. Beneficial burner adjustments were confined to lowered pilot rates which are now offered on current "energy efficient" water heater models. The effects of baffling on water heater recovery efficiency were demonstrated and the benefits to be derived from increased baffling appear to offer a significant energy savings at a relatively small price.

Three other forms of water heater degradation were specifically identified: lifetime, safety, and performance degradation. Each of these forms were evident in some of the used water heaters received for testing. Performance is closely related to the operating efficiency of a water heater and in preliminary tests the possibility of a performance decline in excess of 10 percent was demonstrated.

Calculation Procedure for Water Supply Saturation pH, Saturation Index (Langelier) and Stability Index (Ryznar)

1. Saturation pH = pH_s = $(9.30 + A + B) - (C + D)^{(a)}$
2. Saturation Index = $I_s = pH^{(b)} - pH_s$
3. Stability Index = $2pH_s - pH$

(a) A, B, C, and D are based on water supply characteristics. Values for A, B, C, and D are obtained from the appropriate tables.

(b) pH of water supply

A

Total Solids in ppm

Ppm Total Solids	
50	.07
75	.08
100	.10
150	.11
200	.13
300	.14
400	.16
600	.18
800	.19
1000	.20

B

Temperatures in degrees Fahrenheit

TENS \ UNITS	0	2	4	6	8
30		2.60	2.57	2.54	2.51
40	2.48	2.45	2.43	2.40	2.37
50	2.34	2.31	2.28	2.25	2.22
60	2.20	2.17	2.14	2.11	2.09
70	2.06	2.01	2.03	2.00	1.97
80	1.95	1.92	1.90	1.88	1.86
90	1.84	1.82	1.80	1.78	1.76
100	1.74	1.72	1.71	1.69	1.67
110	1.65	1.64	1.62	1.60	1.58
120	1.57	1.55	1.53	1.51	1.50
130	1.48	1.46	1.44	1.43	1.41
140	1.40	1.38	1.37	1.35	1.34
150	1.32	1.31	1.29	1.28	1.27
160	1.26	1.24	1.23	1.22	1.21
170	1.19	1.18	1.17	1.16	

C

Calcium hardness expressed as ppm $CaCO_3$
(For 8 to 209 ppm $CaCO_3$, use upper table)
(For 210 to 990 ppm $CaCO_3$, use lower table)

TENS \ UNITS	0	1	2	3	4	5	6	7	8	9
0				0.08	0.20	0.30	0.38	0.45	0.51	0.56
10	0.60	0.61	0.68	0.72	0.75	0.78	0.81	0.83	0.86	0.88
20	0.90	0.92	0.94	0.96	0.98	1.00	1.02	1.03	1.05	1.06
30	1.08	1.09	1.11	1.12	1.13	1.15	1.16	1.17	1.18	1.19
40	1.20	1.21	1.23	1.24	1.25	1.26	1.26	1.27	1.28	1.29
50	1.30	1.31	1.32	1.33	1.34	1.34	1.35	1.36	1.37	1.37
60	1.38	1.39	1.39	1.40	1.41	1.42	1.42	1.43	1.43	1.44
70	1.45	1.45	1.46	1.47	1.47	1.48	1.48	1.49	1.49	1.50
80	1.51	1.51	1.52	1.52	1.53	1.53	1.54	1.54	1.55	1.55
90	1.56	1.56	1.57	1.57	1.58	1.58	1.58	1.59	1.59	1.60
100	1.60	1.61	1.61	1.61	1.62	1.62	1.63	1.63	1.64	1.64
110	1.64	1.65	1.65	1.66	1.66	1.66	1.67	1.67	1.67	1.68
120	1.68	1.68	1.69	1.69	1.70	1.70	1.70	1.71	1.71	1.71
130	1.72	1.72	1.72	1.73	1.73	1.73	1.74	1.74	1.74	1.75
140	1.75	1.75	1.75	1.76	1.76	1.76	1.77	1.77	1.77	1.78
150	1.78	1.78	1.78	1.79	1.79	1.79	1.80	1.80	1.80	1.80
160	1.81	1.81	1.81	1.81	1.82	1.82	1.82	1.82	1.83	1.83
170	1.83	1.84	1.84	1.84	1.84	1.85	1.85	1.85	1.85	1.85
180	1.86	1.86	1.86	1.86	1.87	1.87	1.87	1.87	1.88	1.88
190	1.88	1.88	1.89	1.89	1.89	1.89	1.89	1.90	1.90	1.90
200	1.90	1.91	1.91	1.91	1.91	1.91	1.92	1.92	1.92	1.92

