ORNL/Sub-7381/2
Distribution Category UC-95d

ERGY

CONSERVATION

RESEARCH AND DEVELOPMENT OF A HIGH EFFICIENCY GAS-FIRED WATER HEATER

VOLUME 2

TASK REPORTS

Prepared by:

Andrew D. Vasilakis
John F. Pearson
Dr. Joseph Gerstmann

ADVANCED MECHANICAL TECHNOLOGY, INC.
141 California Street
Newton, Massachusetts 02158

Work performed for

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U. S. DEPARTMENT OF ENERGY

Office of Buildings and Community Systems

ORNL/Sub-7381/2
Distribtuion Category UC-95d

RESEARCH AND DEVELOPMENT OF A
HIGH EFFICIENCY GAS-FIRED WATER HEATER

VOLUME 2: TASK REPORTS

JANUARY 1980

Prepared By:

Andrew D. Vasilakis
John F. Pearson
Dr. Joseph Gerstmann

ADVANCED MECHANICAL TECHNOLOGY, INC.
141 California Street
Newton, Massachusetts 02158

Prepared under Subcontract 7381 for the

Oak Ridge National Laboratory
Oak Ridge, TN 37830
Operated by
Union Carbide Corporation
for the
U.S. Department of Energy

Contract No. W-7405-eng-26

ADVANCED MECHANICAL TECHNOLOGY, INC

TABLE OF CONTENTS

ABSTRACT

This report describes the work performed under Phase I of the project to design and develop a cost-effective high efficiency gas-fired water heater. The project goal was to attain a service efficiency of 70% (including the effect of exfiltration) and a service efficiency of 78% (excluding exfiltration) for a 75 GPD draw at a 90°F temperature rise, with a stored water to conditioned air temperature difference of 80°F. Based on concept evaluation, a non-powered natural draft water heater was chosen as the most cost-effective design to develop. The projected installed cost is $374 compared to $200 for a conventional unit. When the project water heater is compared to a conventional unit, it has a payback of 3.7 years and life cycle savings of $350 to the consumer.

A prototype water heater was designed, constructed, and tested. When operated with sealed combustion, the unit has a service efficiency of 66.4% (including the effect of exfiltration) below a burner input of 32,000 Btu/hr. In the open combustion configuration, the unit operated at a measured efficiency of 66.4% Btu/hr (excluding exfiltration). This compares with a service efficiency of 51.3% for a conventional water heater and 61% for a conventional "high efficiency" unit capable of meeting ASHRAE 90-75. Operational tests showed the unit performed well with no evidence of "stacking" or hot spots. It met or exceeded all capacity or usage tests specified in the program test plan and met all emission goals. Future work will concentrate on designing, building, and testing pre-production units. It is anticipated that both sealed combustion and open draft models will be pursued.

FOREWORD

This report is the second of two volumes which describes the work performed during Phase I on UCC-ND Subcontract 7381. In this contract Advanced Mechanical Technology, Inc. (AMTI) is a subcontractor to Union Carbide Corporation-Nuclear Division to research, develop, and demonstrate a high efficiency gas-fired water heater. The water heater concept is a joint development of AMTI and Amtrol Inc., who is a subcontractor to AMTI under this UCC-ND project. AMTI is responsible for the design and development tasks while Amtrol is responsible for the marketing and manufacturing tasks.

Volume 2, this report, contains all of the Phase 1 task reports. Volume 1, which is bound separately, is a summary of the task reports which highlights the important results.

RESEARCH AND DEVELOPMENT OF A

HIGH EFFICIENCY GAS-FIRED WATER HEATER

CONCEPT AND MARKET EVALUATION

TASK 2 REPORT

October 6, 1978

Prepared by:

Advanced Mechanical Technology, Inc.
141 California Street
Newton, Massachusetts 02158

Prepared under Subcontract 7381 for the

Oak Ridge National Laboratory
Oak Ridge, TN 37830
Operated by
Union Carbide Corporation
For The
U.S. Department of Energy
Contract No. W-7405-eng-26

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. INTRODUCTION AND SUMMARY

This report describes the work completed under Task 2, the concept and market evaluation of the high efficiency gas-fired water heater. The concept evaluation work was conducted by AMT, while the market evaluation was performed by Amtrol.

Concept Evaluation

A mathematical model for the water heater was formulated, and the equations required for performance and cost evaluation were developed. This model together with the equations was incorporated into a computer program for the concept evaluation (See Appendix B).

A variety of options was analyzed to compare performance versus cost, with the conclusion that the proposed natural draft water heater could meet the performance criteria of 70% service efficiency* with a projected payback of slightly over 3.5 years, and life-cycle savings of $350. Thus, the proposed natural draft gas-fired water heater was justified for development in Task 3 of this project. Its salient features consist of: a high-efficiency, 100% primary air, naturally aspirated burner; an external bottom-fired natural circulation heat exchanger located under the storage tank; a high efficiency standing pilot; a plastic-lined insulated storage tank; and an external sealed combustion flue.

A "proof-of-concept" experimental gas-fired water heater was built to test the feasibility of the key features and the results are reported in Appendix C.

*Service efficiency includes an allowance for the energy use associated with the use of conditioned air by the water heater.

Market Evaluation

The current water heater market was analyzed in order to establish the approach which should be used for marketing the unit being developed for this project. The main conclusion of this evaluation was that the marketing of a high-efficiency water heater will require a somewhat different strategy to gain market penetration.

The water heating industry is a highly competitive, cost-conscious industry made up of a small number of large manufacturers. Of the three million gas-fired water heaters sold each year, 60% are used in the (emergency) replacement market and the remainder are used in new installations. The distributor determines the units he will sell based mainly on cost. Unlike other appliances, the consumer has very little influence on the type of unit sold.

Initially, Amtrol intends to center its efforts towards the custom home market (10 to 15% of home purchasers). This potential is estimated at 300,000 units/year. Gaining entry will entail the following strategy.

1. Education and motivation of the plumbing trade.

2. Creation of consumer awareness.

3. Presentation and promotions to selected builders.

Items 1 and 3 have the objective of capturing a share of the replacement and new market, respectively. The objective of item 2 is to create an awareness and receptiveness on the part of the consumer by using Amtrol and local gas company advertising and promotion to educate gas users as to the energy savings aspects and durability of the water heater. The unit will be sold as a quality water heater with emphasis on ample hot water, durability (longer tank life) and energy savings.

Further expansion of the market will depend on current trends and their subsequent developments. If government and state regulations regarding energy usage and public awareness of energy priorities result in general public acceptance of more energy efficient but higher cost water heaters, then marketing of the water heater will assume more conventional methods. Amtrol then expects to increase its share of the expanded energy efficient water heater market.

2. CONCEPT EVALUATION

The conceptual evaluation of the high efficiency water heater has been completed. The objectives of this evaluation were:

- To justify the ability of the proposed design to satisfy energy, economic, and market-related goals.
- To establish basic design specifications.
- To identify potential problems, especially market-related ones.

The approach used was to divide the water heater into a number of basic parts for separate consideration. In this way, a performance and cost analysis for each component, as well as for the entire water heater, was obtained. The most promising combination of options was identified and the basic design specifications were selected for development during Task 3.

2.1 Water Heater Performance - Basis for Evaluation

A water heater performance model for this evaluation was obtained by developing equations which followed the DOE "test procedures for water heaters"[(1)]. These equations were modified to include an exfiltration loss which was not a part of the DOE procedure.

The performance comparisons were conducted for a daily hot water draw of 75 gallons at a temperature of 150°F, and an inlet temperature of 60°F. An ambient temperature of 70°F was assumed. The exfiltration loss penalty assumed an average infiltration/exfiltration temperature differential of 30°F, with a space heating furnace efficiency of 100%. Under these assumptions, the gas consumption of a conventional water heater was 109,000 Btu/day (service efficiency of 51.1%), excluding exfiltration, and 119,800 Btu/day (service efficiency of 46.5%), including the allowance for exfiltration. The complete development of the equations describing water heater performance together with the assumptions used to develop these equations is shown in Appendix A. The computer program used for the evaluation is presented in Appendix B.

2.2 Cost/Performance Procedure

Water heaters were separated into five sub-systems: stack, including flue dampers and sealed combustion; storage tank, including plastic and glass linings, foam and fiberglass insulations; the heat exchanger; the burner; and the pilot or other ignition means. Table 1 lists the various sub-systems and the individual options. The energy savings attributable to each option in various combinations with other options were analyzed, and these savings were compared to the estimated differential cost in order to determine their investment value.

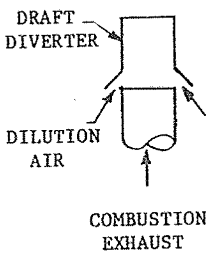
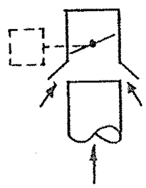
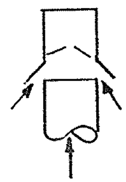
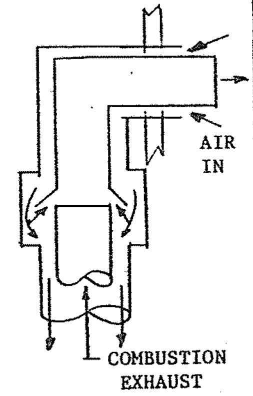
2.2.1 Performance Evaluation Method

Five stack options were evaluated: the conventional stack, which includes the draft diverter; the conventional stack with a mechanical stack damper downstream of the draft diverter; the former configuration but with a thermally actuated stack damper; an undiluted vent (no draft diverter); and a direct vent system (sealed combustion), in which all combustion air is taken from outdoors and is discharged directly to the outdoors. Table 2 shows the different stack options together with the exfiltration loss associated with each stack. The model used to predict this loss is described in Appendix A.

All of the stack configurations with the exception of the undiluted stack (no draft diverter) can be used with any other water heater option. The undiluted stack can only be used with the powered combustion system.

TABLE 1 - WATER HEATER OPTIONS

Subsystem	Option Numbers			
	1	2	3	4
1. Stack	Conventional Stack Including Draft Diverter	Conventional Stack with Vent Damper -Mechanical (2M) -Thermal (2T)	Undiluted Exhaust (No Draft Diverter)	Sealed Combustion
2. Tank	Conventional Glass-Lined Tank	Plastic-Lined Tank	Conv. Glass-Lined Tank with Added Insul.	None
3. Heat Exchanger	Conventional Center Flue	Forced Convection Heat Pipe	Natural Circulation Boiler/Condenser	Natural Circulation Bottom-Fired
4. Pilot	Conventional	Intermittent Ignition Device (IID)	High Efficiency Stratified Pilot	None
5. Burner	Conventional	Powered Combustion	100% Primary Air Natural Draft Burner	None

 CONVENTIONAL STACK	 MECHANICAL STACK DAMPER	 THERMAL STACK DAMPER	 UNDILUTED EXHAUST (FORCED COMBUSTION ONLY)	 SEALED COMBUSTION
BURNER* ON - EXFILTRATION LOSS (BTU/HR)				
729	729	729	340	0
BURNER OFF - EXFILTRATION LOSS (BTU/HR)				
423	21	169	109	0

*Case for Burner Input of 45,000 Btu/hr

TABLE 2 - STACK OPTIONS AND EXFILTRATION LOSSES

ADVANCED MECHANICAL TECHNOLOGY, INC.

Three tank combinations were considered. The first was the conventional glass-lined, center-flue storage tank utilizing 0.75 inches of fiberglass insulation between the tank and the external sheet-metal jacket. The second option was the conventional tank with 1 inch of additional insulation. The third option was a plastic-lined steel tank having no center flue. Because the plastic-lined tank has no center flue, it is only adaptable to an external heat exchanger. The tank losses for these three tanks were 500 Btu/hr, 300 Btu/hr, and 300 Btu/hr, respectively.

Regarding tank option combinations, the conventional glass-lined tank was only considered with the conventional center flue heat exchanger, burner and pilot combinations. On the other hand, the plastic-lined tank was not used in combination with any of the conventional components, but was used with "non-conventional" options.

Four types of heat exchangers were evaluated: three natural convection (gas-side) units and one forced convection unit. The first heat exchanger was a conventional water heater type comprised of a baffled center flue and the tank bottom. The stack efficiency of this unit was taken as 74.5%. This value was calculated using an energy recovery[(2)] of 71.7% for a conventional gas-fired water heater and using the equations of Appendix A, to arrive at the stack efficiency.

The second unit considered was a forced-convection (gas-side) heat exchanger utilizing a heat-pipe principle. Hot gases pass over the lower section which acts as a boiler, and the upper section or condenser is located in the hot water storage tank. The stack efficiency for this unit is 85% based on operating conditions of 30% excess air and a 300°F exhaust temperature. This resulted in an energy recovery efficiency of 81.9%.

The third heat exchanger evaluated was a natural convection (boiling/condensing) unit using a boiler heated by the combustion products. The steam generated in the boiler is piped through a condensing coil located in the hot water storage tank. The unit was considered for use with a natural-draft burner, and under these conditions the stack efficiency is 84%. This was based on 50-60% excess air and a stack temperature of about 300°F. The energy recovery efficiency for this unit was calcuated to be 80.9%.

The last heat exchanger considered was a natural-circulation bottom-fired heat exchanger located under the tank and for use with an atmospheric burner. The stack efficiency for this unit is 84% and the energy recovery efficiency is 80.9%, based on the same operating conditions assumed for the other natural-draft heat exchanger.

Two constraints were used in the evaluation of these heat exchanger units. One constraint was that the heating area in contact with the stored hot water remained below 220°F to avoid liming. Another was that a forced convection heat exchanger required only 50-60% of the surface area required for a similarly rated natural convection heat exchanger. This constraint was based on forced convection units tested at AMT.

Three types of burners were evaluated: the conventional atmospheric burner utilizing both primary and secondary air; a forced-draft burner; and a 100% primary air, natural-draft burner. There are slight differences in performance among the forced and natural draft burners. Forced-combustion enables operation at lower excess air than natural-draft, thus permitting somewhat greater stack efficiency. The fact that powered combustion can reduce the necessary size of the heat exchanger was accounted for by pairing powered combustion with the forced convection heat exchanger, and atmospheric burners with their appropriate heat exchangers. The powered burner included an energy consumption of 20 Watts (210 Btu/hr equivalent) during operation. A conversion factor of 10.5 Btu/Watt-hr was used for electric to thermal energy conversion for service efficiency calculations.

The heat exchangers and burners were paired in the following combinations:

- Conventional center-flue - conventional burner
- Forced-convection heat pipe - powered combustion
- Natural convection boiling or non-boiling - 100% primary air natural-draft burner

The three ignition systems that were evaluated included: a conventional 700 Btu/hr standing pilot with zero net energy recovery; a 300 Btu/hr "stratified" pilot with an energy recovery efficiency of 81.3%; and an Intermittent Ignition Device (IID), which was assumed to consume a negligible amount of electricity.

The conventional pilot was coupled with the conventional tank. The Intermittent Ignition Device (IID) was only considered for use with the "non-center flue" plastic-lined tank. Thus, flue closure to eliminate heat losses from the stored hot water to the flue during burner-off conditions was not required in combination with the IID. The stratified pilot was used in combination only with the natural draft 100% primary air burner. The only ignition system considered for use with forced combustion was IID.

2.2.2 Cost Evaluation Method

Component and sub-assembly costs were estimated by a combination of catalog costs, manufacturer's estimates, estimates from other references, and engineering estimates. The component cost estimates are shown in Table 3, together with a code "key" for the component options.

The costs for the forced-combustion system[2], and the intermittent ignition system (including installation cost[2]) and stack damper[3] are from the literature. The costs of the plastic-lined tank and heat exchanger was estimated by Amtrol, based on an initial manufacturing volume of 10,000-20,000 units per year. These are anticipated costs at market entry. Also shown are tank and heat exchanger costs based on a high volume production. The remaining costs were obtained by AMT based on catalog costs and engineering estimates. Due to the different sources used for cost estimating, small differences in payback (less than 0.25 years) should not be considered significant.

The economic analysis included a gas cost of $3.00 per million Btu. This value was determined in the following manner. Fig. 1 shows projected regional residential rates for natural gas for 1977*. It is believed that the highest market penetration will be in areas of high gas cost and the latest gas costs in the middle Atlantic/New England area are greater than $3.00 per million Btu, as can be seen in Fig. 1. Thus, the $3.00 per million Btu gas cost was felt to be a conservative value to use in the evaluation.

*These rates are not actual rates, but were projected from actual 1976 residential rates[4], corrected for inflation. The correction used for inflation was an increase of 18%, which is the actual increase in the national average price of residential gas from the last quarter of 1976 to the last quarter of 1977[5].

