Development and Testing of an Improved High-Efficiency Water Heater

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INTRODUCTION

This paper describes a high-efficiency water heater that uses a design approach quite different from the conventional center-flue water heater. While high efficiency might have been more readily achieved through the use of a powered combustion system, a cost/benefit analysis showed that a natural-draft system would be more cost-effective for residential water heating.[1] The design and performance of an early prototype is described in a previous paper.[2] The early prototype achieved a service efficiency of 62.5% versus a project goal of 66.3% based on the DOE Test Procedures for Water Heaters.[3] This paper describes the subsequent improvements and the current performance.

WATER HEATER DESCRIPTION

The water heater assembly is shown in Fig. 1. It is a gas-fired automatic storage type having a 40 gal. (150 L) capacity with a burner input of 40,000 Btu/h (11.7 kW). Functionally, it is similar in operation to conventional water heaters, that is, it maintains a stored volume of hot water using a natural-draft gas burner supplied by a combination gas valve. As with conventional water heaters, a thermostat located in the tank actuates this gas valve.

The water heater described in this paper does, however, differ in the method of heating water. The center-flue design used in conventional water heaters was eliminated by separating the heating and storage functions. This was accomplished by designing a heat exchanger that surrounds the burner and is mounted below the tank, as shown in Fig. 1. Water stored in the tank is heated by natural circulation through the heat exchanger. One advantage of this approach is that during the off-cycle, the small inventory of water in the heat exchanger cools quickly, stopping circulation of heated water through the heat exchanger, thus acting as a "thermal check-valve." The tank consists of an internal polyethylene liner encapsulated by foam insulation. An outer steel shell provides the structural support for the storage system. Although conventional water heater designs might allow higher recovery efficiencies to be achieved, it was felt that any water heater retaining the center-flue design had inherently higher heat losses that could not be overcome easily.

The combustion system is of a unique premixed design that operates using natural draft. All the air required for combustion is drawn through an aspirator using regulated gas pressure. This is accomplished using a specially-designed gas nozzle combined with an efficient mixer/diffuser. The gas/air mixture is delivered to a metal screen, which serves as a flameholder, and is ignited by a standing gas pilot. The resulting flame is compact and has very low emissions, especially oxides of nitrogen.[2] In fact, NO_x emissions for this burner are below the limits proposed by the South Coast Air Quality District Board.[4]

DESIGN IMPROVEMENTS

The water heater assembly shown in Fig. 1 was the result of developmental work performed on an early prototype shown in Fig. 2. The main areas of improvement were the combustion system, the heat exchanger, and the storage tank.

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Combustion System

The most notable achievement in the redesign of the combustion system was the development of a compact aspirator that significantly improved the packaging of the combustion system. The early aspirator design shown in Fig. 2 required a total mixing and diffusing length of 30 in. (76 cm) to accomplish the design goal of 40,000 Btu/h (11.7 kW) burner input at 40% excess air. The excessive length resulted in an awkward design that protruded beyond the stand supporting the tank by almost 12 in. (30 cm).

An intensive development effort resulted in the aspirator, shown in Fig. 1, which was 9 in. (23 cm) long and could be packaged entirely beneath the tank with no sacrifice in performance. The reduction in length resulted principally from improvements in the nozzle to achieve better entrainment and mixing and from development of a diffuser permitting more rapid diffusion.

One other improvement to the combustion system was the inclusion of a simplified pilot for lighting the burner. The original pilot concept was integral with the burner and required a piezo-electric ignition device for lighting it. It was also difficult to service and replace. The new pilot system being used, which is mounted on the heat exchanger, can be ignited using a match and can be replaced without removing the burner.

Storage Tank

The original storage tank had a total of five openings that passed through the internal insulation. Two of these were located at the top of the tank, as shown in Fig. 2, and three beneath the tank. The storage tank has been redesigned to have only two penetrations, one fitting at the top of the tank and a flange at the bottom of the tank for mounting the heat exchanger. The elimination of three fittings has improved the reliability of the tank and has decreased the standby losses.

Heat Exchanger

The changes made to the heat exchanger did not appreciably affect performance but were made to improve packaging and manufacturability. The new design allows the use of stampings to form the headers, decreasing the amount of fabrication required. The headers and downcomer were combined so that, instead of a separately fabricated exhaust shroud, a sheet-metal housing could be wrapped around the headers to form the exhaust passages. This had the effect of decreasing the overall dimensions of the heat exchanger, and the simplified construction should result in lower manufacturing costs.

WATER HEATING EFFICIENCY

The service efficiency of the water heater is a measure of the fuel utilization, which includes both the burner-on periods, when the recovery efficiency predominates, and inactive standby periods, when the main burner is off and water storage heat losses and pilot consumption dominate. The combination of gas consumed for useful water heating (recovery) during the active period and gas consumed during the inactive period (standby) determines the service efficiency. Of course, the higher the water usage, the longer the active period, and the higher the service or water heating efficiency.

Recovery Efficiency

The recovery efficiency is determined by the design of the heat exchanger for the system. While several configurations were tested, functionally the design was similar in all cases. The most recent is shown in Fig. 3. The heat transfer surface consisted of 21 6-in. (15-cm) long integral finned copper tubes located on an approximately 7-in. (18-cm) pitch diameter. The total heat transfer area was 7.4 ft^2 (.69 m^2).