HUNDREDS \ TENS	0	10	20	30	40	50	60	70	80	90
200		1.92	1.94	1.96	1.98	2.00	2.02	2.03	2.05	2.06
300	2.08	2.09	2.11	2.12	2.13	2.15	2.16	2.17	2.18	2.19
400	2.20	2.21	2.23	2.24	2.25	2.26	2.26	2.27	2.28	2.29
500	2.30	2.31	2.32	2.33	2.34	2.31	2.35	2.36	2.37	2.37
600	2.38	2.39	2.39	2.40	2.41	2.42	2.42	2.43	2.43	2.44
700	2.45	2.45	2.46	2.47	2.47	2.48	2.48	2.49	2.49	2.50
800	2.51	2.51	2.52	2.52	2.53	2.53	2.54	2.54	2.55	2.55
900	2.56	2.56	2.57	2.57	2.58	2.58	2.58	2.59	2.59	2.60

D

Alkalinity expressed as ppm $CaCO_3$
(For 1 to 209 ppm $CaCO_3$, use upper table)
(For 210 to 990 ppm $CaCO_3$, use lower table)

TENS \ UNITS	0	1	2	3	4	5	6	7	8	9
0		0.00	0.30	0.48	0.60	0.70	0.78	0.85	0.90	0.95
10	1.00	1.04	1.08	1.11	1.15	1.18	1.20	1.23	1.26	1.29
20	1.30	1.32	1.34	1.36	1.38	1.40	1.42	1.43	1.45	1.46
30	1.48	1.49	1.51	1.52	1.53	1.54	1.56	1.57	1.58	1.59
40	1.60	1.61	1.62	1.63	1.64	1.65	1.66	1.67	1.68	1.69
50	1.70	1.71	1.72	1.72	1.73	1.74	1.75	1.76	1.76	1.77
60	1.78	1.79	1.79	1.80	1.81	1.81	1.82	1.83	1.83	1.84
70	1.85	1.85	1.86	1.86	1.87	1.88	1.88	1.89	1.89	1.90
80	1.90	1.91	1.91	1.92	1.92	1.93	1.93	1.94	1.94	1.95
90	1.95	1.96	1.96	1.97	1.97	1.98	1.98	1.99	1.99	2.00
100	2.00	2.00	2.01	2.01	2.02	2.02	2.03	2.03	2.03	2.04
110	2.04	2.05	2.05	2.05	2.06	2.06	2.06	2.07	2.07	2.08
120	2.08	2.08	2.09	2.09	2.09	2.10	2.10	2.10	2.11	2.11
130	2.11	2.12	2.12	2.12	2.13	2.13	2.13	2.14	2.14	2.14
140	2.15	2.15	2.15	2.16	2.16	2.16	2.16	2.17	2.17	2.17
150	2.18	2.18	2.18	2.18	2.19	2.19	2.19	2.20	2.20	2.20
160	2.20	2.21	2.21	2.21	2.21	2.22	2.22	2.23	2.23	2.23
170	2.23	2.23	2.23	2.24	2.24	2.24	2.21	2.25	2.25	2.25
180	2.26	2.26	2.26	2.26	2.26	2.27	2.27	2.27	2.27	2.28
190	2.28	2.28	2.28	2.29	2.29	2.29	2.29	2.29	2.30	2.30
200	2.30	2.30	2.30	2.31	2.31	2.31	2.31	2.32	2.32	2.32

HUNDREDS \ TENS	0	10	20	30	40	50	60	70	80	90
200		2.32	2.34	2.36	2.38	2.40	2.42	2.43	2.45	2.46
300	2.48	2.49	2.51	2.52	2.53	2.54	2.56	2.57	2.58	2.59
400	2.60	2.61	2.62	2.63	2.64	2.65	2.66	2.67	2.68	2.69
500	2.70	2.71	2.72	2.72	2.73	2.74	2.75	2.76	2.76	2.77
600	2.78	2.79	2.79	2.80	2.81	2.81	2.82	2.83	2.83	2.84
700	2.85	2.85	2.86	2.86	2.87	2.88	2.88	2.89	2.89	2.90
800	2.90	2.91	2.91	2.92	2.92	2.93	2.93	2.94	2.94	2.95
900	2.95	2.96	2.96	2.97	2.97	2.98	2.98	2.99	2.99	3.00

REFERENCES

1. Hoskins, Robert A. and Hirst, Eric, "Energy and Cost Analysis of Residential Water Heaters," Oak Ridge National Laboratory, ORNL/CON-10, June, 1977.