TABLE 3 - COMPONENT COSTS

Component	Code: Burner	Code: Pilot	Code: Exchanger	Code: Tank	Code: Stack	Costs Based On 10,000-20,000 Units/Year: Installed Cost $	Costs Based On 10,000-20,000 Units/Year: Added Cost $ (1)	Estimated Costs For High Volume Production (4): Installed Cost $	Estimated Costs For High Volume Production (4): Added Cost $ (1)
A. Stack									
1. Conventional					1			6	0
2. Damper									
i. Mechanical					2M			47	41
ii. Thermal					2T			35	29
3. Undiluted Exhaust					3			6	0
4. Sealed Comb. (2)					4			63	57
B. Tank									
1. Conventional				1				105	0
2. Plastic-Lined				2		218	113	135	30
3. Conv. (added Insul.)				3					5
C. Heat Exchanger									
1. Conventional			1					7	0
2. Forced Convection			2			129	122	48	41
3. Boiling/Condensing			3			260	253	84	77
4. Bottom-Fired			4			200	193	62	55
D. Burner/Control/Pilot									
1. Conventional	1	1						37	0
2. Forced Comb. (3)									
i. Conv. Pilot	2	1						102	65
ii. Stratified Pilot	2	4						102	65
iii. IID	2	2						140	103
3. 100% Primary Natural Draft Burner									
i. IID(3)	3	2						108	71
ii. Stratified Pilot	3	4						42	5

(1) Compared to Conventional Components
(2) Includes $25 Installation Allowance
(3) Includes $40 Electrical Hook-Up Allowance
(4) Included 0.25 Hours/Unit of Labor

1977 Residential Gas Costs - $/million Btu
Obtained by Taking 1976 Gas Prices from
Reference 4 and Increasing by 18%.

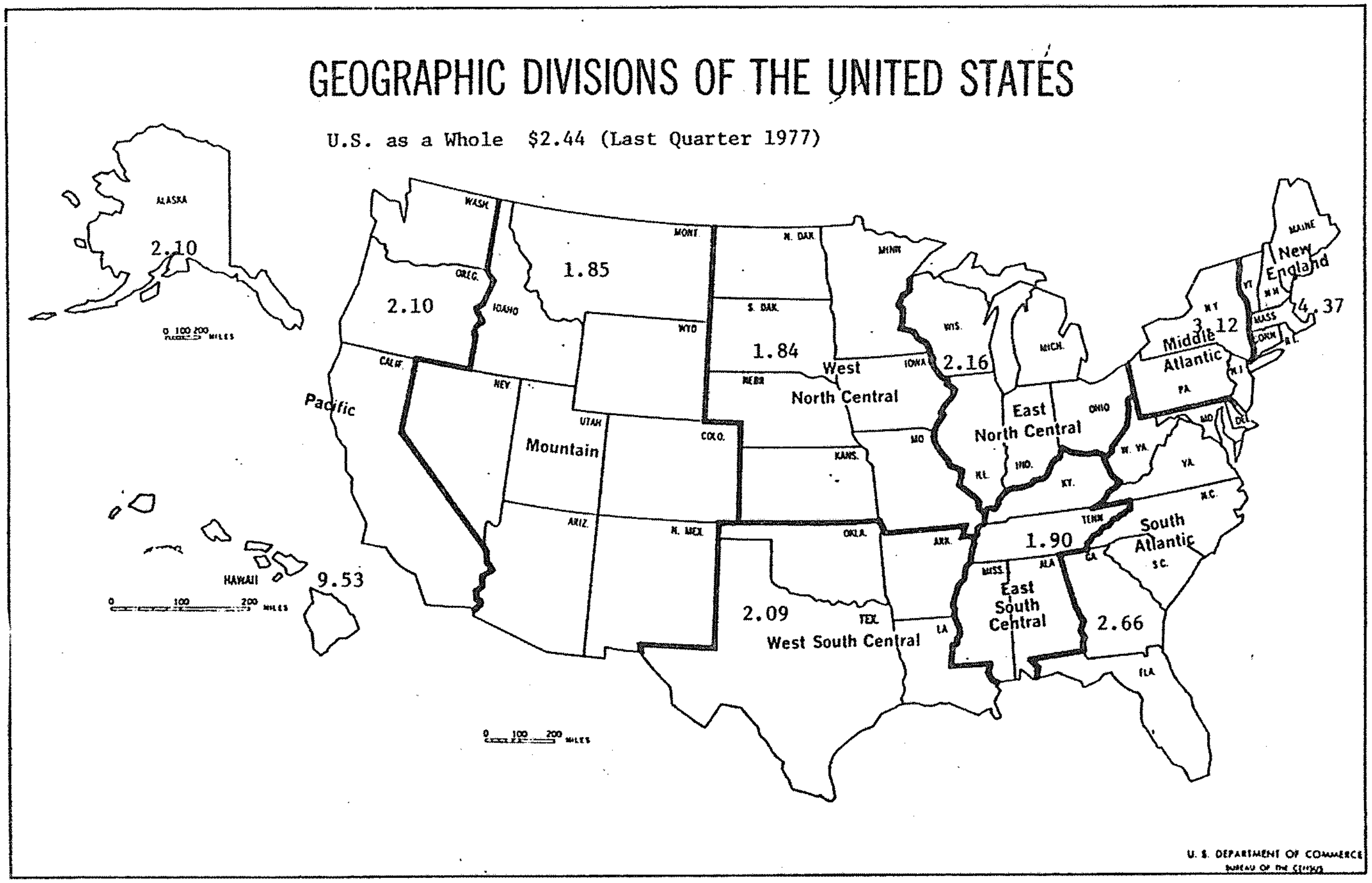


Figure 1 - Residential Gas Costs

ADVANCED MECHANICAL TECHNOLOGY, INC.

The cost/benefit comparisons were made as follows. First, the energy-related performance of various combinations of options were analyzed. The details of the analysis are given in Appendix A. Annual operating savings due to reduced energy consumption relative to conventional water heaters were assumed to occur over an 11-year period, which is regarded as being the average life of a conventional water heater(2). Life-cycle savings were calculated by deducting the additional initial cost relative to a conventional water heater from the 11-year operating savings. The results of the evaluations are shown in Figs. 2-6. At zero years, the savings are negative and equal the increase in cost of the option over a conventional unit. The payback period required to recoup the initial cost (simple payback) is indicated by the time it takes to reach zero savings.

2.3 Component Economic/Performance Evaluations and Selections

2.3.1 Component Economic/Performance Evaluations

The cost-effectiveness of various venting means is shown in Fig. 2. The calculated energy savings relative to a conventional water heater stack is indicated by the figures in parenthesis. It is seen that the energy savings amount to 9.9%, 7.9%, and 4.7% for sealed combustion, a mechanical stack damper, and a thermal stack damper, respectively. While the life-cycle savings range from $38 to $73, all three options have fairly close payback periods ranging from 4.3 to 4.9 years.

Fig. 3 compares the high efficiency pilot (14.6% energy savings) and an intermittent ignition device providing 15.7% savings relative to a conventional water heater with standing pilot. Both ignition devices had acceptable paybacks of 0.3 years for the stratified pilot, and a little over 4 years for the IID. It should be mentioned that when the IID is added to a powered-combustion system, the added cost is only $38 due to cost commonality, so the investment of adding IID to a powered-combustion system becomes one with a payback of 2.2 years.

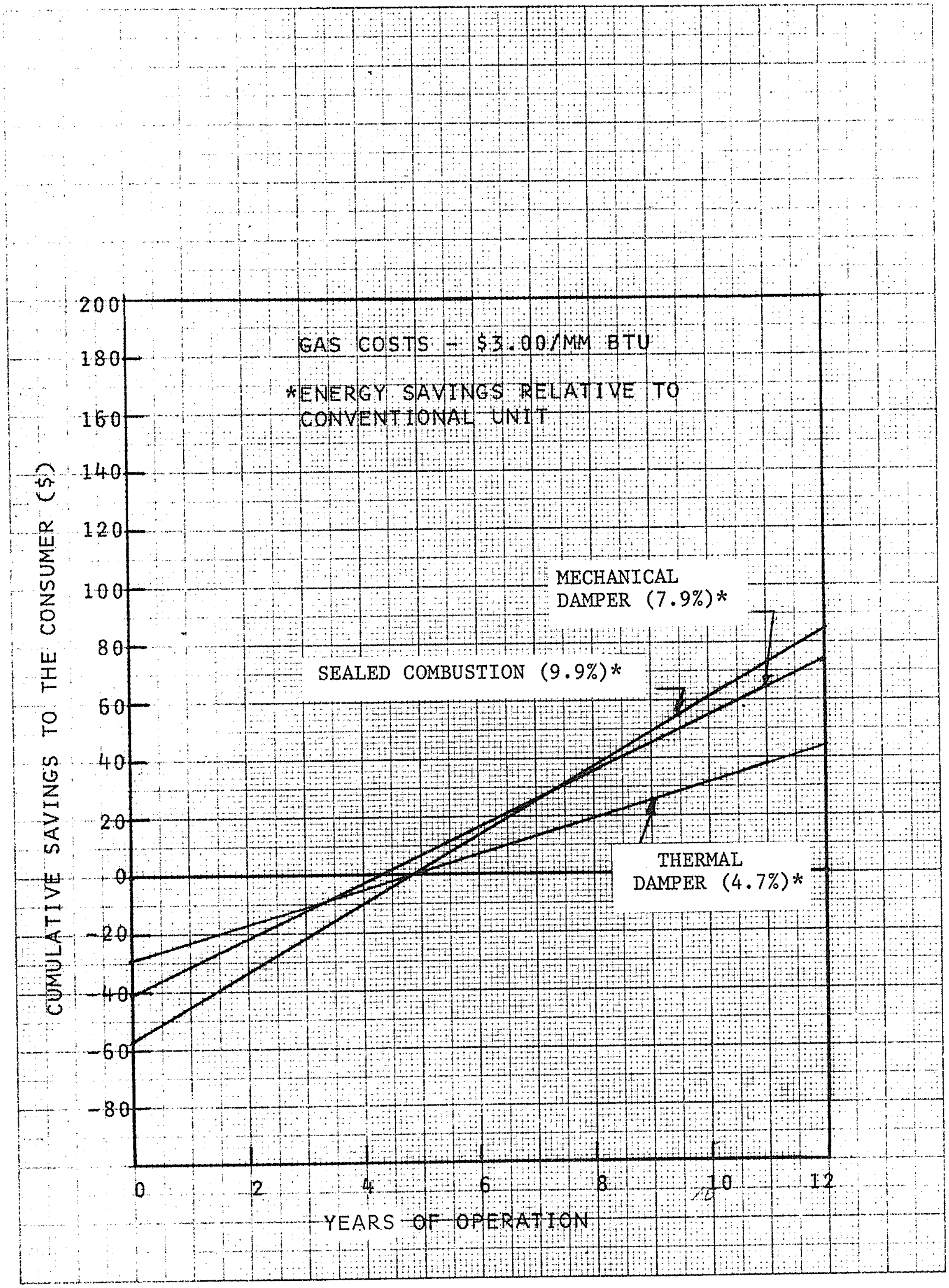


FIG. 2 COMPARISON OF STACK CONFIGURATIONS

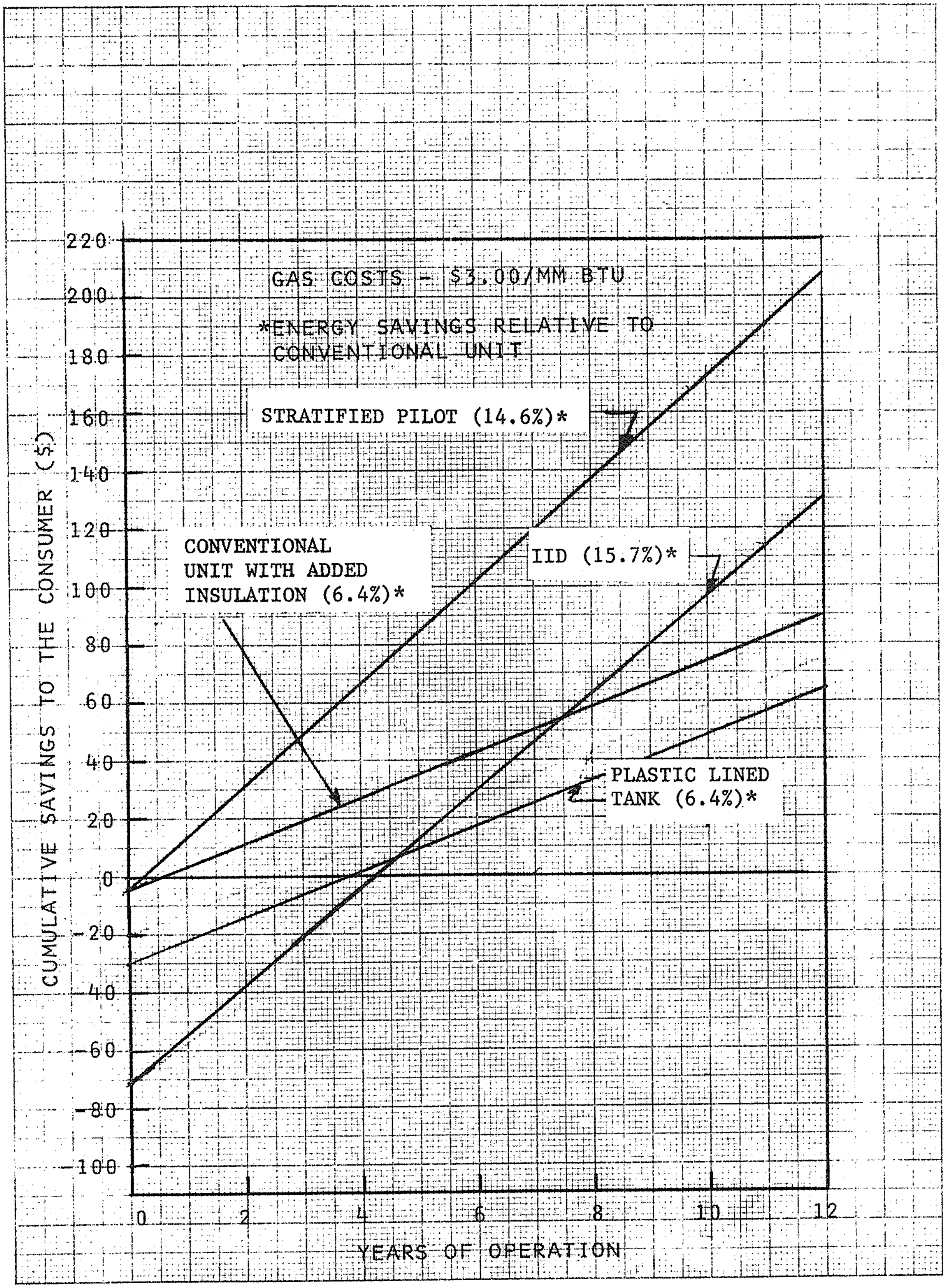


FIG. 3 COMPARISON OF IGNITION SYSTEMS AND TANKS

Also compared in Fig. 3 are a plastic-lined tank and a conventional tank with 1.8 inches of insulation. Both have good paybacks. The conventional tank with added insulation has a payback of about 0.5 years and the plastic-lined tank has a payback of a little over 3.5 years.

Heat exchanger and burner combinations are compared in Fig. 4. All of these options provide similar energy savings over a conventional unit ranging from 8.6% to 9%. Compared to all of the other energy-saving options, burner/heat exchangers provide the poorest payback. The paybacks range from 6 years with the 100% primary air, natural-draft burner with a bottom-fired heat exchanger to 9.5 years for the forced-combustion burner with a heat-pipe water heater.

It should be noted that all of the preceeding options were evaluated using similar stack assumptions. With the exception of sealed combustion venting systems, both natural-draft and forced combustion options included the use of a draft diverter for evaluation of exfiltration losses. The use of an undiluted exhaust with the forced combustion system would have been better for performance considerations due to lower exfiltration losses, as can be seen in Table 2, but was not considered because the ANSI code for water heaters specifies the use of a draft diverter (except for sealed combustion).

2.3.2 Option Selections

The individual options selected for further comparison in a water heater configuration and the reasons for their selection are discussed in this section.

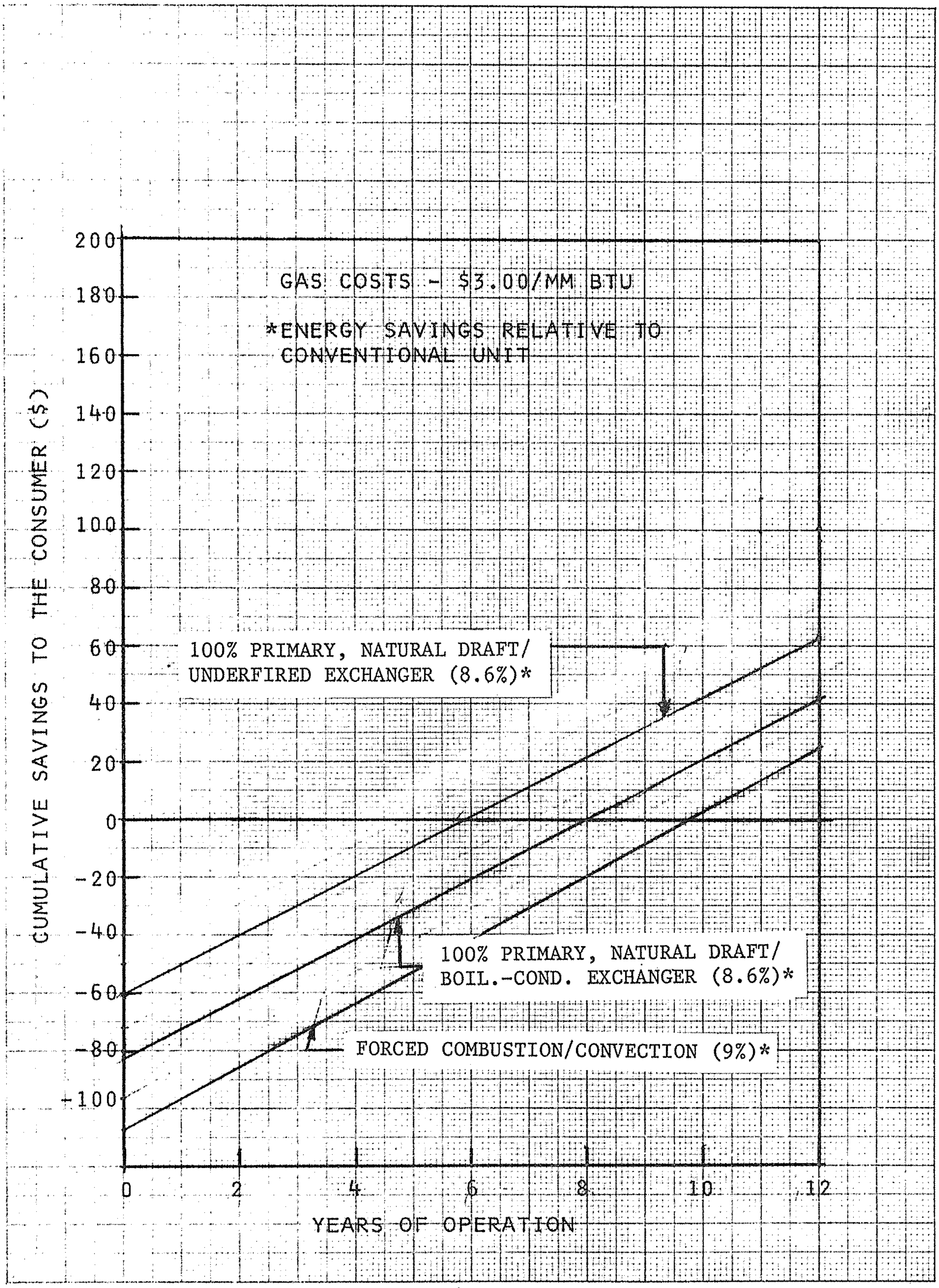


FIG. 4 COMPARISON OF BURNER/HEAT EXCHANGER COMBINATION

Sealed combustion is the primary choice because it has both economic and marketing advantages. Its main economic advantage is its higher life-cycle savings. Another reason for its selection, however, is its greater marketability due to its inherent safety advantage, greater reliability as compared to stack dampers (no moving parts), and its higher energy savings. It was felt that the numerous "selling features" of sealed combustion would enhance the marketability of any water heater.

It is recognized, however, that different installations may well require different stack configurations. In new construction and manufactured homes, sealed combustion can be readily used. In replacement installations which already vent into a chimney, a stack damper or a conventional vent might be more suitable than sealed combustion. In outdoor or in unconditioned space installations, a conventional vent (with or without a draft diverter) would be most applicable.

For a non-powered water heater, the high efficiency stratified pilot is the obvious choice. As an investment, the stratified pilot does not deteriorate greatly as a function of efficiency when compared to a 700 Btu/hr standing pilot with no recovery. This is because even at zero recovery, the stratified pilot is simply a 300 Btu/hr conventional pilot which still has a payback of less than one year. With powered-combustion systems, a case can be made for an IID, since the substantial electrical hook-up cost is already paid for. Of course, the IID is a proven, commercially available component, while the stratified pilot is still in the concept stage. Considering the strong potential for the stratified pilot for use with atmospheric burners, this option was selected for consideration with all natural-draft burners, while the IID was selected for combination with powered-combustion systems.