An important design parameter was a heat exchanger exhaust temperature of 300°F (149°C) at 40% excess air. It was felt that this was the minimum acceptable value that would avoid significant condensation in the exhaust ducting and provide sufficient draft to vent the exhaust products. The principal method of controlling the exhaust temperature was to vary the tube spacing (distance between fin tips). This was done with several heat exchangers, which resulted in recovery efficiencies varying from 78% to 84% at corresponding exhaust temperatures from 400°F (200°C) down to 220°F (104°C). The selected design, shown in Fig. 3, was the best compromise between recovery efficiency and minimum exhaust temperature limitations. It had a recovery efficiency of 80.6% and an exhaust temperature that varied from 280°F (138°C) to 310°F (154°C) during a recovery test. The combustion efficiency of this unit was 84% to 85%. Further gains in recovery efficiency, if any, will have to come by identifying and eliminating the losses that account for the difference between the recovery and combustion efficiency.

Endurance Testing

In order to evaluate the effect of usage or time on the recovery efficiency, a prototype water heater assembly was installed in an endurance test facility, which subjected the unit to an accelerated usage pattern. Two test conditions were used: initial testing was done with the available Newton, MA, city water, which was soft and did not exhibit liming tendencies; the final testing was performed with water that was artificially hardened by adding calcium chloride to the city water supply.

The endurance test facility is shown in Fig. 4. The draw from the water heater was regulated using a combination of timers and a solenoid valve. The test cycle is shown in the lower left of Fig. 4. The chosen draw rate resulted in the heating of 758 gal. (2.87 m^3) per day or 22,750 gal. (86.2 m^3) per month. At the national average daily consumption of 64.3 gal. (.244 m^3) per day,[3] the endurance facility simulated one year's accelerated usage in 30 days.

During the endurance testing with soft water, the water heater operated for 1800 hours heating 68,000 gal. (258 m^3) of water. This was the equivalent of 2.9 years of water heater service. The burner cycled 4067 times during this period. The unit ran unattended, with no maintenance, and the only time it was stopped was to perform recovery efficiency tests. The recovery efficiency with soft water as a function of time is shown in Tab. 1. From the results presented, it can be seen that, while the recovery efficiency varied, there appeared to be no historical trend of performance degradation with operating time. The measured efficiency varied from 79% to 83%. This variation was probably due to the variability in utility gas heating value and instrument errors. The stack temperatures shown in Tab. 1 are relatively constant versus time, indicating no degradation in performance due to deposits on heat exchanger surfaces.

Although the water heater did not show any liming tendencies with normal Newton, MA, city water (20 ppm $CaCO_3$), it was desired to test the unit with hard water to uncover any potential liming tendency of the water heater. Water is considered soft if it contains less than 60 ppm calcium carbonate and is considered very hard if it contains more than 180 ppm.[5] $CaCO_3$ is only one of the constituents contributing to scale formation in water heaters, but it is the major one, and the assumption was made that water treated to 200 ppm $CaCO_3$ would uncover any liming tendencies of the design. The flow passages of the finned tubing heat exchanger were the major area of concern.

The endurance test facility was operated with artificially hardened water for the equivalent of 1.9 year's water heater usage. During this test phase, the burner cycled 3925 times and accumulated 1148 hours of operation. Hot water consumption was 45,200 gal. (171 m^3). The entire endurance testing with soft and hard water resulted in 2949 hours of burner operation representing 4.8 years of water heater operation. During this period, 113,200 gal. (429 m^3) of water were consumed.

The recovery efficiency with hard water versus operating time is shown in Tab. 1. Again, little degradation in performance can be seen as a function of time. On the average, there might be a difference of one percentage point between the beginning and final tests, but this is within the range of variability in the test conditions and measurement uncertainty.

At the planned end of the endurance testing with hard water, the heat exchanger was removed from the water heater. The outside heat exchanger surfaces showed some products of corrosion but no significant metal loss. The top and bottom headers had the heaviest deposits, while the finned tube core showed some discoloration but very little metal loss. The internal flow passages did not show any evidence of scale due to the presence of lime in the water. However, the flange connecting the exchanger to the tank did show evidence of lime buildup as can be seen in Fig. 5. The picture on the left in Fig. 5 also shows the buildup of lime on the thermocouple probe in the downcomer. This was unexpected, especially since it was in one of the colder sections of the heat exchanger. It is felt that some kind of galvanic cell might have caused this buildup.

While no evidence of scaling on the heat exchanger surfaces could be found visually (the heat exchanger was not cut apart for close examination), heat exchanger wall temperatures were monitored for any increase that would show a decrease of the water-side heat-transfer coefficient. This would indirectly indicate the presence of scale on the inside tube wall. A 30°F (17°C) wall temperature rise would be equivalent to a scale thickness of about .0025 in. (.064 mm). Fig. 6 shows the temperature-time history of three positions on one of the finned tubes in the heat exchanger. The temperatures plotted were for approximately the same conditions, that is, firing rate, excess air, and water inlet temperature. Again, while there is some variation in the measured temperatures, there is no upward trend to indicate the building up of scale in the heat exchanger, which supports the visual evidence.

Standby Losses

Standby losses for this water heater consist of two components: heat loss from the storage system (tank and fittings) and pilot loss. The relationship among standby loss, pilot loss, and tank and fitting losses is shown in Fig. 7. The tank and fitting losses in the figure include tank skin losses, heat exchanger losses, and fitting losses. The pilot loss is a function of pilot recovery, since all of the pilot heat is not necessarily lost.

Tab. 2 shows the standby losses for three different configurations tested. These were 2.7%/h, 3.6%/h, and 3.2%/h. The first case was for a handmade prototype used early in the program, and the second case shows the standby losses for the first version of the production tank. Since the first two tanks were similarly configured, the drop in standby loss is attributed to changes in the manufacturing process and materials. The third case shown in Tab. 2 represents the standby losses for the latest production version of the tank (this is the one in Fig. 1). The difference in standby losses between the second and third tanks is due to fewer tank penetrations. The second tank in Tab. 2 had four fittings (two at the top and two at the bottom) plus a flange at the bottom of the tank. The third tank had only one fitting at the top and a flange at the bottom. This decrease of three fittings lowered the standby losses by .3%/h.