2. Wan, C. A. and Pierson, R., "Test Procedures for Water Heaters," NBSIR, to be published.

3. American Gas Association Laboratories, "Fundamentals of Gas Combustion," January, 1973.

4. U.S. Public Health Service Drinking Water Standards, 1962.

5. Sonnen, M. B., "Quality Related Costs of Regional Water Users," ASCE - Journal of the Hydraulics Division, October, 1973.

6. Tihansky, D. P., "Damage Assessment of Household Water Quality," ASCE-Journal of the Environmental Engineering Division, August, 1974.

7. Patterson, W. L. and Banker, R. F., "Effects of Highly Mineralized Water on Household Plumbing and Appliances," JAWWA, Vol. 60, No. 9, September, 1968.

8. Black and Veatch, Consulting Engineers, "Economic Effects of Mineral Content in Municipal Water Supplies," Office of Saline Water, Research and Development Progress Report No. 260, May, 1967.

9. Aultman, W. W., "Synthetic Detergents as a Factor in Water Softening Economics," JAWWA, Vol. 50, No. 10, October, 1958.

10. DeBoer, Lloyd M. and Larson, Thurston E., "Water Hardness and Domestic Use of Detergents," JAWWA, Vol. 53, No. 7, July, 1961.

11. Hudson, H. E. Jr. and Gilcreas, F. W., "Health and Economic Aspects of Water Hardness and Corrosiveness," JAWWA, Vol. 68, No. 4. April, 1976.

12. Neri, L. C., et al, "Health Aspect of Hard and Soft Waters," JAWWA, Vol. 67, No. 8, August, 1975.

13. Langelier, W. F., "The Analytical Control of Anti-Corrosion Water Treatment," JAWWA, Vol. 28, No. 10, October, 1936.

14. Ryznar, J.W., "A New Index for Determining the Amount of Calcium Carbonate Scale Formed by a Water," JAWWA, Vol. 36, No. 4, April, 1944.

15. Garaghty, J. J., et. al., "Water Atlas of the United States," Water Information Center, Port Washington, New York, 1973.

16. Arthur D. Little, Inc., "Study of Energy Saving Options for Refrigerators and Water Heaters," May, 1976.

17. Miller, P. D., Stephan, E. F., Boyd, W. K., "Prevention of Corrosion and Burnout of Electric - Water - Heater Tanks and Heating Elements," Battelle Memorial Institute, 1966.

18. Digurda, P., Rheem, Private Communication.

19. Hõll, K., Water Treatment and Conditioning of the Water.

20. Powell, S. T., Water Conditioning for Industry, McGraw Hill, 1954.

21. Nordell, E., Water Treatment for Industrial and Other Uses, Pheinhold Publishing Corporation, New York 1961.

22. Durfor, C. and Becker, E., "Public Water Supplies of the 100 Largest Cities in the United States, 1962," U.S. Geological Water Survey Paper 1812, 1964.

23. Energy Conservation Program for Appliances, Test Procedures for Water Heaters, Federal Register, Tuesday, October 4, 1977, Part III.

24. American Gas Association, "Fundamentals of Domestic Gas Water Heating," Research Bulletin No. 9, January 1940.

25. Scott, T. J., "Direct Powered Storage Water Heaters," Fifth API Research Conference, Chicago, June 1965.

26. Nelson, F. W., Stearns, W. E., "Glass Lining Requirements for Domestic Water Heaters," Metal Products Manufacturing, January, 1962.

27. Krappe, J. M., "Scale Formation in Water Heaters and Methods of Prevention," Purdue University Engineering Bulletin, Vol. XXIV, No. 3a, June, 1940.

28. Appliance Energy Efficiency Improvement Target for Water Heaters, National Bureau of Standards, Center for Consumer Product Technology, December 1, 1976.

29. American Gas Association, "The Application of Heat to Domestic Gas Storage Water Heaters," Research Bulletin No. 71, August, 1956.

30. Palla, R. L. and Pierson, R., "Laboratory Evaluation of Innovative Features for Water Heaters," NBSIR, to be published.

31. Gas Engineers Handbook, Industrial Press Inc., New York, 1974.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The energy efficiency degradation of gas-fired water heaters was measured in laboratory tests of old water heaters collected from different sections of the country. Three other forms of degradation (lifetime, safety, and performance degradation) were also identified. The causes and potential effects of each degraded condition were assessed through literature surveys. Supplementary laboratory evaluations were conducted in the areas of energy efficiency and performance degradation. Reductions in the recovery efficiency of water heaters of 5 percentage points were measured, while simulated performance declines in excess of 20 percent were noted. Larger decreases in recovery efficiency are expected for water heaters containing significant deposits of scale or sediment.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Degradation; energy efficiency; mineral deposits; performance degradation; test methods; water heaters (gas-fired)

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