The plastic-lined tank was selected as the most promising tank option. Both tank options are good investments, with the conventional tank with added insulation being the better of the two, if only investment criteria were used. However, the following considerations favor the plastic-lined tank:

1. The plastic-lined tank takes greatest advantage of Amtrol's present manufacturing capabilities.

2. The plastic-lined tank is more durable (15 years expected life), so that savings for the plastic-lined tank will continue for four years longer than the conventional tank. Furthermore, life-cycle savings of any associated options will likewise be amplified.

3. The cathodic effect of any of the copper heat exchanger options would accelerate corrosion of a glass-lined tank, thereby making a plastic-lined tank highly desirable.

The best choice of burner/heat exchanger was the 100% primary air burner, combined with the bottom-fired heat exchanger. It had the best payback of any burner/heat exchanger combination. The forced combustion burner/forced convection heat exchanger was also selected for comparison, even though it had a poorer payback, to allow a comparison to be made between natural-draft and forced-draft systems.

2.4 Water Heater Configurations - Economic/Performance Evaluations

Table 4 shows the combinations of options that were compared. A standard conventional water heater is used as the reference or baseline case. The cost bases for all but the conventional units are for purchased components and materials plus one hour of labor for fabrication and assembly.

TABLE 4 - WATER HEATER COMBINATIONS

Water Heater Code (5)	Gas-Fired Water Heater Type	Estimated Costs For High Volume Production Units		Service Efficiency
		Installed Cost $	Added Cost $ (7)	E_S (%) (1)
11111	Conventional Glass-Lined Center Flue (Baseline)	205 (2)	0	46.5
A.	Conventional "High Efficiency" Model (Increased Energy Recovery, Reduced Pilot, Added Insulation)			
90-75 (8)	1. Conventional Stack	285 (9)	80	55.5
90-75 (8)	2. Sealed Combustion	342 (9)	137	62.1
B.	Natural Draft (6) (Stratified Pilot, Plastic-Lined Tank, Bottom-Fired)			
34421	1. Conventional Stack	317 (2)	112	63.7
34424	2. Sealed Combustion	374 (2)(3)	169	72.5
C.	Forced Combustion (6) (IID, Forced Convection Burner, Plastic-Lined Tank)			
22221	1. Conventional Stack	400 (2)(4)	196	64.1
22224	2. Sealed Combustion	458 (2)(3)(4)	253	73.1

(1) Includes Exfiltration Loss
(2) Includes $50 Plumbing Installation and $5 for Pressure/Temperature Valve
(3) Includes $25 Installation Allowance for Sealed Combustion
(4) Includes $40 Electrical Hook-Up Allowance
(5) See Table 3 for Explanation of Code
(6) Costs Based on Parts Plus One Hour of Labor
(7) Compared to Conventional ($205)
(8) Code Refers to ASHRAE Standard 90-75
(9) Cost Arrived at by Averaging List Price of Three Units Currently Being Sold and Adding Installations Costs(2).

The assumption of one hour of labor was employed to put the comparison on a high production volume basis comparable to that for conventional water heaters. The installed cost for both the standard and "high efficiency" conventional water heaters, is an actual cost, reported from several sources.

Three basic systems: (1) a "high efficiency" conventional water heater incorporating increased flue baffling and/or reducing firing rate (75% energy recovery efficiency), reduced pilot consumption (300 Btu/hr) and 1 inch of added insulation*; (2) the proposed 100% primary air, natural-draft burner with a stratified pilot; and (3) a forced combustion/heat-pipe system using IID, are compared to the baseline both with and without sealed combustion. The life-cycle savings and paybacks for these combinations are shown in Figs. 5 and 6. The "high efficiency" conventional unit has the lowest energy savings of the three. The energy savings for this unit is 20% if sealed combustion is not used and 34% if the unit is supplied with sealed combustion. The payback for these conditions is 4 and 4.2 years, respectively, which is acceptable.

Both the powered combustion and natural-draft units meet or exceeded the project goal of a 70% service efficiency, including the effect of exfiltration. The powered combustion system is slightly more efficient than the natural-draft system, but has an $83 higher cost resulting in lower life-cycle savings. Without sealed combustion, a savings of 38% relative to a conventional unit is possible, while with sealed combustion the savings increased to 57%. The natural-draft system has a payback from 3-3.7 years, depending upon whether or not sealed combustion is used, while powered combustion has a payback of approximately 5.5 years.

---

*This unit is representative of newer units capable of meeting ASHRAE Standard 90-75. It would not meet the project goal of 70% service efficiency; however, it has been included here for comparison since it is representative of most new units sold today.

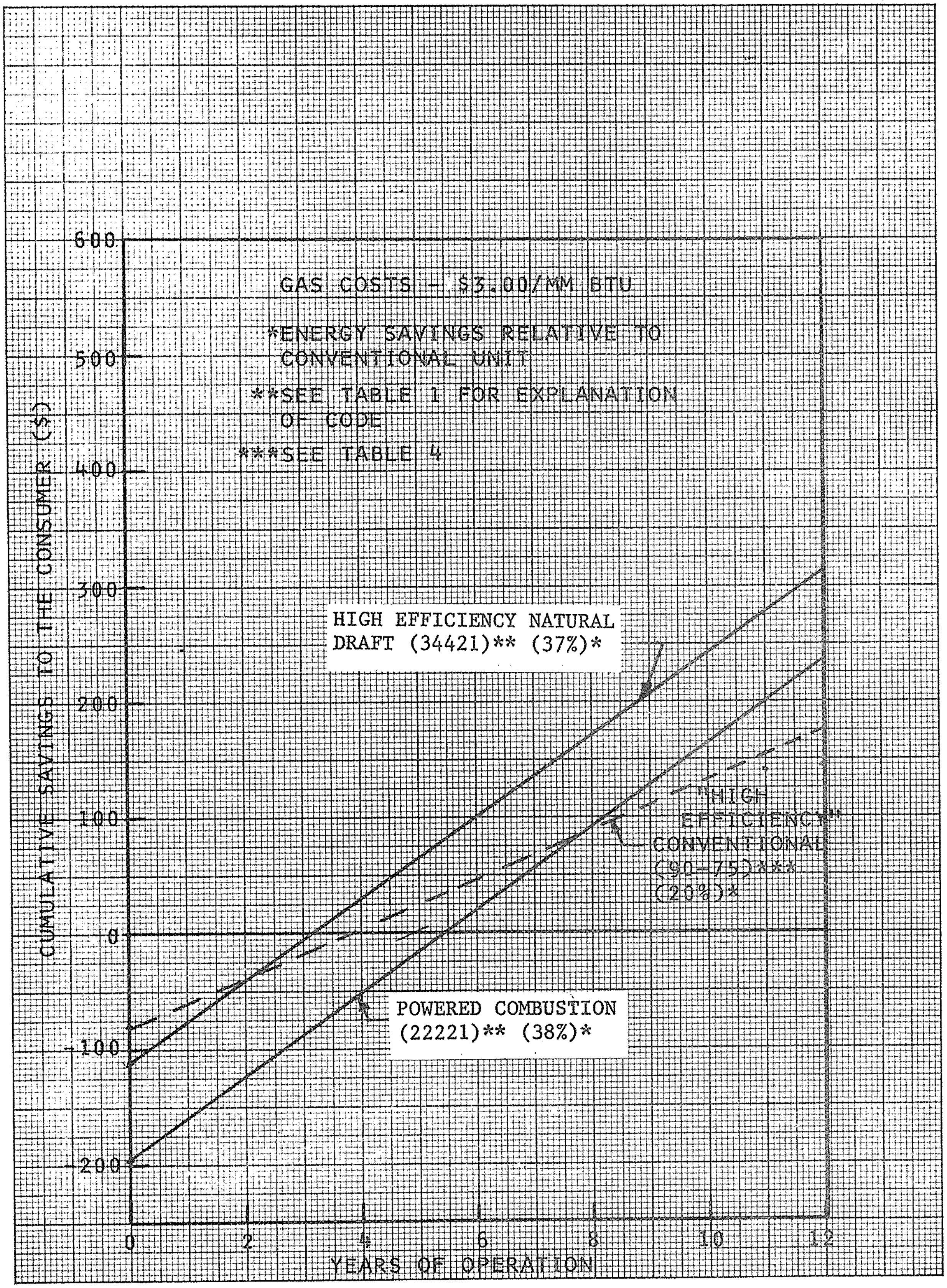


FIG. 5 COMPARISON OF HIGH EFFICIENCY CONVENTIONAL, NATURAL DRAFT, AND POWERED COMBUSTION WATER HEATERS WITHOUT SEALED COMBUSTION.

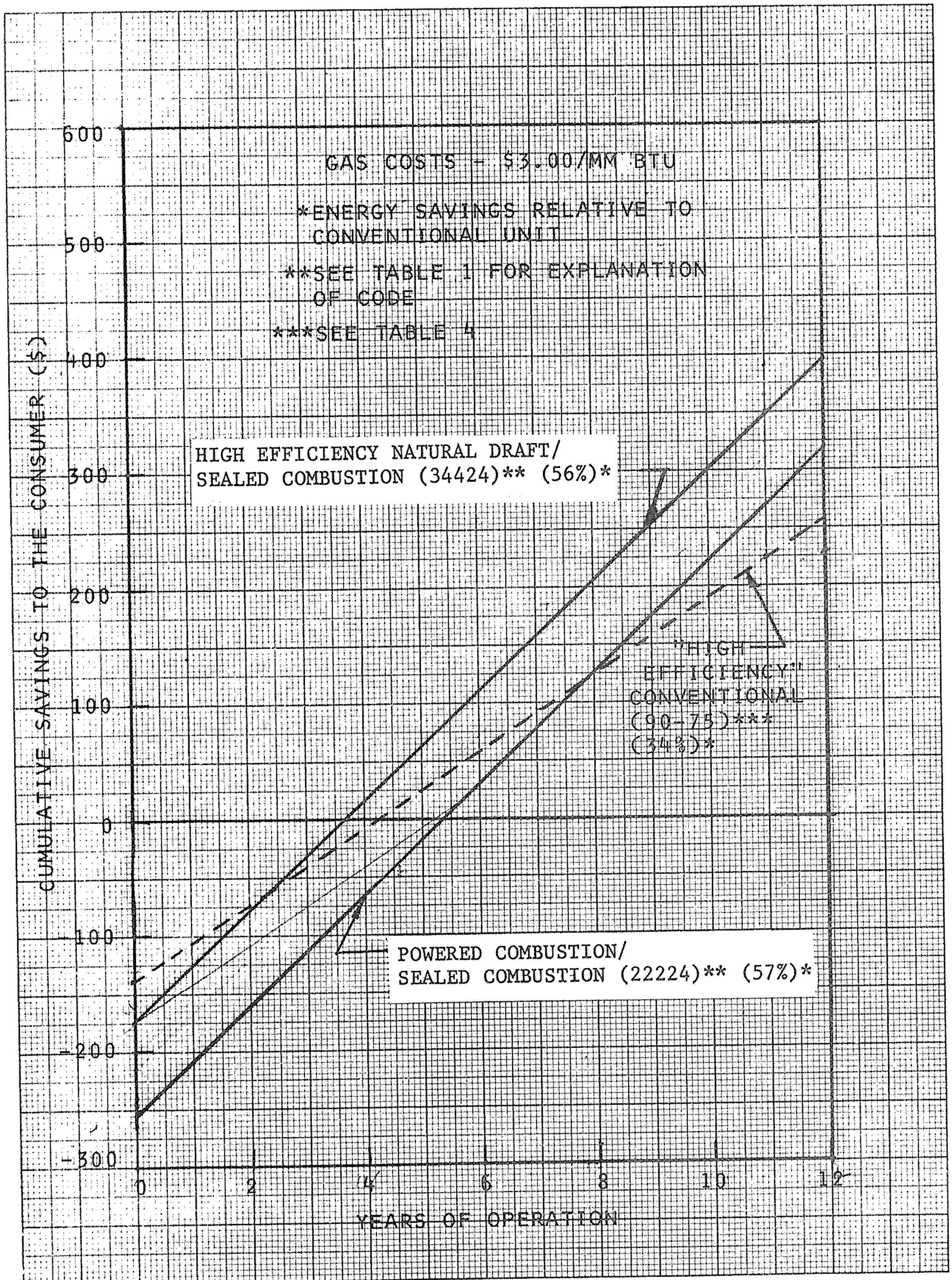


FIG. 6 COMPARISON OF HIGH EFFICIENCY CONVENTIONAL, NATURAL DRAFT, AND POWERED COMBUSTION WATER HEATERS WITH SEALED COMBUSTION.

The powered combustion system shows a poorer payback relative to the natural-draft system in spite of a higher efficiency and lower forced convection heat exchanger costs. The reason for this is the high costs for electrical components, controls, and installation.

Thus, the natural-draft combustion system provides an economic advantage. Additionally, the added feature of independence from electric power retains the favorable characteristic of current gas-fired water heaters of providing hot water during power outages.

2.5 Recommended Water Heater Configuration

Based upon the preceeding evaluations, a natural-draft system appears justified for Phase I development of a high efficiency gas-fired water heater. Its salient features consist of: a high efficiency 100% primary air, naturally-aspirated burner; an external, bottom-fired natural circulation heat exchanger located under the tank; a high efficiency standing pilot; a plastic-lined, foam-insulated storage tank; and an external sealed-combustion flue. This system has a projected service efficiency of 72.5%, and it has a payback period of slightly over 3.5 years.

Since the service efficiency goal is 70%, the sensitivity of the service efficiency to the three main performance parameters - pilot recovery efficiency, tank and fitting thermal losses, and the burner/heat exchanger stack efficiency was calculated. Table 5 shows the target values for each of these parameters used to obtain the projected efficiency of 72.5% and Table 6 shows the minimum acceptable values which would maintain the serfice efficiency at 70%. In this analysis, two of the three parameters were kept at the target values and the third decreased until the service efficiency was 70%.

TABLE 5 - RECOMMENDED UNIT FOR DEVELOPMENT TASK

Component	Recommended Configuration	Performance Targets
1. Stack	Sealed Combustion	No Exfiltration
2. Tank	Insulated, Plastic Lined, Steel Tank	Volume - 40 Gallons Tank and Fitting Losses - 300 Btu/Hr
3. Heat Exchanger	Natural Circulation, Non-boiling, Bottom-fired Heat Exchanger	Stack Efficiency 84%
4. Pilot	Continuous Stratified Pilot	Firing Rate - 300 Btu/Hr, Recovery Efficiency - 81.3%
5. Burner	Natural Draft 100% Primary Air Burner	Firing Rate* - 45,000 - 50,000 Btu/Hr

- Unit Installed Cost - $374
- Service Efficiency (Including Exfiltration) - 72.5%
    - 75 Gallon Daily Draw
    - 150°F Water Out; 60°F Water In
    - 70°F Ambient Temperature

* For an explanation of target firing rate, see Appendix D

TABLE 6 - PERFORMANCE OPTIONS - SENSITIVITY ANALYSIS

Minimum Acceptable Performance	Target	Tank and Fittings	Burner/Heat Exchanger	Pilot
Tank and Fitting Losses (Btu/Hr)	300	390	300	300
Burner/Heat Exchanger Stack Efficiency (%)	84	84	80.8	84
Pilot Recovery Efficiency (%)	81.3	81.3	81.3	47.1
Service Efficiency	72.5%	70%	70%	70%

In order to attain the target performance, three main areas require significant development: the combustion system, the stratified pilot, and the heat exchanger. "Proof-of-concept" tests have been conducted on all three of these components, see Appendix C. However, further careful design work will be required to assure the specified performance.

Following is a list of the anticipated development areas:

- Limiting heat exchanger temperature to avoid liming.
- Providing a method to light pilot in sealed combustion configuration.
- Avoiding "blowout" problems at low pilot input.
- Developing compact, inexpensive 100% primary air burner.
- Designing the sealed combustion system for several installations and proper draft control.

3. MARKET EVALUATION

As part of the overall feasibility assessment, Amtrol, Inc., has examined the current water heater market, both with regard to existing "conventional" gas-fired water heaters and with regard to the market potential of a significantly more efficient water heater embodying several new design concepts. From this market evaluation, a preliminary market strategy tailored to promote the unique features of the high efficiency water heater has been formulated.

3.1 Current Water Heater Market

3.1.1 Industry Characterization

The gas water heater industry is basically a conservative one which has had little change or innovation over past decades. There has been considerable consolidation in the industry over the past 10 years, with the number of water heater manufacturers decreasing from 60 to 80 to about 9 or 10. Table 7 shows the ranking of the major water heater manufacturers from 1973 to 1976[9]. The top five manufacturers now account for approximately 85% of the total water heating shipments. They deal on a high volume production basis with minimal product differentiation and a highly competitive pricing structure. Net profit after taxes is about 4%, compared to the norm of 7% to 10%.

The high volume/low-profit nature of the industry may be explained at least in part by the character of the product. A water heater is different from most other home appliances in that most sales are not made directly to the consumer. Usually, the installer will purchase the water heater for the consumer from a distributor. The distributor's main concern in selecting his product line is competitive cost and satisfying his customer, the installer. Consumer-related features such as appearance or operating costs are not major factors since the consumer is not involved in the "buying chain".

TABLE 7 - RANKING OF WATER HEATER MANUFACTURERS

Manufacturer	Ranking (Numerical)			
	1973	1974	1975	1976
Bradford-White	4	8	4	4
Briggs		6		
Jackson		7	6	
Mor Flo	5	4	5	5
Philips		5		
Republic*	6			
Rheem/Rudd	2	2	1	1
Smith, A.O.	3	3	3	2
State Stove	1	1	2	3

*No longer in the water heating business.

3.1.2 Current Product Characteristics

The mainstay of the water heater industry is the glass-lined water heater with a baffled center flue. Burner input typically ranges from 30,000 to 50,000 Btu/hr, with recovery efficiencies of about 70%, and service efficiencies of about 50%, not including exfiltration losses. Generally, the smaller the tank size, the smaller the input. Thus, it is common that a 30-gallon tank will have a 30,000 Btu/hr input, whereas a 40-gallon tank will have a 40,000 Btu/hr burner. However, a "premium" water heater will have a larger burner relative to the size of the tank. The lower burner inputs generally correspond to either "economy" models, or "conservationist" units, which are discussed further below.

A typical water heater sells to the distributor for about $80; the distributor then marks it up 25% (negotiable) to the installer or plumber; who will charge the consumer approximately $200, including installation.