The pilot losses remained constant throughout all of the standby loss tests. The pilot input was 275 Btu/h (80.6 W) and based on cool-down tests, about 85 Btu/h (25 W) or 30% of the pilot input was recovered. Fig. 8 shows one of this test series. In this case, a tank of heated water was allowed to cool down several times with and without the pilot operating. The difference in heat loss was attributed to heat recovered from the pilot. While the pilot input was low, problems with pilot outage in the field were not expected, since the pilot is protected from drafts because of its location inside the combustion chamber formed by the heat exchanger. In addition, similar pilot inputs are being used by some conventional water heater manufacturers.

The approach being taken to lower standby losses is to decrease both the tank and pilot losses. A computer model of the water heater was developed that included the effect of insulation thickness, tank and fitting losses, heat exchanger losses, and pilot losses. Tab. 3 shows an analysis of the standby losses for the water heater for three different configurations. The first column shows the components of heat loss that make up the standby loss of the current MK III prototype shown in Fig. 1. The tank and fitting losses (excluding the heat exchanger) are 541 Btu/h (159 W); the heat exchanger losses, 100 Btu/h (29 W); and the pilot losses, 173 Btu/h (51 W). If the tank and fitting losses are made up at the recovery efficiency of 80.6%, the total heat loss would be 968 Btu/h (284 W), or 3.2%/h.

The second column shows the predicted effect of increasing the thickness of insulation having a thermal conductivity of .012 Btu•ft/ft^2•h•^{o}F (20.7 W•mm/m^2•^{o}C) from .75 in. (1.9 cm) to 2 in. (5 cm). This results in a twofold reduction. First and most obvious is a decrease of the tank and fitting losses from 159 W to 54 W for a decrease of 355 Btu/h (105 W). However, a further decrease of 85 Btu/h (25 W) is due to the recovery efficiency (80.6%) to make up these losses.

A prototype tank with an internal, rotationally molded polyethylene liner and two inches of external low-density foam insulation is shown in Fig. 9. This tank is expected to be tested shortly to confirm these predictions.

The effect of eliminating the standing pilot in favor of an intermittent ignition device (IID) in addition to increasing the insulation thickness is shown in column three of Tab. 3. This further decreases the standby loss by 173 Btu/h (51 W), resulting in a predicted standby loss of 1.2%/h. In keeping with the design goal not to use external power, the IID design uses a battery for its power source. An ignition circuit was designed using a penlight-size lithium battery having a storage capacity of 3 watt-hours. Based on requiring 42 10-mJ sparks per day (3 sparks per ignition, 14 starts per day,[6] 1.7 watt-hours of storage are required at a circuit efficiency of 38% for a 15-year life. This circuit was built and tested. Operating continuously, more than 230,000 sparks were produced using a single battery, thus demonstrating a battery storage capacity in excess of 15 years. Battery shelf life determined the type of battery selected. Rechargeable batteries, which were considered initially, did not have adequate shelf life for this application. The selected lithium battery is expected to retain 80% of its storage capacity after being stored for 10 years at 70^{o}F (21^{o}C). Thus, it has the best potential for use with this ignition system.

In addition to the ignition circuit, a gas valve was constructed to be used with this system. Its operation is as follows:

1. The tank thermostat calls for heat.

2. A first gas valve opens admitting gas to a pilot and to the inlet of a second valve.

3. The ignitor lights the pilot and, after sensing a flame, turns itself off to conserve battery energy.

4. The pilot flame causes the second valve to admit gas to the burner, where it is ignited by the pilot.

5. When the thermostat is satisfied, the gas is turned off.

6. If the pilot fails to light within 45 seconds, the main gas valve (Step 2) closes, shutting down all gas to the system.

This ignition system has been completed and is undergoing component testing before being installed in the water heater assembly. (The ignition system and gas valve are developmental models and have not been AGA-certified.)

SERVICE EFFICIENCY

The recovery efficiency and standby losses can be used to predict the water heating or service efficiency of the water heater. Fig. 10 shows service efficiency plotted versus recovery efficiency and standby losses for the DOE test conditions.[3] Plotted in this figure are the results for the various configurations discussed in this paper. First, the original prototype at the beginning of this phase with a recovery of 82% and standby losses of 2.7%/h. This results in a service efficiency of 63%. Next, the most recent assembly (MK III), which used some production components and had a service efficiency of 59%. A service efficiency of 67% is predicted for the assembly (MK IV) being built with increased insulation when used with a standing pilot and 71% when equipped with an IID. This compares with 44% for a conventional unit (70% recovery efficiency and 6%/h standby loss[7] and 53% for a unit meeting the ASHRAE standards.[8]

SUMMARY AND CONCLUSIONS

1. The test results indicate that the external heat exchanger in combination with a premixed burner is capable of achieving the highest recovery efficiency consistent with a stack temperature high enough to prevent condensation and to provide adequate draft.

2. Endurance tests simulating almost five years of normal operation indicate no significant performance degradation due to scale formation or accumulation of corrosion products. However, the presence of corrosion products suggests the need for corrosion protection.

3. The small load factor of residential water heaters requires close attention to minimization of standby losses if high service efficiency is to be attained. Insulation improvements should reduce standby losses by approximately 40%. Elimination of the standing pilot will reduce standby losses by an additional 30% for an overall reduction of approximately 60%. The resulting service efficiency will be approximately 71%, as compared to 44% for a conventional water heater, or 53% for one meeting current ASHRAE standards.

4. A novel battery-operated intermittent ignition device has been developed, which is expected to provide at least ten years of service using a single nonrechargeable battery. This IID may find application in other gas-fired appliances besides residential water heaters.