In response to the demand for more energy efficient appliances and the more stringent requirements of codes such as ASHRAE 90-75, most manufacturers have introduced a line of more efficient units. The basic approach has been to improve the efficiency of conventional designs as opposed to any radical changes in the design concept. Recovery efficiency is improved by reducing burner input and increasing flue baffling. Standby losses have been reduced by lowering the pilot burner input and by increasing the amount of jacket insulation. Such measures may increase recovery efficiency to approximately 75%. The distributor will pay a premium of approximately $50 for the high efficiency water heater, and will charge about $90 more. The high efficiency water heater is marketed as a "top of the line" unit and may be warranteed for a 10-year tank life as an added feature. Often, the 10-year tank warranty will include additional anode protection, but in some cases there appears to be no additional physical protection.

The service efficiency of conventional (center flue) water heaters is basically limited by the integration of the heat exchanger and exhaust function of the center flue. This integration requires that, without some means of flue closure, heat from the stored water will be lost to the flue during the off-cycle. Based on current manufacturing strategy which retains the glass-lined tank/center-flue concept, additional improvements in the service efficiency of gas-fired water heaters are expected to be limited. There appears to be no movement in the industry towards a radically different type of water heater.

3.1.3 Water Heater Market Characteristics

Water Heater Sales

Water heater sales are made up primarily of electric and gas-fired units. The sales for both are about equal at roughly 3 million units per year. Fig. 7 shows the actual shipments of both electric and gas-fired water heaters from 1965 to 1977, and projected shipments through 1982. Sales of gas-fired units are expected to remain steady at a little over 3 million units per year, while electric units are projected to overtake gas unit sales sometime between 1978 and 1979.

The classification of gas water heater shipments with respect to size is shown in Fig. 8. Units under 30-gallons make up about 3% of sales, while units over 47.5-gallons account for about 14% of sales. The remainder of the market falls in the range from 30 to 47.4 gallon sizes. Although Fig. 8 does not specifically indicate shipments of 40-gallon water heaters, most of the units designated as 30-47.4 gallon range are in the "40-gallon" size, i.e., 38 to 42 gallon capacity.

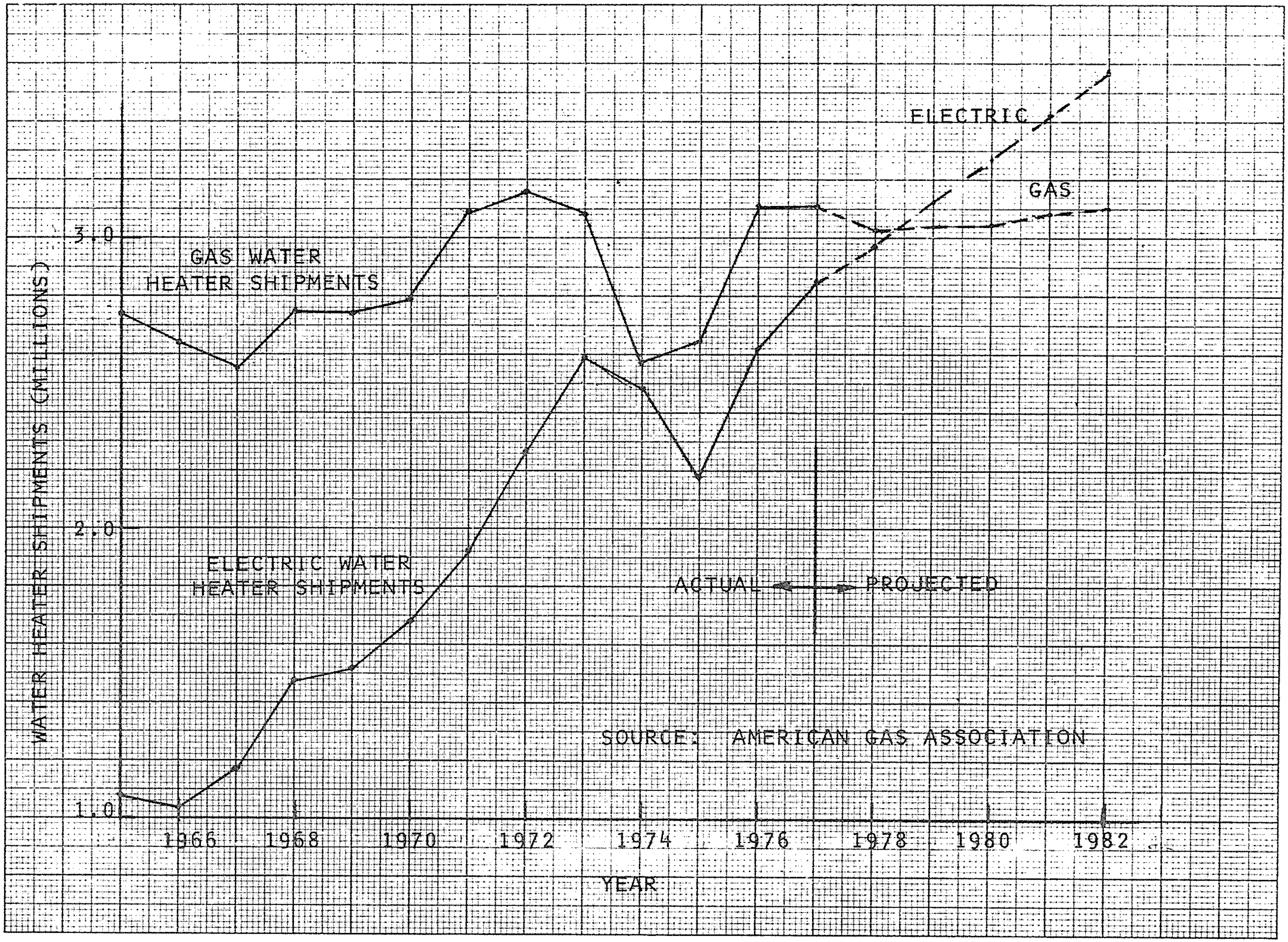


FIG. 7 ACTUAL AND PROJECTED WATER HEATER SHIPMENTS

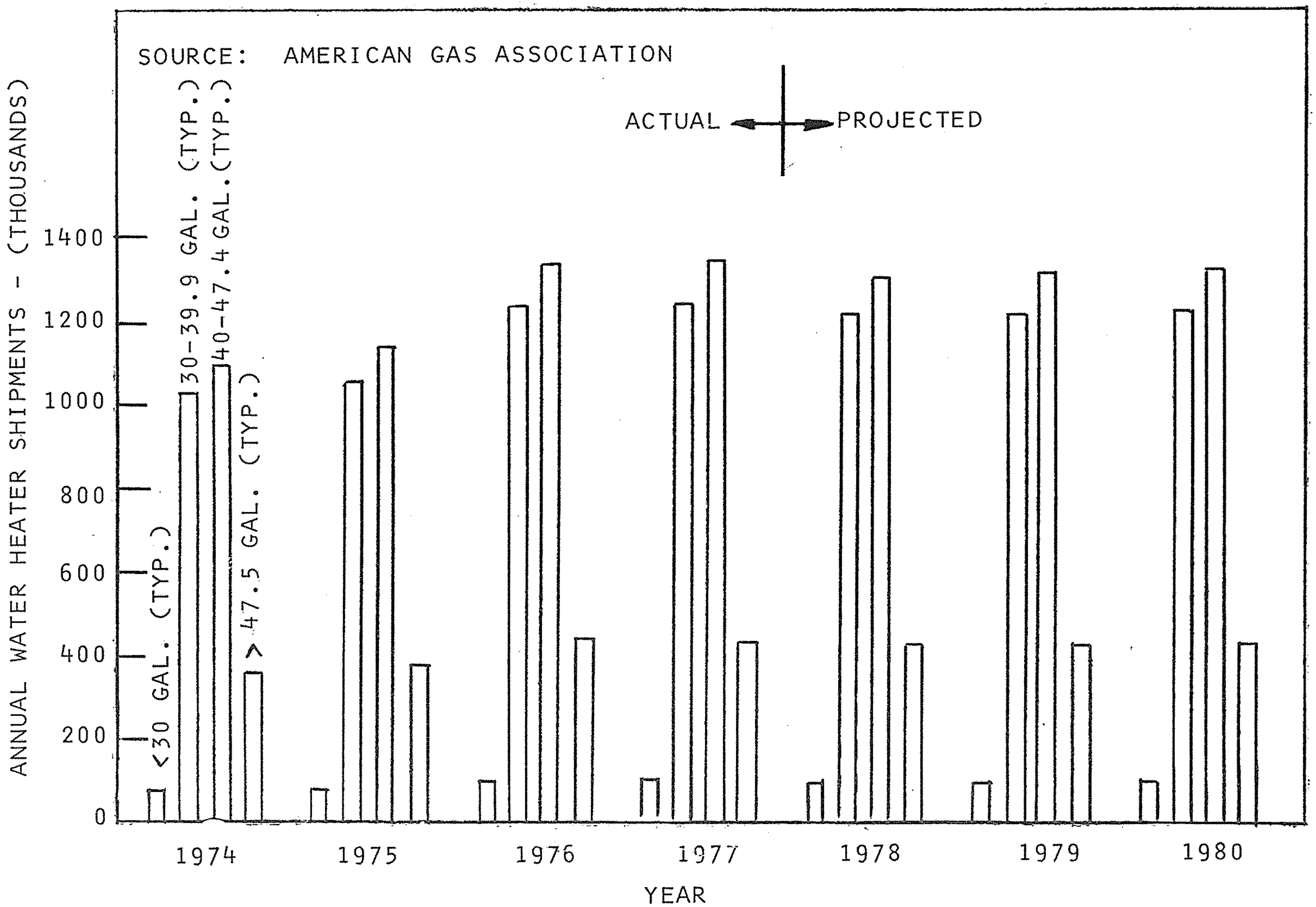


FIG. 8 GAS WATER HEATER SHIPMENTS - BREAKDOWN BY SIZE

ADVANCED MECHANICAL TECHNOLOGY, INC.

Commercial direct-fired storage-type gas water heaters account for about 3% of unit sales, versus 97% for residential units. Commercial units usually are classifed as those having a burner input of 75,000 Btu/hr or more. Commercial storage-type water heaters generally have larger tank volumes than residential units, and will usually be designed for higher water temperatures (typically 180°F) than residential units (typically 160°F). The more stringent requirements of commercial units result in a more conservative design than residential heaters.

Water heaters may be installed either indoors or outdoors. While data is not available on the nation-wide split between indoor and outdoor installations, it is known that in California approximately 60% of the installations are indoors and 40% are outdoors. Of the outside installations, approximately 75% will be in the garage, while the remainder would be installed in some type of weather-proof enclosure. No special provisions are made for outdoor units such as weather-proofing or freeze protection. Statistics on sales of "weather-proof" water heaters could not be found, so these must account for a negligible fraction of sales.

Current Market Description

The majority of gas-fired water heaters are used in single family homes, and to an increasing extent, in some individual dwelling units in multi-family housing (due to the trend away from central hot water service in multi-family units in some states). The water heater is not considered an appliance by the homeowner or tenant in the context that it is not in direct use by the consumer.

The gas water heater market falls into two basic categories: those which are sold to replace a failed existing unit; and those sold for new installations. Approximately 4% of the existing gas water heater population is replaced annually. This accounts for approximately 60% of all gas water heater sales, or about 1.86 million units per year. New installations account for approximately 1.24 million units, or 40% of the market.

Replacement Market

In the replacement market the consumer is reacting to the crisis of complete cessation of hot water service or leaking water, and turns to the local plumber or retail outlet (Sears, hardware store, gas company, etc.), for an immediate replacement. In essence, the objective is to restore the source of hot water as quickly as possible and at the lowest cost, and the consumer will accept almost any reasonable replacement that is offered to him. As a result, it is the trade, i.e., the plumbing contractor or retail outlet, that determines the brand choice. Water heaters are rarely replaced because of poor performance or concern over excessive energy costs. Thus, there presently exists no refit or retrofit market as such.

Approximately 65 to 70% of all replacement water heaters are distributed through the plumbing trade. The consumer outlet in this case is the local plumbing contractor. His source is the plumbing or heating distributor who ultimately controls the brand or choice of water heater by the line he carries. Since most contractors deal with one or possibly two wholesalers for all their needs, and are heavily involved with credit, the contractor will usually sell the water heater brand that his wholesaler carries.

The major retail chains (Sears, Montgomery Wards, etc.), account for a significant share of replacement sales and will also install and service water heaters, as well as extend credit. Water heaters sold through these channels are privately labelled, and manufactured by a select few major heater manufacturers. Again, selection is made on lowest price and on the ability to furnish demand. To a lesser extent, some replacement water heaters are sold through hardware stores, chain and independent lumber yards, home centers, and those gas utilities who also sell appliances.

New Installation Market

In new home sales, there is no discrimination of brand or type exhibited by the prospective buyer, since the water heater is furnished by the builder, and the homeowner exercises no choice in its selection. The builders or their subcontractors usually purchase water heaters from the plumbing and heating distributor from whom they obtain their other plumbing and heating supplies. Consequently, there has been little or no purchase influence exhibited by the end user for a particular brand or type of water heater in new installations.

Consumer Preference

Although consumers tend to be out of the marketing chain, they do have preferences which may differ from those who control the selection of the water heater. Prelminary surveys indicate that the average consumer is concerned with: inadequate hot water capacity; short life (they expect glass-lined units to last only 5 to 8 years); and to some extent warrantee protection. There is little indication that homeowners react to energy savings, pollution, or quality features when it comes to water heaters, since they tend to be unaware of water heating costs or product features which determine performance characteristics.

In summary, the homeowner exerts very little influence over the type or brand of water heater that he purchases. Moreover, at present the consumer is mostly concerned with quantity of hot water and the useful life of his water heater. Since he is generally unaware of water heating costs or the features which affect operating cost, these aspects would play a minor role in his selection even if the consumer were to influence the brand selection.

3.2 Amtrol Market Strategy

Since the marketing of a premium-priced, high-efficiency water heater is expected to meet significant sales barriers as the market is presently constituted, a somewhat different strategy is needed to gain market penetration.

3.2.1 Initial Market Strategy

With regard to intial market penetration, Amtrol intends to center its efforts in the upper end of the market towards the 10 to 15% of purchasers who exhibit a quality preference in their buying habits. This potential is estimated at about 300,000 units/year. Gaining entry will entail a strategy aimed at the replacement market and at the new installation market with the objective of making consumer preferences more important to the buying process.

The market strategy will consist of the following elements:

1. Education and Motivation of the Plumbing Trade

   A. Educational Seminars focusing on new energy technology, lower emissions, ease of installation, greater customer satisfaction, lower life-cycle costs to the consumer, and greater earnings potential.

   B. Wholesaler presentations emphasizing the profit motivation in carrying a second quality line. The objective here would be to assure a supply on hand for emergency replacement sales.

2. Publicity to and Local Gas Utility Indoctrination of the Consumer

Direct promotion and advertising to the consumer would be extremely costly to Amtrol, providing a poor return on the investment. Amtrol will focus its publicity towards local gas utilities, and will support local gas company efforts to indoctrinate consumers in the energy savings, low emissions, durability, and performance features of the water heater. The objective would be to create an overall atmosphere of awareness at all levels to promote trade sales.

3. Presentations and Promotions to Selected Builders

Joint promotions by Amtrol and gas utilities to both custom home builders as well as multi-family builders would be aimed at achieving a share of the new construction market.

The first element of the market strategy, education and motivation of the plumbing trade, is intended to overcome the general lack of product differentiation among water heaters by the trade. By educating both the distributor and the installer as to advantages of the new product to the consumer and to their own profitability, sales of the new water heater can be stimulated by the merchandizing efforts of the trade. Promotion of the new product at this level will stimulate demand through the plumber's efforts to convince the homeowner to replace his failed unit with a higher quality, more efficient unit and through the distributor's desire to increase his earnings by carrying a second, more profitable line.

The second element, promotion to the consumer, will generate the necessary awareness as to the costs of water heating and the potential for savings that is presently lacking at the consumer level. Thus, the consumer will be able to differentiate among products which offer varying degrees of cost savings, and will be receptive to making a larger investment in the replacement of the failed water heater in return for significantly lower operating costs. This will counteract the current tendency to simply restore the hot water service in an emergency, without regard to investment value or future costs.

The third element, promotions to builders, is aimed at generating a recognition among new home builders that water heating costs are a significant portion of overall energy costs, and that the water heater deserves as much attention as is now being given to the space conditioning system. The recognition by the quality home builder that he can promote an additional quality feature that will be appreciated by his prospective customer should enable the high efficiency water heater to achieve a share of the new construction market that presently ignores the promotional value of water heating savings.

3.2.2 Long Range Trends

Long range growth would be another aspect of the Amtrol market strategy. Further expansion of market share will depend on current trends and their subsequent developments:

1. Government legislation regarding energy efficiency, such as HUD's mandating of sealed combustion.

2. State and local emissions regulations, such as the proposed California NO_x Standards.

3. Generating greater public awareness of energy priorities through continuing government actions in this area.

4. Appearance and acceptance of other brands of efficient water heaters.

If such trends continue in the future, Amtrol anticipates an increase in price levels of water heaters as well as increasing acceptance by the general public of higher first costs. Under these circumstances, marketing of the high efficiency water heater would assume more conventional methods, and Amtrol would then expect to increase its share of the expanded market for energy efficient water heaters. At such time when energy efficient water heaters are more the norm, Amtrol would expect that additional outlets would open up such as the private label market of the mass retailers.

3.2.3 New Product Features

Recognizing that energy efficiency alone is not sufficient to generate a market for a new type of water heater, Amtrol has conducted a preliminary survey of consumer attitudes, which, along with their market survey, points out those features that should be emphasized in the new product. The preliminary survey was limited in scope to consumer attitudes with regard to present water heaters, mainly because the proposed water heater was not yet sufficiently defined at the time of the survey to obtain consumer responses to its features. Amtrol plans to continue to gauge consumer reaction and marketability of the high efficiency water heater later on in the development program once the unit and its performance have been better defined. In general, the marketing of the new water heater will capitalize upon:

- energy savings and lower life cycle costs
- longer tank life
- higher hot water recovery rates
- lower emissions

The relative merits of the various product features are discussed further below.

Selling Price

Initially at least, until a greater market for high efficiency water heaters develops, sales are not expected to justify the high capital investment needed for high volume production, so a moderate volume production facility entailing lower market entry cost but somewhat higher production cost is envisioned. Amtrol recognizes that the higher price of high efficiency water heaters will initially limit their market to the premium end of today's market, and estimates the potential of this market to be about 10% of total gas-fired water heater sales, or about 300,000 units per year. This market would be receptive to the quality features offered by the proposed water heater concept, and can support the somewhat higher cost resulting from a lower manufacturing base. As the market for efficient water heaters expands, the production base would be expanded, and production costs would be expected to diminish, thereby increasing the potential share of the market to an ever increasing portion.

Thus, Amtrol's opinion is that a higher price will not be a significant drawback insofar as its initial marketing plan is concerned (especially if payback and life-cycle savings are favorable) and that the combination of market trends and a gradual increase in production base will eventually enable this water heater to broaden its market potential.