REFERENCES

1. A.D. Vasilakis, J.F. Pearson, and J. Gerstmann, "Research and Development of a High-Efficiency Gas-Fired Water Heater, Volume 2: Task Reports" (Phase I Final Report to Oak Ridge National Laboratory, Report No. ORNL/Sub-7381/2, Jan. 1980).

2. A.D. Vasilakis et al, "Development of a High-Efficiency Gas-Fired Water Heater" (presented at the 1981 International Gas Research Conference).

3. "Energy Conservation Program for Appliances: Test Procedures for Water Heaters," Federal Register, Part III, Oct. 4, 1977.

4. South Coast Air Quality Management District, El Monte, CA 91731, Rules and Regulations, Rule 1121, "Control of Nitrogen Oxides from Residential-Type Natural Gas Fired Water Heaters," December 1, 1978.

5. ASHRAE Guide and Data Book: 1967 Systems and Equipment, (New York: ASHRAE 1967).

6. Measurements made on 40-gal. automatic storage water heaters using 250 GPD during non-published field test performance by AMTI.

7. "Study of Energy-Saving Options for Refrigerators and Water Heaters, Vol. 2: Water Heaters" (Arthur D. Little, Inc. prepared for the Office of Transportation and Appliance Programs, FEA, Contract No. 0004-50228-00, May 1977).

8. ASHRAE Standard 90A-1980, "Energy Conservation in New Building Design" (New York: ASHRAE, 1980).

ACKNOWLEDGMENT

The authors would like to thank AMTROL, Inc., of Warwick, RI, for providing prototype and production tanks during development and testing and for manufacturing support of the project in general.

Table 1. Endurance Testing Results

	Soft Water(1)	Hard Water(2)	Total
Hours of Operation	1,801	1,148	2,949
Burner Cycles	4,067	3,925	7,992
Water Consumption $-m^3$ (gallons)	258 (68,000)	171 (45,200)	429 (113,200)
Years at .243 m^3/day (64.3 gpd)	2.9 yrs	1.92	4.82

RECOVERY EFFICIENCY (Natural Gas)

Hours of Operation	Excess Air (%)	Stack Temperature Variation During Test (°C)	(°F)	Recovery Efficiency (%)
A. SOFT WATER				
0	40-45	162/188	(323/371)	83.6
324	40-50	160/186	(320/366)	79.0
396	40-45	160/192	(320/377)	82.9
832	38-42	154/183	(309/361)	79.3
854	34-40	157/187	(314/369)	79.3
1576	34-40	166/193	(330/380)	80.7
1800	50-60	149/182	(300/360)	80.2
B. HARD WATER				
1800	40-47	160/188	(320/370)	79.0
1898	46-55	166/193	(330/380)	76.0
2064	39-44	154/182	(310/360)	78.1
2274	40-46	141/171	(285/340)	79.5
2461	48-52	121/149	(250/300)	77.7
2567	45-48	121/149	(250/300)	77.7
2714	43-50	149/177	(300/350)	80.0
2776	43-50	149/177	(300/350)	80.0
2890	46-48	157/177	(315/350)	78.0
2890	39-44	141/166	(285/330)	77.0

(1) Hardness - 20 ppm $CaCO_3$

(2) Hardness - 200 ppm $CaCO_3$

Table 2. Measured Standby Losses

Configuration	Standby Loss %/h
Development Prototype (Ref. 1)	2.7
Manufactured Prototype	3.6
MK III Prototype	3.2

Table 3. Standby Loss Analysis

	Configuration		
	Measured	Predicted	
	Current Version (MK III)	Increased Insulation	Increased Insulation and IID
Tank and Fitting Losses - W (Btu/h)	159 (541)	54 (186)	54 (186)
Heat Exchanger Losses - W (Btu/h)	29 (100)	29 (100)	29 (100)
Loss Due to 80.6% Recovery - W (Btu/h)	45 (154)	20 (69)	20 (69)
Pilot Losses - W (Btu/h)	51 (173)	51 (173)	0 (0)
Total - W (Btu/h)	284 (968)	154 (528)	103 (355)
Standby Losses (%/h)	3.2	1.8	1.2

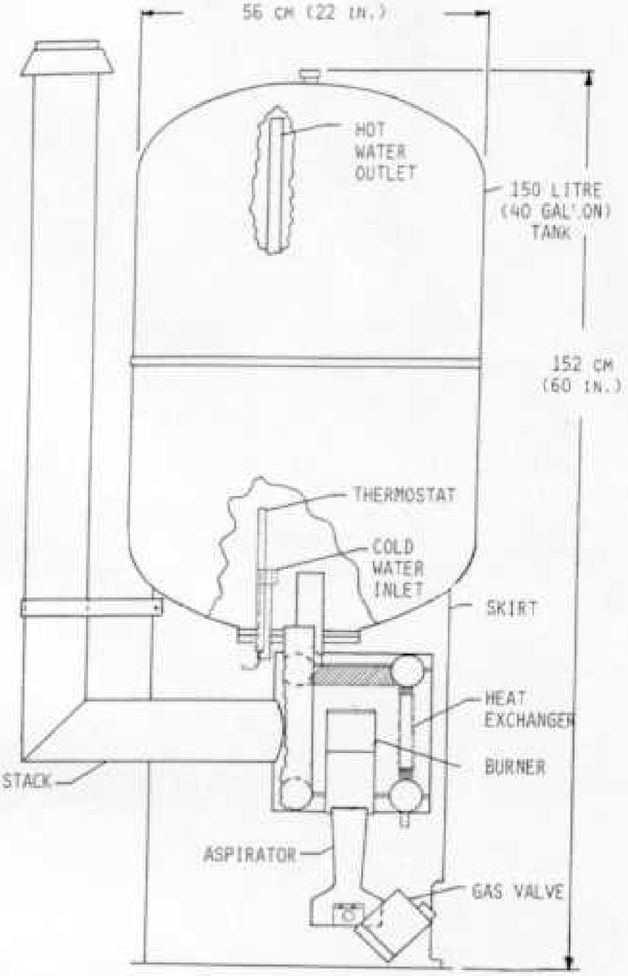

Figure 1. Existing prototype assembly (MK III)