Energy Savings

There is really not enough feedback on the sales of current energy conserving units to be able to quantify their success. Consumer surveys indicate relatively little appreciation of water heating costs or savings potential. Nevertheless, it is clear that the homeowner is the only one who would be seriously interested in reduced operating costs. Therefore, operating economy must be considered an important feature, but can only be capitalized upon if the homeowner is brought closer to the buying chain.

Payback/Life-Cycle Costs

At the present time very little is understood by the public about payback and life-cycle costs. They appreciate savings and durability, and can relate to these features, but actual return on investment or life-cycle savings are not well understood. Thus, one of the main efforts of the marketing strategy will be to educate the public as to the nature of these economic factors, and how the high efficiency water heater will be a better investment than a less expensive, less efficient unit.

Durability

If the new water heater is to be marketed as a premium product, it must offer better durability than conventional equipment, and equally important, must have a durable appearance. The plastic lining will be an important sales feature, since it eliminates corrosion problems caused by voids and pin-holes in conventional glass linings, and will eliminate the necessity of the sacrificial anode which results in accelerated tank failure after it becomes depleted.

Today's water heaters typically have a 5-10 year tank warranty. Although the industry claims an average 11 year tank life, the homeowner perceives expected tank life of about 5-8 years. Amtrol expects the life of their plastic lined tank to be in excess of 15 years, and feels that they can afford to warranty the tank for a longer period than is customary. The exact warranty terms have yet to be established.

Another quality feature will be a rugged outer jacket which will be more durable in contrast to the "tinny" appearance of the sheet metal housings used on conventional units.

Performance

The two most important performance aspects are high service efficiency and high supply capacity. Service efficiency must be substantially higher than the new "high efficiency" center flue water heaters, not just earlier versions. Higher recovery rate will be a very important feature, as it will be important to differentiate between the high recovery rate of Amtrol's product versus the much lower rates of current "high efficiency" units. It is felt that a nominal 40-gallon tank size should be selected, since this capacity would not be so small as to be considered a "small" water heater, nor would it be so large as to lead to excessive jacket losses. Since hot water supply capacity is determined both by storage volume and recovery rate, high hot water capacity must be achieved through higher recovery rate rather than larger storage volume. Tentatively, it is felt that a recovery rate of 40-50 gallons per hour at 100°F rise combined with the 40-gallon tank volume should be the design target.

Appearance

Distinctive appearance is not important for conventional water heaters, since for the most part, the consumer does not enter into the buying decision. Amtrol feels that since they will be marketing closer to the consumer, the unit should have distinctively different appearance, preferably one which imparts a "space-age" look indicative of modern design. Since it will be marked as a different breed of water heater, its appearance should express its uniqueness. In addition, as there is a possibility that the heater will be placed in a finished room such as a kitchen or playroom, it should have more of a finished appliance look, as opposed to the current utilitarian appearance.

Sealed Combustion and Stack Dampers

Although these devices are now receiving some public exposure, the general public does not have a good understanding about the energy saving impact of such systems. Sealed combustion is currently used in manufactured homes, but more to provide sufficient combustion air because of the tightness of the home, rather than just for energy savings. Amtrol feels that the public must be educated as to the energy saving and safety aspects of sealed combustion, and that sealed combustion will be a worthwile energy saving feature with significant promotional value. Sealed combustion will be of greatest value in new construction, especially in manufactured housing and in slab-type homes. In certain applications where the installation of a sealed combustion vent is less practical, such as in homes with a basement below grade, stack dampers should be considered as an alternative. For outdoor installations, the option of a conventional stack should be kept. However, the development objective of this program should be for a unit designed for use with sealed combustion.

Noise

Noise is not a factor with current water heater, and need not be considered at all in the new unit as long as it is as quiet as conventional units. Even if the burner is noisier than conventional units, this would not be a drawback unless the new water heater was noisier than other home appliances, such as refrigerators, freezers, furnaces, etc.

Maintenance and Safety

Ideally, the water heater should not require any maintenance at all, as is the case with present water heaters.

Safety should not be considered a trade-off item. Safety requirements are set by the regulatory agencies, so that there is no freedom of choice in the area of safety from a design standpoint.

Manufacturing Considerations

Amtrol feels quite strongly that the design approach should capitalize on Amtrol's current manufacturing capability to the maximum reasonable extent. This will minimize market entry costs and also has a favorable influence on production cost. The main areas in which this consideration has an impact are in the tank and liner, and in the use of integrally finned copper tubing for the heat exchanger module.

From a manufacturing standpoint, there are no limitations on storage volume or heat exchanger size. However, it will obviously be helpful to use a tank which is presently in Amtrol's product line. Because of shipping and installation limitations, the tank diameter should not exceed 22", which corresponds to the Amtrol WX-250 series tank.

Code Requirements

The new water heater must of course comply with all mandatory ANSI codes and Federal Labelling requirements. In addition, the unit should comply with as many existing and proposed codes as possible, such as HUD, DOE Model Code for New Building Construction, ASHRAE 90-75, etc. In addition, the unit should be in compliance with the newly proposed California emissions standards. Amtrol feels that historically emission codes which have been developed by the state of California have eventually evolved into other state or federal requirements. For this reason, the unit should be designed for the most stringent present or near-term standards in order to avoid future obsolence.

The new Federal energy labelling requirements will be a definite marketing benefit, especially in the near-term when the differences in energy consumption between the high-efficiency water heater and competitive types will be the greatest.

There is, however, one aspect of current labelling standards that will place the proposed design at a marketing disadvantage. The present testing and labelling requirements do not charge the water heater with any exfiltration losses associated with its operation. Hopefully, this aspect of the labelling requirements can be modified to promote sealed combustion rather than denying its advantages.

3.2.4 Recommended Specifications

The foregoing product features are presented as recommended product specifications in Table 8. Specifications are given both for the production version and for the initial demonstration unit.

TABLE 8

PRELIMINARY GAS-FIRED WATER HEATER PRODUCT SPECIFICATIONS

General

Efficiency	• Substantially higher than conventional "high efficiency" units. • Comply with existing and proposed energy codes.
Performance	• Comparable to water heaters prior to "high efficiency", low recovery units. • Provide greater supply through higher recovery rate versus higher storage volume.
Overall Dimensions	• Maximum width not to exceed 22" diameter. • Height not to exceed conventional units.

Components Configurations

Item	Production Version	Demonstration Unit
Tank	Plastic-lined insulated steel tank. Heat transfer/burner module flange mounted under tank.	Modified version of WX-250 tank.
Heat Exchanger	Flange-mount under tank.	Allow 13" height between base and tank bottom. Should use copper integral finned tubing.
Burner	Must provide higher output than competitive units for equal tank size.	Same
	Can be natural-draft or powered-combustion.	Natural-draft burner.
	Must meet proposed California emissions standards.	Same
Pilot	Must be high efficiency type, either stratified pilot or IID.	Same
Stack	To be compatible with sealed combustion, stack damper, or conventional flue.	Designed for sealed combustion but must not preclude other types.

4. REFERENCES

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

2. "Study of Energy-Saving Options for Refrigerators and Water Heaters", Volume 2: Water Heaters; Arthur D. Little, Inc., May 1977.

3. "An Assessment of Retrofit Automatic Vent Dampers for Residential Heating Systems", Arthur D. Little, Inc., November 1977.

4. Private Communication with Howard Perry, Director of Regulatory Assistance Utility Systems, ERA.

5. Energy User News, Volume 3 No. 16, April 17, 1978.

6. Private Communication with Walter Bartlett, Amtrol, Inc.

7. "Water Heaters: Gas and Electric", Consumer Reports, March 1976.

8. E.C. Hise and A.S. Holman, "Heat Balance and Efficiency Measurement of Central, Forced Air, Residential Gas Furnaces", Oak Ridge National Laboratory, Report No. ORNL/NSF/EP-88, October 1975.

9. Philip Barrett, Director of Education, Amtrol, Inc.

APPENDIX A

WATER HEATER COST/PERFORMANCE MODEL

Technical Approach

The technical approach which was selected was to follow the "Test Procedures for Water Heaters", outlined in the Federal Register dated October, 1977[(1)]. The rationale for using this procedure is that eventually labeling requirements will be based on this procedure or one similar to it and this would just require following it at a later date. The federal test procedure has been modified to include an exfiltration loss.

The service efficiency of the water heater is defined as*:

$$E_s = \frac{\text{useful energy delivered}}{\text{total energy input}} \times 100$$

And on a daily basis:

$$E_s = \frac{GC_g (T_w - T_o)}{E_g + P + EXF} \times 100 \qquad (1)$$

The exfiltration loss was evaluated as:

$$EXF = CFD \, \rho_{air} \, \Delta T \, C_P = 0.54 \, CFD$$

The daily gas consumed (E_g) consists of the gas consumed to heat up the water, that consumed to make up for the heat losses, and the pilot gas consumption. This can be expressed as:

---

*See nomenclature (pp. A-9 and A-10), for explanation of symbols and values for constants used in equations.

$$E_g = \frac{GC_g (T_w - T_o)}{(E_r/100)} + VC_g (T_w - T_a)(S/100)(24 - t_m)$$

and $$t_m = (G(T_w - T_o)C_g)/(\dot{Q}E_r/100)$$

The energy recovery (E_r) is defined as the theoretical energy required to bring the stored water volume from T_o to T_w divided by the actual gas input energy expressed as a percent. The actual test requires that the water and tank be at T_O and burner turned on and allowed to go through one heating cycle while measuring the gas consumption. Thus, the losses which go into this test are the heat required to bring the tank material to T_w, the jacket and fitting losses, and the burner heat losses. The equations describing E_r are:

$$E_r = (Q_{wx}/Q_{gas}) \times 100$$

where:

$$Q_{wx} = VC_g (T_w - T_o)$$

$$Q_{gas} = \dot{Q}\tau = Q_{wx}/\eta_s + Q_{mx}/\eta_s + (\dot{Q}_{TF}\tau)/\eta_s + (\dot{Q}_B\tau)/\eta_s$$

$$Q_{mx} = W_t C_{pt} (T_w - T_o)$$

The standby losses (S) are the losses associated with the water heater during standby operation. These are the tank heat losses, the fitting losses, and the losses associated with operation of the pilot. The standby losses are obtained by bringing the water heater up to operating temperature (T_w) and measuring the gas consumption required to maintain this temperature for a period of time. These losses are the percent standby loss per hour expressed as a percentage of the total heat content of the stored water above room temperature. Thus, the standby losses can be represented by:

$$S = [\dot{Q}_{GL}/\{VC_g\ (T_w - T_a)\}] \times 100$$

where:

$$\dot{Q}_{GL} = Q_{GL}/t_s$$

or written in terms of daily water heater operation

$$\dot{Q}_{GL} = \{\dot{Q}t' + \dot{Q}_p\ (24 - t_m - t')\}/(24 - t_m)$$

The pilot energy recovery enters the analysis through the equation describing the daily tank and fitting losses.

$$\dot{Q}_{TF} = \dot{Q}\ (E_r/100)t' + \dot{Q}_p\ (E_{rp}/100)\ (24 - t_m - t')$$

With these equations, a computation technique is now available for calculating the performance of the water heater as it would perform under federal testing procedures.

Water Heater Model

The water heater has been divided into five basic parts:

1. Burner

2. Pilot

3. Heat Exchanger

4. Tank

5. Stack

The burners considered were a conventional natural-draft burner, a forced combustion burner, and a naturally aspirated 100% primary air burner. The pilots considered were a conventional 700 Btu/hr pilot, a 120 Vac intermittent ignition device (IID), and a high efficiency gas pilot. The heat exchangers evaluated were a conventional tank bottom/center flue, a heat pipe, a natural-circulation boiler/condenser combination, and a natural convection bottom-fired unit. Two tanks were considered, a conventional glass-lined tank and a plastic-lined tank. Five types of stacks were considered - a conventional stack, a conventional stack with mechanical or thermal vent damper downstream of the draft diverter, an undiluted vent (no draft diverter), and a direct-vent sealed combustion system.

Table A.1 shows some of the assumptions used in the analysis. The firing rate ($\dot{Q}$) chosen is that required for a nominal 40 gallon tank, which is the target size range. The burner loss[2] has been given as 300 Btu/hr for a conventional water heater. This same penalty was imposed on all the burners. A gas consumption of 700 Btu/hr and energy recovery efficiency of 0% were used for a conventional pilot[2]. The gas consumption for a high efficiency pilot is a target value as is the pilot recovery. The value used for stack efficiency for a conventional heater was calculated using measured values of E_r[2]. A stack efficiency of 85% was used for forced combustion and 84% for natural draft non-conventional combustion. This was based on an exhaust temperature of 300°F and 30% excess air for forced combustion and 50% excess air and an exhaust temperature of 300°F for natural draft. Stack efficiencies of 84.5% and 83% were achieved at AMT with a bottom-fired heat exchanger operating with a forced combustion system and a natural draft system, respectively.

The tank and fitting losses ($\dot{Q}_{TF}$) were calculated in the following manner. The fitting losses[2] have been estimated to be 17 Btu/hr for each fitting in contact with the hot tank. It was assumed that each

TABLE A.1 - OPTION PERFORMANCE PARAMETERS

Burner	Q	Q_B	P
	BTU/HR	BTU/HR	BTU/DAY
1. Conventional	45,000	300	-
2. Powered Combustion	45,000	300	210 (t_m+t')
3. 100% Primary	45,000	300	-

Pilot	Q_p	Erp
	BTU/HR	(%)
1. Conventional	700	0
2. IID	0	0
3. Stratified	300*	81.3*

Heat Exchanger	Stack Efficiency (η_s/100)
1. Conventional	74.5
2. Heat Pipe	85*
3. Reflux/Natural Circulation	84*
4. Bottom-Fired/Natural Circulation	84*

*Target Values

tank has five fittings which gives a total fitting heat loss of 85 Btu/hr. The tank losses were calculated using conventional heat transfer techniques and the results agree with heat loss values for conventional tanks with 3/4 of an inch of insulation.

The electrical power consumed for the forced-combustion burner at a rate of 45,000 Btu/hr is assumed to be 210 Btu/hr. The conversion to primary thermal energy used was 10.5 Btu/Watt-hr.

The exfiltration loss is the hardest of all the parameters to fix. There are serious questions as to how to evaluate the losses for not only the area of the country, but also for the venting and chimney characteristics of the house, the house construction, the placement of the unit in the house, etc. Also, most of the experimental work has been understandably done for space heating systems, since they represent a larger potential for savings, and as such are the first to be examined critically. The published results(3) indicate variations of 2% to 30% savings in fuel consumption by eliminating exfiltration losses.

In this analysis the exfiltration loss is taken as 3 times stoichiometric air while the burner is operating with a dilution type of vent system and 1.4 times stoichiometric air for a forced combustion system with no dilution. During standby or burner-off operation, the exfiltration losses(8) of 58% of the burner-on values for natural draft and 32% for forced convection are used. The thermal value of this exfiltration loss is based on a constant temperature difference of 30°F between the conditioned air and the outside temperature. A heating furnace efficiency of 100% was assumed. This resulted in an energy use increase of about 10% in the water heater consumption for the conventional water heater. This exfiltration loss model will provide adequate comparative information.

The methods of eliminating exfiltration losses which were examined are sealed-combustion and stack dampers. Sealed combustion, the primary approach identified in this project, is assumed to have no exfiltration loss, since all of the combustion air is routed to the burner from outside the conditioned space.

There are basically three types of stack dampers available for use in the exhaust systems of gas appliances - electrically, mechanically (gas pressure), and the thermally actuated. The values used for performance were the percentage of total exfiltration flow which the dampers will allow to escape. Currently, electrically actuated units[3] are estimated to lose 5% of the exfiltration flow, while thermal units are estimated at 40%. Data on mechanical units were not available, but they were assumed to have the same effectiveness as electrical units.

Cost Evaluation

The cost evaluation technique used in the analysis was to calculate payback and life-cycle savings. This was done with and without exfiltration losses. The energy consumption of the conventional water heater was calculated to be 109,000 Btu/day, excluding exfiltration and 119,800 Btu/day, including exfiltration. These were used as reference values for the daily energy consumed (D_{gr}). The daily energy consumption was then calculated using the service efficiency defined in the preceeding section with and without the exfiltration term (EXF).

The daily energy consumed (D_g) then becomes:

$$D_g = (GC_g (T_w - T_o)/E_s$$

And the yearly energy savings are:

$$Y_{gs} = 365 \times (D_{gr}-D_g)$$

The yearly dollars saved are:

$$Y_s = (Y_{gs} \times G_c)/(1 \times 10^6)$$

The payback period in years (P_B) then becomes:

$$P_B = D_c/Y_s \text{ (Years)}$$

Where D_c is the difference in cost between the option or options and the conventional water heater, and the life-cycle savings (LCS) are:

$$LCS = (Y_S x N) - D_c$$

APPENDIX A - NOMENCLATURE

Symbol	Description	Units	Value Used
CFD	Exfiltration Loss	Ft^3/Day	
C_g	Gallon Based Specific Heat	Btu/Gal-°F	8.25
C_p	Specific Heat of Air	Btu/LBM-°F	0.24
C_{pt}	Specific Heat of Tank Material	Btu/LBM-°F	0.11
D_c	Increased Cost of Water Heater Being Analyzed	$	--
D_g	Total Daily Energy Consumed	Btu/Day	--
D_{gr}	Reference Daily Energy Consumed		
	- No Exfiltration	Btu/Day	109,000
	- With Exfiltration	Btu/Day	119,800
E_g	Daily Gas Consumed	Btu/Day	--
E_r	Energy Recovery - Main Burner	%	--
E_{rp}	Energy Recovery - Pilot	%	--
E_s	Service Efficiency	%	--
EXF	Daily Exfiltration Loss	Btu/Day	--
G	Daily Hot Water Usage	Gals/Day	75
G_c	Gas Cost	$/MMBTU	$3.00
LCS	Life-Cycle Savings	$	--
N	Useful Life of Water Heater	Years	11
P	Electrical Energy Consumed	Btu/Day	
P_B	Simple Payback	Years	
$\dot{Q}$	Burner Firing Rate	Btu/Hr	45,000
$\dot{Q}_B$	Burner Heat Loss During Operation	Btu/Hr	300
Q_{gas}	Gas Consumed During Energy Recovery Test	Btu	--
$\dot{Q}_{GL}$	Hourly Gas Consumed During Standby	Btu/Hr	
Q_{GL}	Gas Consumed During Standby Test	Btu	--
Q_{mx}	Heat Required to Heat Tank Material from T_o to T_w	Btu	--
$\dot{Q}_p$	Pilot Firing Rate	Btu/Hr	--
$\dot{Q}_{TF}$	Tank and Fitting Losses	Btu/Hr	--
Q_{TF}	Daily Tank and Fitting Losses	Btu/Day	

APPENDIX A - (CONTINUED

Symbol	Description	Units	Value Used
Q_{wx}	Heat Absorbed by Water During Energy Recovery Test	Btu	--
S	Standby Loss	(%/Hr)	--
t'	Burner on Time to Make-up Heat Losses	Hrs/Day	--
T_a	Ambient Temperature	°F	70
t_m	Main Burner on Time for Useful Heating	Hrs/Day	--
T_o	Inlet Water Temperature	°F	60
t_s	Duration of Standby Test	Hrs	--
T_w	Outlet Water Temperature	°F	150
V	Tank Capacity	Gals.	40
W_t	Dry Tank Weight	Lbs	50
Y_{gs}	Yearly Energy Savings	Btu/Year	--
Y_s	Yearly Dollars Savings	$/Year	--
ρ_{air}	Density of Air	LBM/Ft^3	.075
η_s	Efficiency Based on Stack (Expressed as Fraction)	(%/100)	--
τ	Duration of Energy Recovery Test	Hrs	--
ΔT	Exfiltration/Infiltration Temperature Difference	°F	30

APPENDIX B

COMPUTER PROGRAM

Exhibits

1. Flow Diagram
2. Sample Input File
3. Main Program
4. Tank and Fitting Loss Subroutine
5. Sample Output

EXHIBIT 1. WATER HEATER EVALUATION PROGRAM

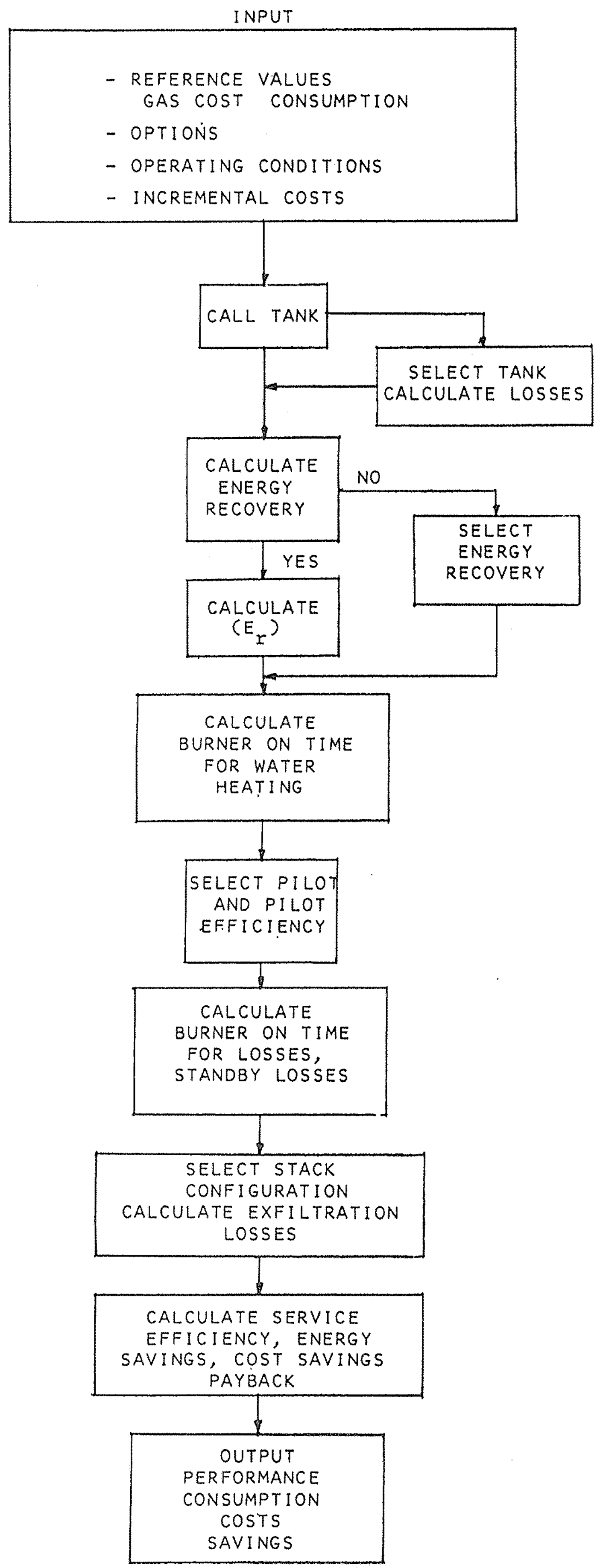


EXHIBIT 2. SAMPLE INPUT FILE

```
1.000 EFFR=T,OUT=F,CGAS=3.00
        |            |      |
        |            |      └──── GAS COST ($/MMBTU)
        |            └──── SUMMARY OUTPUT;OUT=T, FULL OUTPUT
        └──── CALCULATE ENERGY RECOVERY;EFFR=F, INPUT ENERGY RECOVERY

1.500 DCGREF=109024,YREFEX=119809
        |                  └──── DAILY ENERGY CONSUMPTION (BTU) INCLUDING
        |                        EXFILTRATION FOR CONVENTIONAL UNIT
        └──── DAILY ENERGY CONSUMPTION (BTU) EXCLUDING
              EXFILTRATION FOR CONVENTIONAL UNIT

1.600 XXLT=20.125;TXXM=.75
        |               └──── FOAM INSULATION THICKNESS(IN)
        └──── PLASTIC LINED TANK LENGTH(IN)

1.7 COMP=T
      └──── COMPONENT ANALYSIS;COMP=F, TOTAL UNIT ANALYSIS

2.000 *

3.000 1,1,1,1,1
      | | | | └──── STACK CONFIGURATION
      | | | └──── TANK SELECTION
      | | └──── HEAT EXCHANGER SELECTION
      | └──── PILOT SELECTION
      └──── BURNER SELECTION

4.000 75,150,60,70,45000,85,11
      |  |   |  |  |     |  └──── LIFE(YEARS)
      |  |   |  |  |     └──── INPUT ENERGY RECOVERY(%)
      |  |   |  |  └──── BURNER FIRING RATE(BTU/HR)
      |  |   |  └──── AMBIENT TEMPERATURE (F)
      |  |   └──── WATER INLET TEMPERATURE (F)
      |  └──── HOT WATER OUTLET TEMPERATURE (F)
      └──── DAILY HOT WATER DRAW (GALS)

5.000 40,16,.75,.024
      |  |  |   └──── INSULATION CONDUCTIVITY (BTU/HR-FT-F)
      |  |  └──── CONVENTIONAL INSULATION THICKNESS(IN)
      |  └──── TANK DIAMETER(IN)
      └──── TANK VOLUME (GALS)
```

EXHIBIT 2. (CONTINUED)

INCREMENTAL COSTS OVER CONVENTIONAL COMPONENTS ($)

```
6.000 0,65,5
      | |  └── 100% PRIMARY NATURAL DRAFT BURNER
      | └── FORCED COMBUSTION
      └── CONVENTIONAL BURNER

7.000 0,71,71,0
      | |  |  └─ STRATIFIED PILOT
      | |  └── NOT USED
      | └── IID
      └── CONVENTIONAL PILOT

8.000 0,31,67,45,100
        |  |  |   └── NOT USED
        |  |  └── UNDERFIRED HEAT EXCHANGER
        |  └── NATURAL CONVECTION BOILER/CONDENSER
        └── FORCED CONVECTION HEAT PIPE

9.000 0,20,100
      | |  └─NOT USED
      | └── PLASTIC LINED TANK
      └── CONVENTIONAL GLASS LINED TANK

10.000 0,41,41,57
       | |  |  └── SEALED COMBUSTION SYSTEM
       | |  └── MECHANICAL DAMPER UNDILUTED EXHAUST
       | └── MECHANICAL DAMPER DRAFT DIVERTER
       └── CONVENTIONAL STACK

11.000 END
```

EXHIBIT 3. WATER HEATER ANALYSIS - MAIN PROGRAM

```
C     WATER HEATER ANALYSIS PROGRAM
       DIMENSION CB(3),CP(4),CHE(5),CT(3),CS(4),BURN(3),
     &PILOT(4),HEATEX(5),TANX(3),STACK(4)
       COMMON/MAIN 1/V,DT,THKINS,TW,TAMB,NT,NHE,KINS,QLT,
     &QLF,QLTF,DCINS
       LOGICAL QFX,EFFR,OUT,COMP
       REAL KINS,KL,KM,NLIFE
       NAMELIST QFX,EFFR,OUT,CGAS,DCGREF,NB,NP,NHE,NT,NS,G,TW,TO,TAMB,
     &Q,ER,NLIFE,V,DT,THKINS,KINS,CB,CP,CHE,CT,CS,DEGDAY,YREFEX,
     &XXLT,TXXM,COMP
       DATA(BURN(I),I=1,3)/4HCONV,4HFRCD,4H100%/
       DATA(PILOT(I),I=1,4)/4HCONV,4HIID ,4HBATT,4HSTRD/
       DATA(HEATEX(I),I=1,5)/4HCONV,4HPIPE,4HRFLX,4HUFRD,4HISTK/
       DATA(TANX(I),I=1,3)/4HGLSL,4HPLST,4HSTNL/
       DATA(STACK(I),I=1,4)/4HCONV,4HDMP2,4HDMP1,4HSLDC/
       INPUT
       READ 200,NB,NP,NHE,NT,NS
  200  FORMAT(5I)
       READ 202,G,TW,TO,TAMB,Q,ER,NLIFE
  202  FORMAT(7F)
       READ 206,V,DT,THKINS,KINS
       VX=V
       DTXX=DT
  204  FORMAT(3F)
       READ 204,(CB(I),I=1,3)
       READ 206,(CP(I),I=1,4)
  206  FORMAT(4F)
       READ 210,(CHE(I),I=1,5)
  210  FORMAT(5F)
       READ 204,(CT(I),I=1,3)
       READ 206,(CS(I),I=1,4)
       PRINT 1001
  220  CONTINUE
  1000 FORMAT(1X,'******INPUT NEW VALUES*******')
  1001 FORMAT(//)
       PRINT 330
  330  FORMAT(24X,'WATER HEATER OPTIMIZATION PROGRAM',//)
```

```
      CALL TANK(V,DT,THKINS,TW,TAMB,NT,NHE,KINS,QLT,QLF,
     &QLTF,XXLT,TXXM,DCINS,VX,DTXX)
      TLR=QLTF$TLS=QLTF
      IF(.NOT.EFFR)GO TO 270
C   CALCULATION OF ENERGY RECOVERY
      IF(NT.EQ.1)WT=50.
      IF(NT.EQ.2)WT=50.
      IF(NT.EQ.3)WT=50.
      QUND=300.
      QWX=V*8.25*(TW-TO)
      QMX=WT*.11*(TW-TO)
      IF(NHE.EQ.1)EFF=.745
      IF(NHE.EQ.2)EFF=.85
      IF(NHE.EQ.3)EFF=.84
      IF(NHE.EQ.4)EFF=.84
      IF(NHE.EQ.5)EFF=.8
      HELR=0.0$HELS=0.0$BLR=QUND$BLS=0.0
      TIMON =1.
      NTMON=0
  250 TIMONX=(QWX+QMX+QLTF*TIMON)/(Q*EFF)+QUND*TIMON/Q
      NTMON=NTMON+1
      DTMON=ABS(TIMON-TIMONX)
      IF(DTMON.LT..001)GO TO 260
      TIMON=TIMONX
      IF(NTMON.GT.20)GO TO 999
      GO TO 250
  260 CONTINUE
      QGAS=QWX/EFF+QMX/EFF+QLTF*TIMON/EFF+QUND*TIMON
      ER=(QWX/QGAS)*100.
  270 CONTINUE
      TM=(G*(TW-TO)*8.25)/(Q*(ER/100.))
C  ELECTRICAL POWER CONSUMED
      IF(NP.EQ.1)WATTP=0.0
      IF(NP.EQ.2)WATTP=.01
      IF(NP.EQ.3)WATTP=.01
      IF(NP.EQ.4)WATTP=0.0
      IF(NB.EQ.1)WATTB=0.0
      IF(NB.EQ.2)WATTB=20.
```

EXHIBIT 3. (CONTINUED)

```
      IF(NB.EQ.3)WATTB=0.0
      WATTS=WATTP+WATTB
      PLKW=WATTP;BLKW=WATTB
C    SELECT PILOT AND PILOT EFFICIENCY
      IF(NP.EQ.1)QP=700.
      IF(NP.EQ.2)QP=0.0
      IF(NP.EQ.3)QP=0.0
      IF(NP.EQ.4)QP=300.
      IF(NP.EQ.1)ERP=0.0
      IF(NP.EQ.2)ERP=0.0
      IF(NP.EQ.3)ERP=0.0
      IF(NP.EQ.4)ERP=81.34
C   CALCULATE TIME ON FOR BURNER AND PILOT TO MAKE UP LOSSES
      TP=(QLTF-QP*(ERP/100.))*(24.-TM)/(Q*(ER/100.)
     &-QP*(ERP/100.))
      PLR=0.0;PLS=QP*(1-ERP/100.)
C  CALCULATE S(STANDBY LOSS AS DEFINED BY AGA AND FEDERAL REG.
      QGL=(Q*TP+QP*(24-TM-TP))/(24.-TM)
      S=(QGL/((V*8.25)*(TW-TAMB)))*100.
      ENER=G*8.25*(TW-TO)/(ER/100.)+V*8.25*(TW-TAMB)*(S/100)
     &*(24.-TM)
C    CALCULATE EXFILTRATION LOSSES
      GO TO (280,290,300,310),NS
  280 CONTINUE
C   CONVENTIONAL STACK
      CFHB=Q/100.
      CFHD=CFHB*2.
      CFHBS=.58*CFHB
      CFHDS=.58*CFHD
C UNDILUTED EXHAUST-FORCED COMBUSTION ONLY
      IF(NB.EQ.2)CFHB=1.4*CFHB
      IF(NB.EQ.2)CFHBS=.32*CFHB
      IF(NB.EQ.2)CFHD=0.0
      IF(NB.EQ.2)CFHDS=0.0
      GO TO 320
  290 CONTINUE
C     STACK DAMPER  DRAFT DIVERTER-MECH, PEFFS,PEFFD=.05;THERM=.4
```

```
      PEFFS=.05;PEFFD=.05
      CFHB=Q/100.
      CFHD=(Q/100.)*2.
      CFHBS=.58*CFHB*PEFFS
      CFHDS=.58*CFHD*PEFFD
      GO TO 320
  300 CONTINUE
C     VENT DAMPER UNDILUTED STACK-POWER BURNER CASE ONLY
      IF(NB.NE.2)GO TO 999
      PEFFS=.05
      CFHB=(Q/100.)*1.4
      CFHD=0.0;CFHDS=0.0
      CFHBS=.32*CFHB*PEFFS
      GO TO 320
  310 CONTINUE
C     SEALED COMBUSTION
      CFHB=0.0;CFHD=0.0;CFHBS=0.0;CFHDS=0.0
  320 CONTINUE
       XFF=.54
      CFD=(CFHB+CFHD)*(TM+TP)+(CFHBS+CFHDS)*(24.-TM-TP)
      SLR=(CFHB+CFHD)*XFF;SLS=(CFHBS+CFHDS)*XFF
      EXF=CFD*XFF
C   CALCULATE SERVICE EFFICIENCY
      ES=(G*(TW-TO)*8.25)/(ENER+(WATTS*10.5*(TM+TP))
     &+EXF)
      ESX=(G*(TW-TO)*8.25)/(ENER+(WATTS*10.5*(TM+TP)))
C   CALCULATE ANNUAL GAS CONSUMPTION
      DCG=(G*(TW-TO)*8.25)/ESX
      DCEXF=DCG*ESX/ES
      YCG=DCG*365
      YCEXF=DCEXF*365.
      YCGREF=DCGREF*365.
      YSAV=YCGREF-YCG
      YSEXF=YREFEX*365.-YCEXF
      CSAV=(YSAV/1000000.)*CGAS
      CSEXF=(YSEXF/1000000.)*CGAS
      XLSAV=CSAV*NLIFE
      XLEXF=CSEXF*NLIFE
```

```
C     COST DIFFERENTIALS
       IF(NP.EQ.2)CB(2)=32.
       COSDIFF=CB(NB)+CP(NP)+CHE(NHE)+CT(NT)+DCINS+CS(NS)
       IF(.NOT.COMP.AND.NB.EQ.2.AND.NS.EQ.1.)COSDIFF=196.
       IF(.NOT.COMP.AND.NB.EQ.2.AND.NS.EQ.4.)COSDIFF=253.
       IF(.NOT.COMP.AND.NB.EQ.3.AND.NS.EQ.1.)COSDIFF=112.
       IF(.NOT.COMP.AND.NB.EQ.3.AND.NS.EQ.4.)COSDIFF=169.
       PAYBAK=COSDIFF/CSAV
       PAYEXF=COSDIFF/CSEXF
       COS3=3.*CSAV;COS5=5.*CSAV
       COS3EX=3.*CSEXF;COS5EX=5.*CSEXF
       XLCC=XLSAV-COSDIFF
       XLEXF=XLEXF-COSDIFF
       PRINT 340,G,DCG,ESX*100.,ES*100
 340   FORMAT(1X,'DAILY DRAW= ',F7.2,1X,'GALS',1X,'DAILY',1X,
      &'CNSMD=',F9.0,1X,'BTU',3X,'SRVC EFF=',F6.1,
      &'%','(',F5.1,'EXF)',/)
       PRINT 350,CSAV,CGAS,COSDIFF
 350   FORMAT(1X,'YEARLY SAVINGS = $',F8.2,6X,'COST GAS= $',
      &F5.2,'-MBTU',2X,'ADDED COST = $',F8.2,/)
       PRINT 360,NB,NP,NHE,NT,NS,XLCC,PAYBAK
 360   FORMAT(1X,'NO EXF-',1X,'HEATER CODE=',5(I1),2X,'LIFE CYCLE SAV=',
      &F9.2,2X,'PAYBACK=',F7.2,1X,'YEARS',/)
       PRINT 361,COS3,COS5
 361   FORMAT(7X,'-PAYBACK COST DIFFERENCE -  3 YEARS= $',F8.2,
      &3X,'5 YEARS = $',F8.2,/)
       PRINT 355,XLEXF,PAYEXF
 355   FORMAT(1X,'WITH EXFILTRATION',3X,'LIFE CYCLE SAV= $',F9.2,
      &3X,'PAYBACK',F7.2,1X,'YEARS',/)
       PRINT 361,COS3EX,COS5EX
       PRINT 370,TW,TO,TAMB
 370   FORMAT(1X,'TWATER OUT=',F6.1,'*F',10X,'TWATER IN=',
      &F6.1,'*F',10X,'TAMBIENT=',F6.1,'*F',/)
       PRINT 380,V,THKINS,KINS
 380   FORMAT(1X,'TANK VOLUME =',F7.2,1X,'GALS',2X,'INSULATION',1X,
      &'THK.=',F6.2,1X,'IN.',2X,'K=',F6.3,1X,'BTU/HR-FT-*F',/)
       PRINT 390,Q,ER,S
 390   FORMAT(1X,'BURNER CAPACITY=',F7.0,1X,'BTU/HR',3X,'ER=',
```