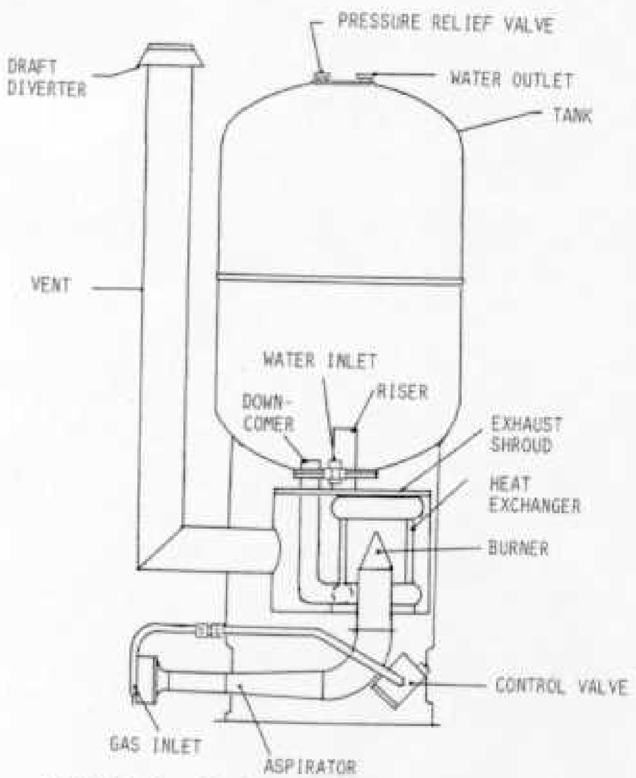

Figure 2. Early prototype water heater

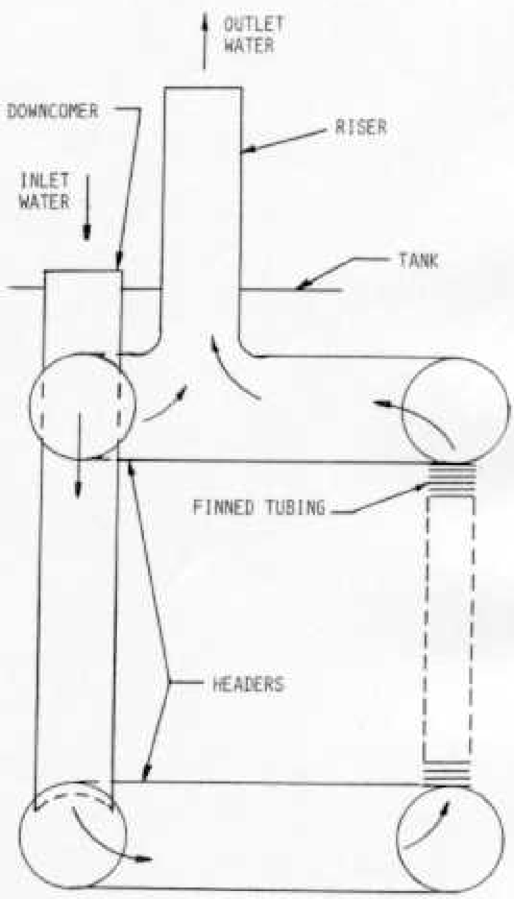

Figure 3. Heat exchanger

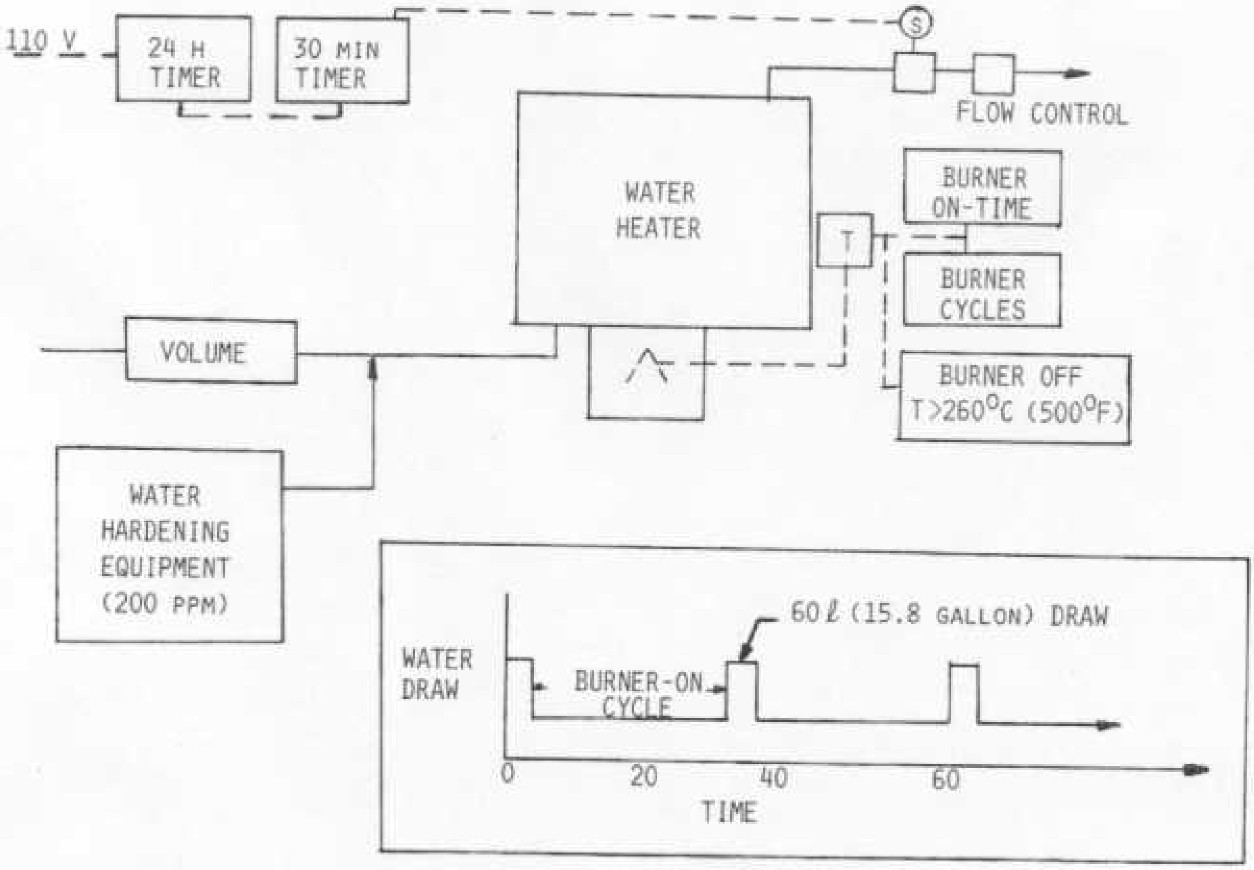