EXHIBIT 3. (CONTINUED)

```
     &F6.2,1X,'%',3X,'STANDBY LOSSES=',F6.2,'%/HR',//)
      IF(.NOT.OUT)GO TO 500
      PRINT 400
400   FORMAT(2X,'ITEM',4X,'TYPE',5X,'TIME ON',1X,'TIME ON',
     &2X,'EFF.',1X,'LOSS',4X,'LOSS',4X,'LOSS',5X,'ADDED')
      PRINT 410
410   FORMAT(19X,'USEFUL',2X,'LOSSES',7X,'RUNNING',
     &1X,'STANDBY',1X,'ELECT.',4X,'COST')
      PRINT 420
420   FORMAT(20X,'(HRS)',3X,'(HRS)',3X,'(%)',2X,'BTU/HR',
     &1X,'BTU/HR',2X,'WATTS',6X,'$',/)
      PRINT 430,BURN(NB),TM,TP,BLR,BLS,BLKW,CB(NB)
430   FORMAT(1X,'BURNER',2X,A4,4X,F6.2,4X,F6.2,7X,F7.0,
     &1X,F7.0,1X,F6.0,F8.2)
      PRINT 440,PILOT(NP),(24.-TM-TP),ERP,PLR,PLS,PLKW,
     &CP(NP)
440   FORMAT(1X,'PILOT',3X,A4,4X,10X,F6.2,1X,F5.1,1X,F7.0,1X,
     &F7.0,1X,F6.0,F8.2)
      PRINT 450,HEATEX(NHE),EFF*100.,HELR,HELS,CHE(NHE)
450   FORMAT(1X,'HT EX',3X,A4,4X,17X,F5.1,1X,F7.0,1X,F7.0,7X,F8.2)
      PRINT 460,TANX(NT),TLR,TLS,(CT(NT)+DCINS)
460   FORMAT(1X,'TANK',4X,A4,4X,23X,F7.0,1X,F7.0,7X,F8.2)
      PRINT 470,STACK(NS),SLR,SLS,CS(NS)
470   FORMAT(1X,'STACK',3X,A4,4X,23X,F7.0,1X,F7.0,7X,F8.2)
500   CONTINUE
      WRITE(10,1000)
      INPUT(10);PRINT 1001
      GO TO 220
999   STOP
            END
```

EXHIBIT 4. TANK AND FITTING LOSS SUBROUTINE

```
      SUBROUTINE TANK(V,DT,THKINS,TW,TAMB,NT,NHE,KINS,QLT,QLF,QLTF,
     &XXLT,TXXM,DCINS,VX,DTXX)
      REAL KL,KM,KINS,LFCT
      V=VX
      DT=DTXX
      GO TO (10,20,30),NT
 10   CONTINUE
C GLASS LINED TANK
      LFCT=1.08
      TM=.066/12.$KM=25.$DAV=DT+THKINS
      XLT=((V*231.-.1025*DT**3)/(.7854*DT**2))*LFCT-.268*DT
      TL=.006/12$KL=.51
      ATOP=.8419*DT**2
      ATOP=ATOP/144.
      GO TO 40
 20   CONTINUE
C PLASTIC LINED TANK
      TL=.05/12.$KL=.1$LFCT=1.000
      TM=TXXM/12.$KM=.015
      XLT=XXLT
      DT=21.868-24.*TL-24.*TM
      AXISA=DT/2.$AXISB=6.-12.*TL-12.*TM
      EPSI=(1.-(AXISB/AXISA)**2)**.5
      XLNEP=ALOG((1.+EPSI)/(1.-EPSI))
      V=(4.189*AXISA**2*AXISB+.7854*DT**2*XXLT)/231.
      ATOP=2.*3.1416*AXISA**2+(3.1416*AXISB**2/EPSI)*XLNEP*.5
      ATOP=ATOP/144.
      GO TO 40
 30   CONTINUE
C STONE LINED TANK DON'T USE THIS OPTION OBSOLETE
      TL=.001/12.$KL=.1$LFCT=1.125
 40   CONTINUE
      TINS=THKINS/12.$TS=.032/12.
      NTWALL=0
C ASSUME TEMPERATURE OF OUTSIDE WALL
      TWALL=100.
C CALCULATE TANK SIDE  LOSS
      RI=DT/24.$DF=DT/12.$XLF=XLT/12.
```

EXHIBIT 4. (CONTINUED)

```
      RL=(R1/KL)*ALOG((R1+TL)/R1)
      RT=(R1/KM)*ALOG((R1+TL+TM)/(R1+TL))
      IF(THKINS.EQ.0.0)RINS=0.0
      IF(THKINS.EQ.0.0)GO TO 65
      RINS=(R1/KINS)*ALOG((R1+TL+TM+TINS)/(R1+TL+TM))
 65   CONTINUE
      RW=(R1/25.)*ALOG((R1+TL+TM+TINS+TS)/(R1+TL+TM+TINS))
 70   CONTINUE
      NTWALL=NTWALL+1
      HRAD=.1713E-8*.9*((TWALL+460.)**4-(TAMB+460.)**4)/(TWALL-TAMB)
      HOS=.27*(TWALL-TAMB)**.25
      HOS=HOS+HRAD
      ROS=R1/((R1+TL+TM+TINS+TS)*HOS)
      US=1./(RL+RT+RINS+RW+ROS)
      QLS=US*3.1416*DF*XLF*(TW-TAMB)
      TOD=(R1+TL+TM+TINS+TS)*2.
      QAS=QLS/(3.1416*TOD*XLF)
      XXDT=QAS/HOS$TWALLX=XXDT+TAMB
      IF(NTWALL.GT.10)GO TO 888
      DTCHK=ABS(TWALL-TWALLX)
      IF(DTCHK.LT.0.1)GO  TO 60
      TWALL=TWALLX
      GO TO 70
 60   CONTINUE
CCALCULATE TANK TOP LOSS
 90   CONTINUE
      HRAD=.1713E-8*.9*((TWALL+460.)**4-(TAMB+460.)**4)/(TWALL-TAMB)
      HOT=.38*(TWALL-TAMB)**.25
      HOT=HOT+HRAD
      RTOP=TL/KL+TM/KM+TINS/KINS+TS/25.+(1./HOT)
      UTOP=1./RTOP
      QLTOP=ATOP*UTOP*(TW-TAMB)
      TWALLX=QLTOP/(ATOP*HOT)+TAMB
      DTCHK=ABS(TWALL-TWALLX)
      IF(DTCHK.LT..1)GO  TO 80
      TWALL=TWALLX
      NTWALL=NTWALL+1
      IF(NTWALL.GT.20)GO TO 888
      GO TO 90
 80   CONTINUE
```

EXHIBIT 4. (CONTINUED)

```
C CALCULATE TANK BOTTOM LOSS
 110  CONTINUE
      HRAD=.1713E-8*.9*((TWALL+460)**4-(TAMB+460)**4)/(TWALL-TAMB)
      HBOT=.2*(TWALL-TAMB)**.25
      HBOT=HBOT+HRAD
      RBOT=TL/KL+TM/KM+TINS/KINS+TS/25.+1./HBOT
      UBOT=1./RBOT
      QLBOT=ATOP*UBOT*(TW-TAMB)
      TWALLX=QLBOT/(ATOP*HBOT)+TAMB
      DTCHK=ABS(TWALL-TWALLX)
      IF(DTCHK.LT..1)GO  TO 100
      TWALL=TWALLX
      NTWALL=NTWALL+1
      IF(NTWALL.GT.30)GO TO 888
      TWALL=TWALLX
      GO TO 110
 100  CONTINUE
      IF(NHE.EQ.1.OR.NHE.EQ.5)GO TO 120
      IF(NHE.GT.1.OR.NHE.LT.5)GO TO 130
 120  QLT=QLTOP+QLS
      GO TO 140
 130  QLT=QLTOP+QLS+QLBOT
 140  CONTINUE
      IF(NT.EQ.1)XNLKS=5.
      IF(NT.EQ.2)XNLKS=5.
      IF(NT.EQ.3)XNLKS=5.
      QLF=XNLKS*17.
      OUTPUT QLTOP,QLBOT,QLS
      QLTF=QLF+QLT
      DAV=DT+THKINS
      SAT=(.7854*DAV**2)*1+3.1416*DAV*60.
      VINS=SAT*THKINS
      DVINS=SAT*(THKINS-.75)/1728.
      CINS=1.90
      DCINS=CINS*DVINS
 888      CONTINUE
      RETURN
      END
```

EXHIBIT 5. SAMPLE OUTPUT

WATER HEATER OPTIMIZATION PROGRAM

```
QLTOP = 37.4980
QLBOT = 35.9172
QLS = 391.593
DAILY DRAW=   75.00 GALS DAILY CNSMD=  109024. BTU   SRVC EFF=  51.1%( 46.5EXF)

YEARLY SAVINGS = $      .00      COST GAS= $ 3.00-MBTU  ADDED COST = $      .00

NO EXF- HEATER CODE=11111  LIFE CYCLE SAV=       .00  PAYBACK=     .00 YEARS

      -PAYBACK COST DIFFERENCE -  3 YEARS= $      .00   5 YEARS = $      .00

WITH EXFILTRATION   LIFE CYCLE SAV= $       .00   PAYBACK     .00 YEARS

      -PAYBACK COST DIFFERENCE -  3 YEARS= $      .00   5 YEARS = $      .00

TWATER OUT= 150.0*F          TWATER IN=  60.0*F          TAMBIENT=  70.0*F

TANK VOLUME =  40.00 GALS  INSULATION THK.=   .75 IN.  K=  .024 BTU/HR-FT-*F

BURNER CAPACITY= 45000. BTU/HR   ER= 71.67 %   STANDBY LOSSES=  5.33%/HR
```

ITEM	TYPE	TIME ON USEFUL (HRS)	TIME ON LOSSES (HRS)	EFF. (%)	LOSS RUNNING BTU/HR	LOSS STANDBY BTU/HR	LOSS ELECT. WATTS	ADDED COST $
BURNER	CONV	1.73	.36		300.	0.	0.	.00
PILOT	CONV		21.92	.0	0.	700.	0.	.00
HT EX	CONV			74.5	0.	0.		.00
TANK	GLSL				514.	514.		.00
STACK	CONV				729.	423.		.00

APPENDIX C

AMTROL-FUNDED "PROOF-OF-CONCEPT" TESTS

A "proof-of-concept" prototype water heater has been built and tested for the purpose of evaluating the natural-circulation heat exchanger, the natural draft 100% primary-air burner concept, and the high efficiency pilot concept. A general description of the results is given in the following discussion.

The water heater utilizes an external heat exchanger which effectively separates the water storage function from the heat transfer function. This enables good insulation of stored water while permitting excellent thermal contact between combustion products and water to be heated.

In order to eliminate any electric power requirements, the standing pilot is retained, but in a configuration which permits a high energy recovery efficiency to be attained - the target value is 81.3%. This requires a special heat exchanger and (natural-draft) burner configuration, as well as a particular placement of the pilot burner with respect to the heat exchanger.

The preliminary tests on the "proof-of-concept" model have shown the following:

- Approximately 4-6 gpm natural circulation of stored water through the heat exchanger is achieved at a gas input of 40,000-42,000 Btu/hr.

- Heat exchanger wall temperature is approximately 70°F to 80°F above local water temperature.

- The feasibility of using a 100% primary air, high intensity, natural draft burner with a natural convection heat exchanger has been demonstrated.

- The feasibility of using a 300 Btu/hr standing pilot with the above burner has been demonstrated.

- Stack loss was measured to be 15.5% (HHV) for a forced draft version of the 100% primary air burner, and 17-18% with the natural-draft version. The latter loss was higher due to higher excess air levels.

APPENDIX D

WATER HEATER FIRING RATE

One "sales" feature that Amtrol felt was important was that the water heater provide an "above average" hot water draw. A major complaint of "energy efficient" water heaters is that they provide insufficient hot water compared to older conventional units[7]. Water heaters were rated as to "acceptable" water draw rates. By defining the heat available in a one hour draw, Fig. D.1 was prepared for the "high efficiency" water heater. Plotted on this figure are test results[7] as to below, above, and average water draws. Most of the heaters rated "above average" fall between a firing rate of 45,000 to 50,000 Btu/hr with a 40-gallon tank. This was the reasoning used to select the firing rate for the proposed unit. This specification will be further refined during the design phase to select a final design firing rate.

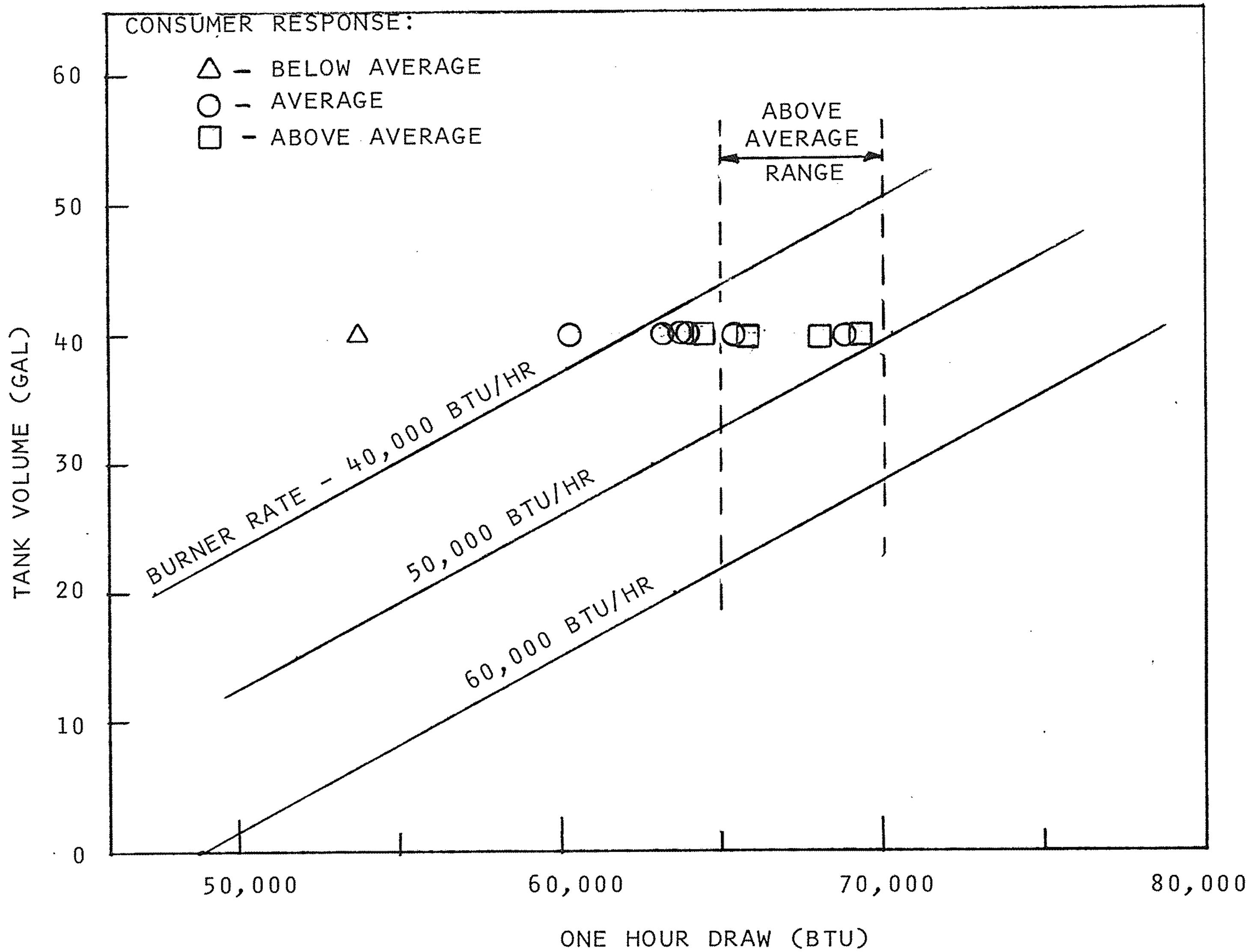


FIG. D.1 RATING OF TANK VOLUME/BURNER SIZE(7)

RESEARCH AND DEVELOPMENT OF A
HIGH EFFICIENCY GAS-FIRED WATER HEATER

PROTOTYPE WATER HEATER DESIGN

Task 3.1 Report

June 4, 1979

Prepared By:

Advanced Mechanical Technology, Inc.
141 California Street
Newton, Massachusetts 02158

Prepared under Subcontract 7381 for the

Oak Ridge National Laboratory
Oak Ridge, TN 37830
Operated by
Union Carbide Corporation
For The
U.S. Department of Energy
Contract No. W-7405-eng-26

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The object of this task was to design a gas-fired water heater using the performance and product specifications developed in Task I.2, the market and concept evaluation. The design goal is an overall service efficiency of 70% including exfiltration losses. Some of the major design features required were a low jacket loss plastic lined tank, a high recovery efficiency heat exchanger module, a sealed combustion system, and complete independence from electric power.

The design task was broken down into five major subsystems - the heat exchanger, the combustion system, the storage tank, the sealed combustion system, and the controls.

2. DESIGN POINT CONDITIONS

The design point performance specifications are shown in Table 1. The methodology used to develop these performance specifications is described in detail elsewhere(1). The following sections of this report describe the methods used to design the various components to meet the values listed in Table 1. These values represented the maximum practical performance, with the exception of the stratified pilot, which could be attained using state-of-the-art components and materials. The stratified pilot is an untested concept and while some qualitative design features are included in the current water heater design, its design is better accomplished during the developmental tasks of this project.

TABLE 1

PERFORMANCE SPECIFICATIONS

	COMPONENT	PERFORMANCE TARGETS
1.	Burner	Firing Rate - 45,000 BTU/HR
2.	Heat Exchanger	Stack Efficiency - 84%
3.	Tank	Volume - 40 Gallons, Tank and Fitting Losses - 300 BTU/HR
4.	Stack	No Exfiltration
5.	Pilot	Firing Rate - 300 BTU/HR Recovery Efficiency - 81.3%

- Target Service Efficiency (Including Exfiltration) - 72.5%) (Based on:)
  - 75 Gallon Daily Draw
  - 150°F Water Out; 60°F Water In
  - 70°F Ambient Temperature
- Non-Electric Powered

3. COMPONENT DESIGNS

While there are five components or subsystems to be designed, there are three components whose performance bears directly on the service efficiency of the water heater; the heat exchanger, the tank, and the pilot. The burner, aspirator, ducting systems (except for leaks) and controls do not directly affect efficiency, but they do affect operational characteristics. Fig. 1 is a schematic of the water heater showing its component parts.