Figure 4. Endurance test facility

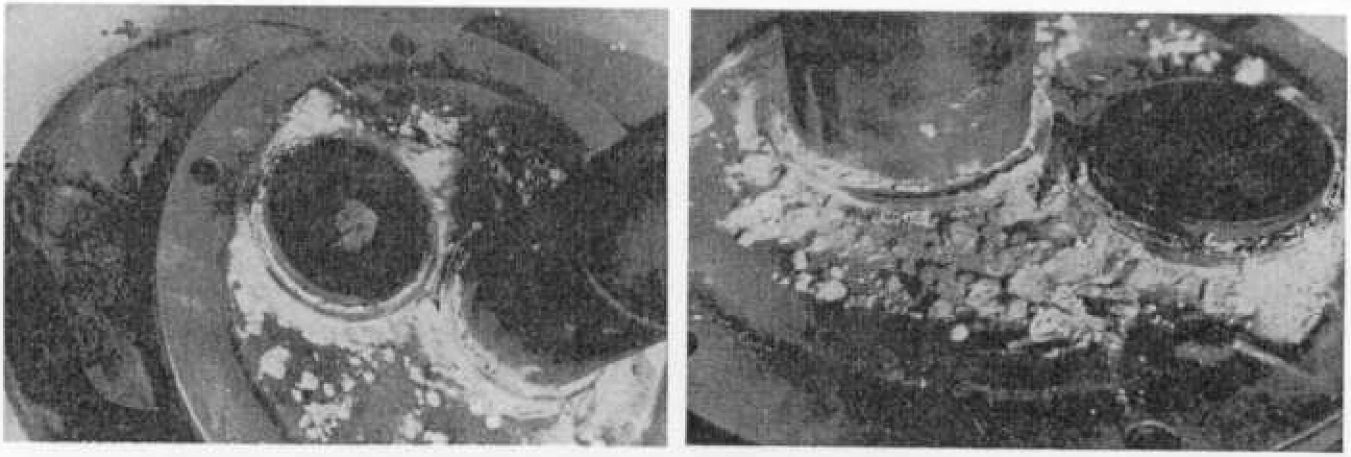

Figure 5. Photographs of lime deposits on heat exchanger flange after 1.8 years of accelerated usage tests

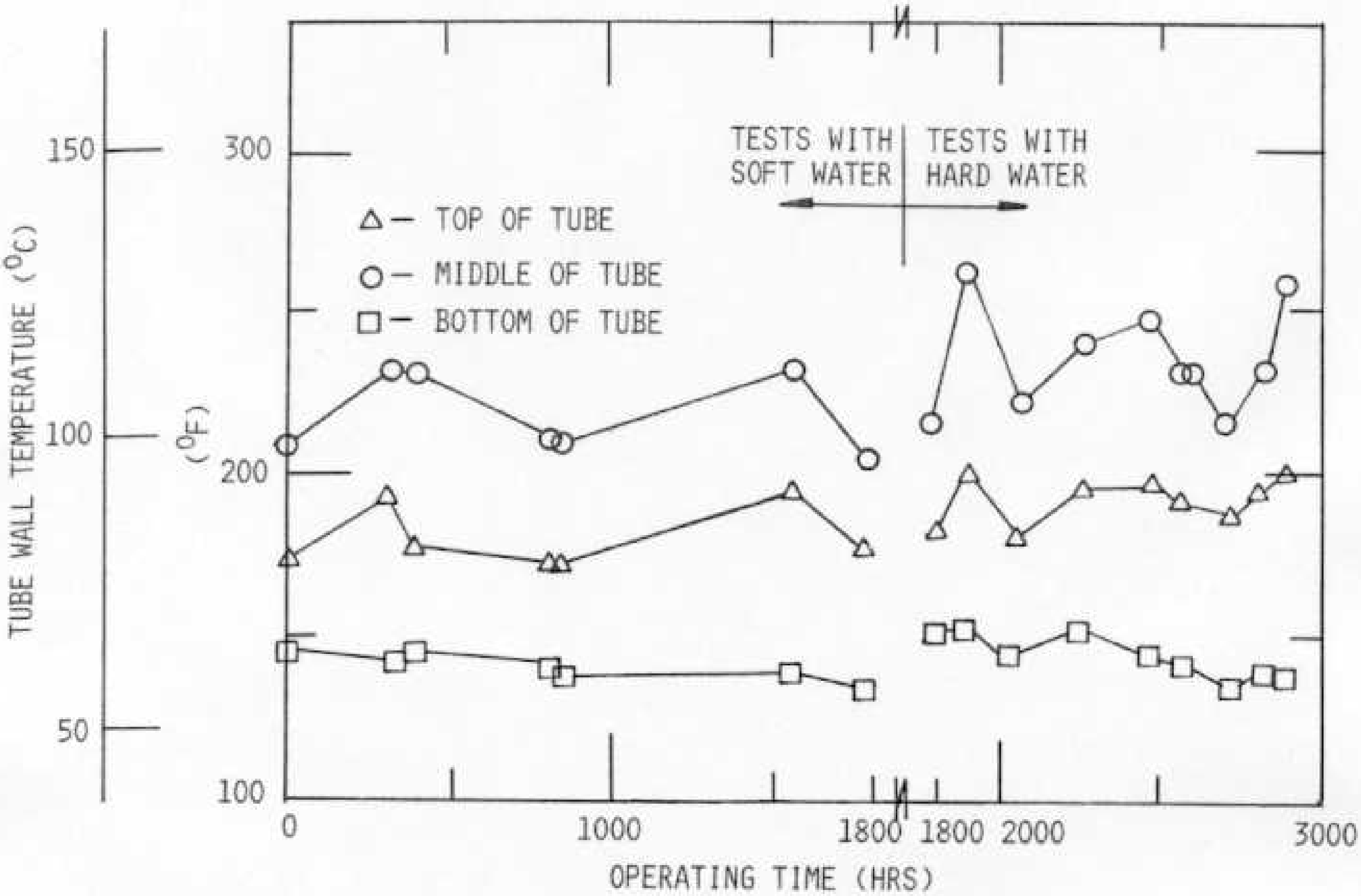

Figure 6. Heat exchanger tube wall temperature history during endurance testing

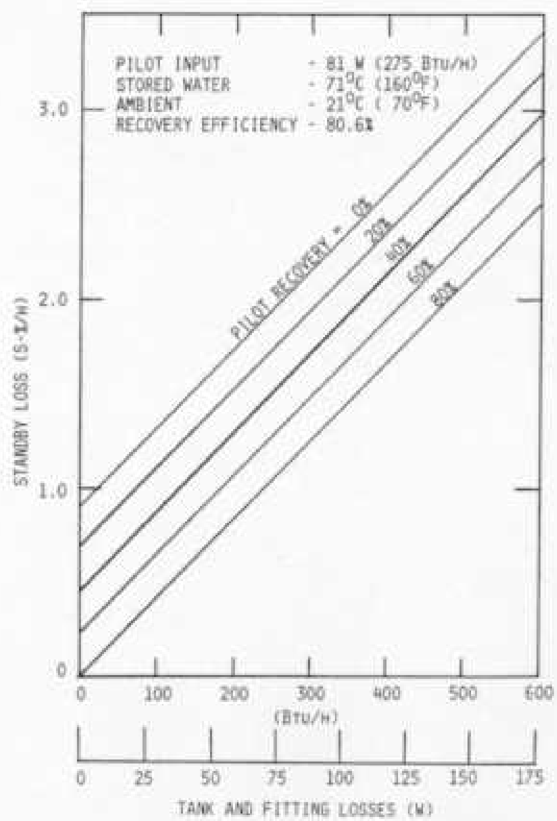

Figure 7. Standby loss as a function of tank and fitting losses and pilot recovery

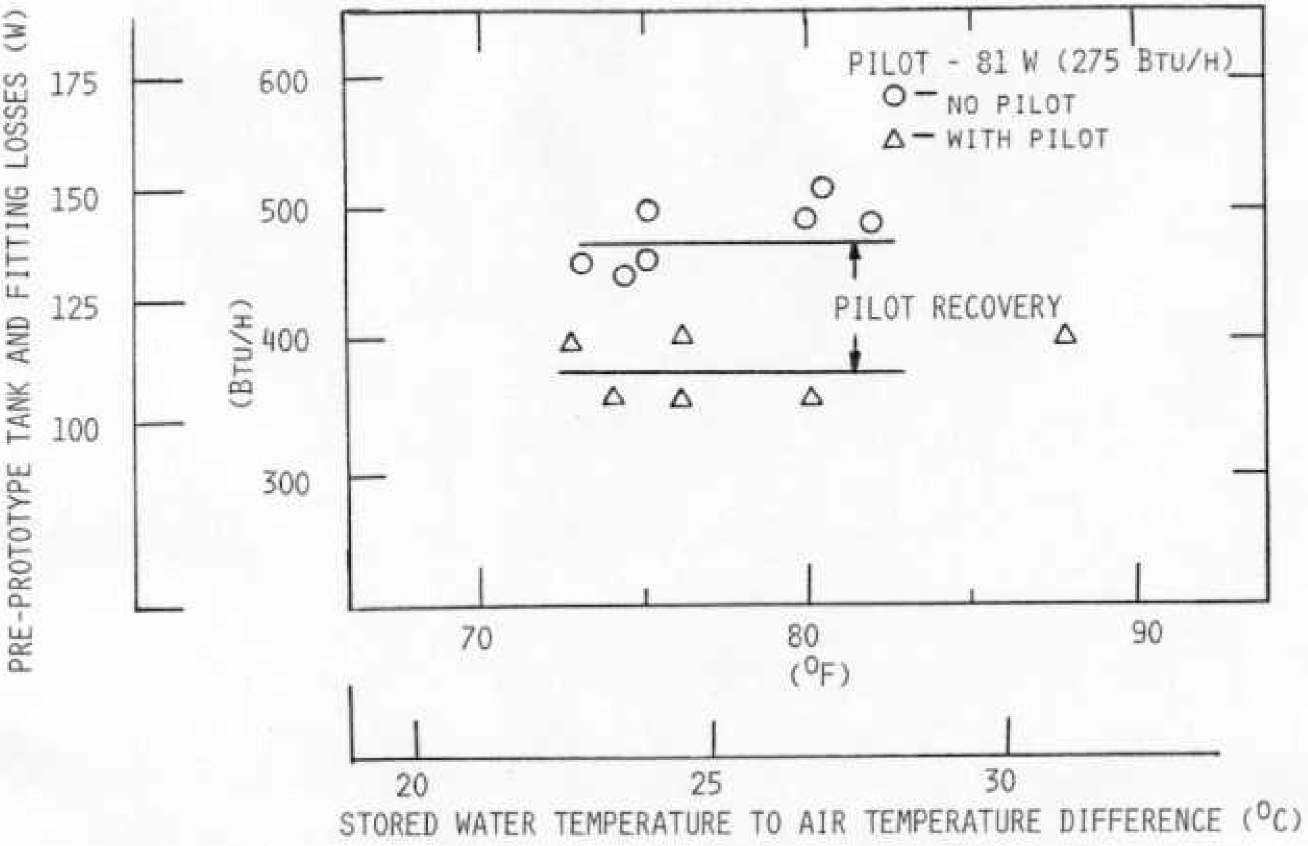

Figure 8. Pre-prototype tank and fitting losses with and without pilot

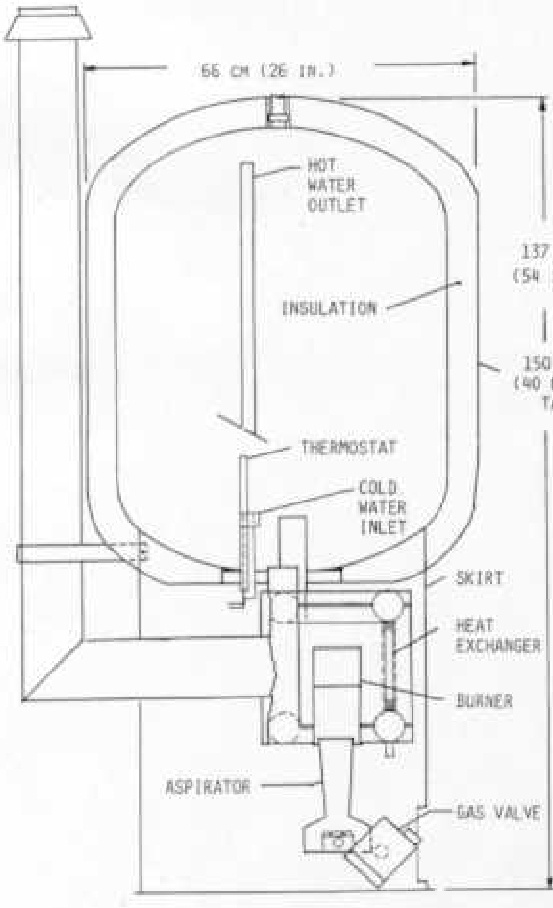

Figure 9. MK IV prototype

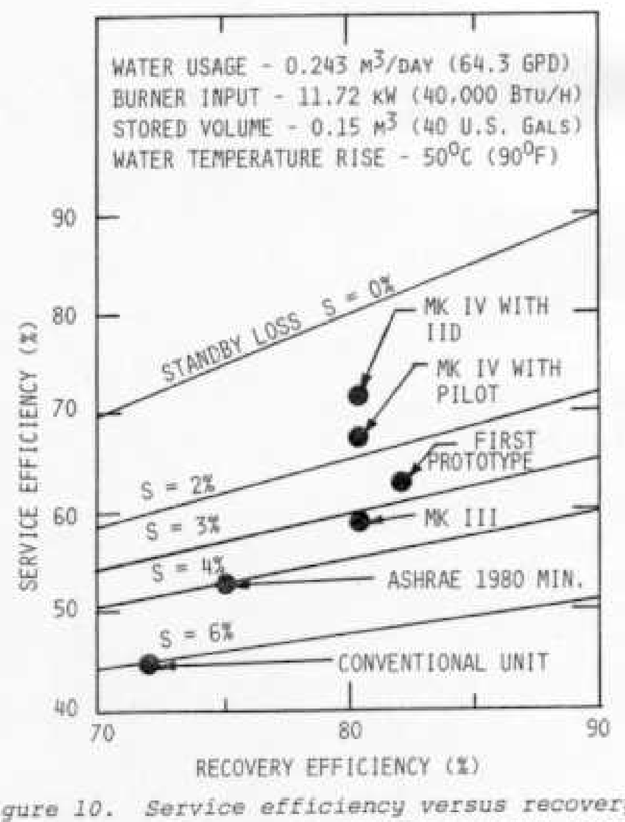

Figure 10. Service efficiency versus recovery efficiency at various standby losses

DISCUSSION

J. Overall Canadian Gas Resch. Inst., Ontario: At what water temperature did you do your endurance tests?

A.D. Vasilakis: The tests were conducted using a nominal stored-water temperature of 160^{o}F. This would be the highest expected stored-water temperature with a residential water heater. The actual temperature in the heat exchanger was not monitored during the endurance tests. However, estimates based on recovery test data would be a heat exchanger inlet and outlet temperatures of 115^{o}F and 140^{o}F at the beginning of a recovery cycle and inlet and outlet temperatures of 150^{o}F and 170^{o}F at the end of a recovery cycle. These were bulk temperatures measured in the riser and downcomer of the heat exchanger during heater operation.