3.1 Heat Exchanger

The heat exchanger, having both internal natural circulation of water and external convection of combustion products, required a low pressure drop design for both internal and external heat transfer surfaces. In addition, it had to have a fairly high stack efficiency (84%). This combination required a low velocity design with a large surface area. The available heat transfer surfaces were a choice between two sizes of integral finned copper tubing in Amtrol's product line.

The required design conditions are shown in Table 2. The critical conditions are the high stack efficiency at a pressure drop of 0.005 inches of water on the gas-side of the exchanger and the non-boiling maximum wall temperature restriction on the water-side of the exchanger. Both the gas-side and water-side of the heat exchanger operate in the laminar or laminar/turbulent transition flow regions. This compounds the design problems because correlations could not be used with confidence in the operating range of the unit. Fortunately, some test data had been taken previously with Amtrol's heat transfer surface in this operating region with the "proof of concept" heat exchanger[(1)]. While this data had not directly measured individual heat transfer coefficients, it did measure overall heat transfer rates. An analytical technique was used to derive design equations from this data.

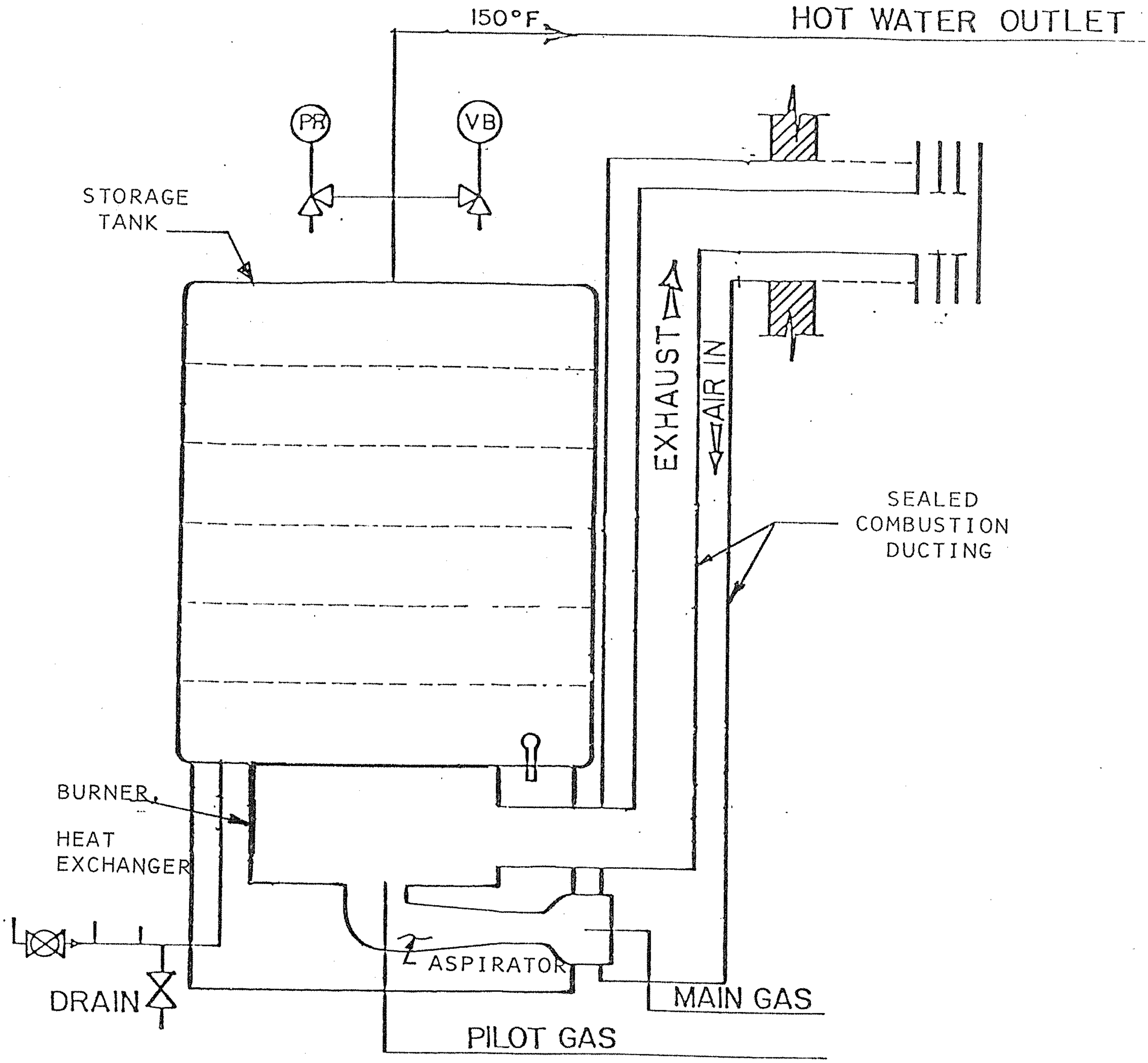


FIG. 1 SCHEMATIC OF WATER HEATER AND COMPONENTS

TABLE 2

HEAT EXCHANGER DESIGN REQUIREMENTS

Gas Side

Firing Rate	45,000 BTU/HR
Mass Flow	53 LBM/HR
Pressure Drop	0.005 Inches of Water*
Stack Efficiency	84%
Exhaust Temperature	300°F
Inlet Air Temperature	60°F

Water-Side

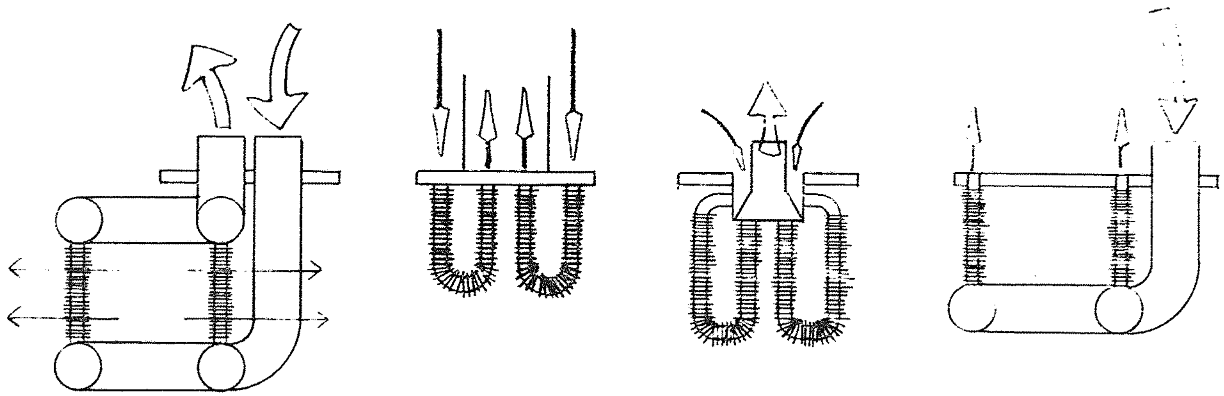
Water Side Transfer Rate	37,800 BTU/HR
Water Inlet Temperature	100°F
Maximum Wall Temperature	Non-Boiling

*Allotted to heat exchanger based on total system pressure drop of 0.030 inches of water.

Once the design equations were developed, a computer program was written which used these basic equations to predict the thermal performance of various heat exchanger configurations.

Four different heat exchanger arrangements were examined in detail. These are shown schematically in Fig. 2. The first arrangement had a single row of heat transfer tubes attached to headers with a separate riser and downcomer to establish the circulation of water. This was similar to the "proof of concept" configuration. The second and third had two rows of tubes (U-tubes) with the hotter inner row acting as the riser and the outer colder row acting as the downcomer. This eliminated the need for headers. Two variations of this type were designed to satisfy different packaging constraints. The fourth arrangement had a single row of tubes, as did the first, which performed the function of the riser tube and a separate downcomer which was not part of the heat transfer surface. This arrangement required a bottom header, but the top header was eliminated by inserting the tubes directly into the tank cover plate. These heat exchangers were drawn up in preliminary layouts and reviewed by Amtrol. The result of these meetings was selection of the first arrangement. This unit was selected due to the high confidence level Amtrol had in this design based on the "proof of concept" tests.

The final design details for the heat exchanger are given in Table 3. The top half of the table gives the performance parameters and the bottom half the physical details. The conditions are for the design values given in Table 1. The design stack efficiency was a little above the specified value of 84%. Flow rates and pressure drops are in the acceptable ranges for satisfactory performance.



FIRST ARRANGEMENT | SECOND ARRANGEMENT | THIRD ARRANGEMENT | FOURTH ARRANGEMENT

FIG. 2 HEAT EXCHANGER CONFIGURATIONS

TABLE 3

HEAT EXCHANGER DESIGN DETAILS

PERFORMANCE

Parameter	Gas-Side	Water Side	Overall
Q (BTU/HR)	45,000	38,020	
Stack Efficiency (%)			84.52
Inlet Temperature	2,660°F	100°F	
Outlet Temperature	313°F	130°F	
Effectiveness	--	--	0.917
Heat Transfer Coefficient (BTU/HR-FT^2-°F)	6.31	304	5.44
Flow Rate (LB/HR)	53.6	1,268	--
Pressure Drop (Inches of Water)	0.005	0.070	--

GEOMETRY

Tubing - 0.5 Inch O.D. Copper Integral Finned Tubing; 25 Six Inch Lengths

Fin Details - 11 Fins/Inch; 0.75 Inch O.D.; 0.125 Inch Fin Height; 0.010 Inch Fin Thickness

Heat Transfer Area - 7.4 Square Feet (Total)

Pitch Diameter - 6 Inches

Header Diameter - 2 Inches I.D.

3.2 Storage Tanks

The storage tank, although a passive component, is usually the one which determines the useful life of the product. In other words, if the tank leaks the entire water heater is replaced. Additionally, the heat loss from the tank together with the pilot determines the standby loss of the water heater. The design requirements of the tank are a forty gallon storage capacity, a longer life than conventional heaters, a 300 psi pressure requirement, and a heat loss not exceeding 300 Btu/hr. The design approach used was a steel tank with an internal one-piece plastic liner to prevent corrosion, and two part urethane foam insulation between the liner and the tank wall to reduce heat loss. A cross-section of the tank wall is shown in Fig. 3. The tank liner is similar to ones used in Amtrol's water well system products. Based on their past experiences, Amtrol expects a 15-year life for this tank.

The tank design is based on the Amtrol Model WX-250 tank, which has a total volume of approximately 44 gallons. This tank size was selected to provide the nominal 40-gallon storage volume indicated by the market analysis (Ref. 1), and because it could be manufactured with existing production facilities. The original version of this tank utilized toro-spherical end-caps which exceeded the maximum deflections allowed by AGA under their 300 psig hydrostatic test. The end-caps were redesigned to conform to an ellipsoidal shape which provided greater stiffness. At the same time that this modification was made, the tank volume was increased from its original 44 gallons to approximately 50 gallons, so that after allowance for the insulation, the useful tank volume would be approximately 40 gallons. Prototypes of the new tank were produced by Amtrol and subsequently tested by AMTI according to the AGA hydrostatic test procedure. The test results indicating satisfactory performance relative to AGA requirements are shown in Fig. 4.

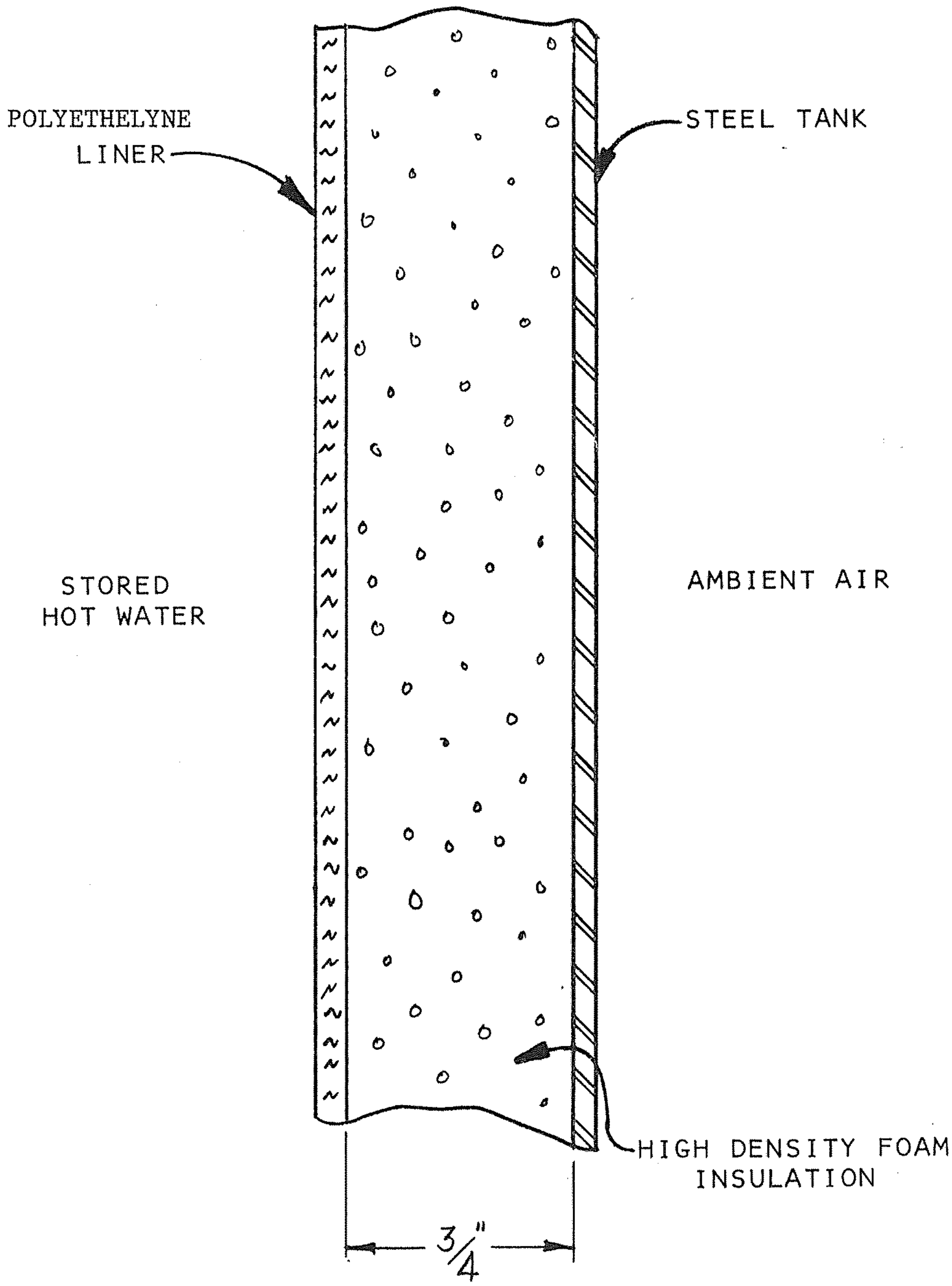


FIG. 3 CROSS SECTION OF TANK WALL

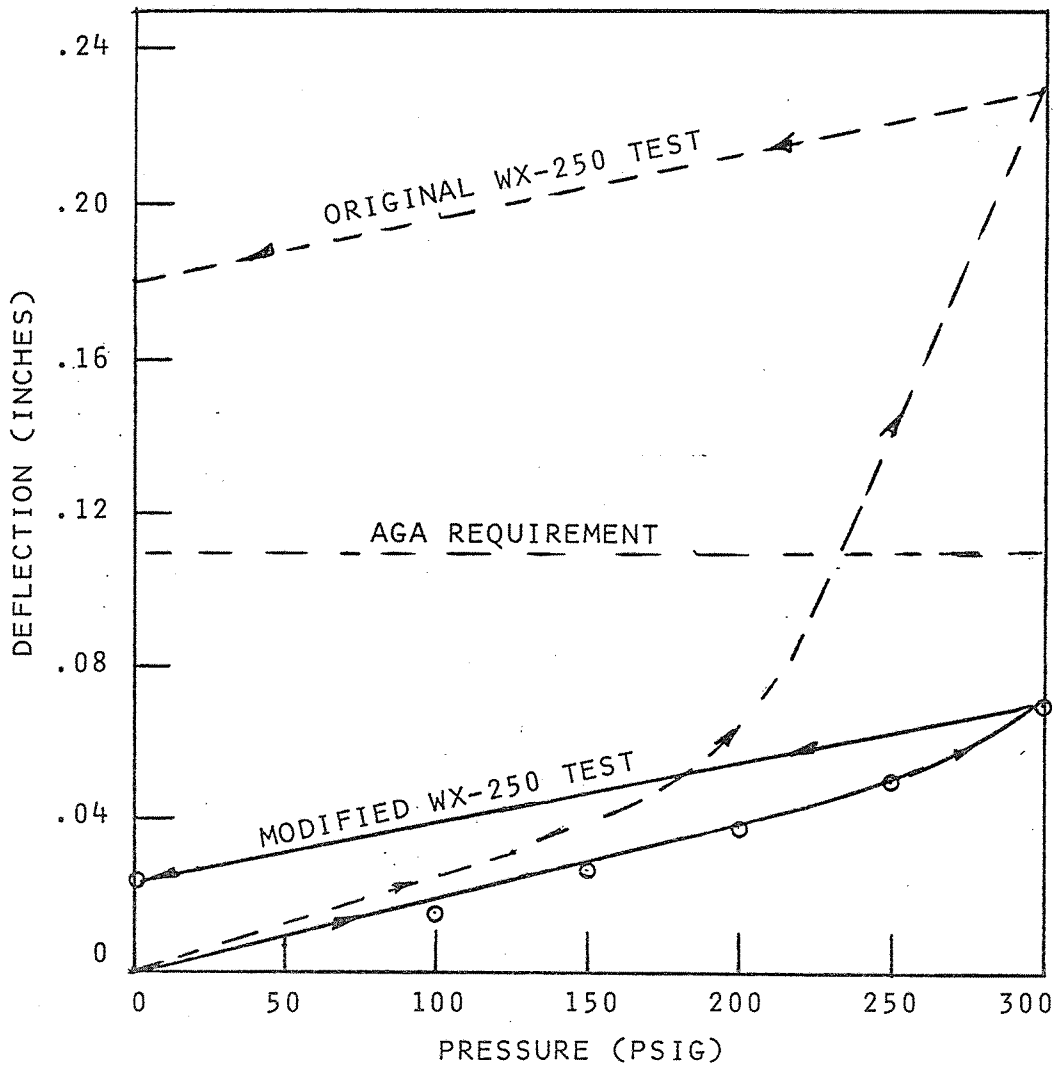


FIG. 4 WX-250 TANK DOME DEFLECTION TESTS

With regard to the tank heat losses, it was felt that the higher density, higher quality foam insulation combined with the smaller surface area to volume requirements of the tank would result in acceptable heat losses. Fig. 5 shows two curves with various predicted losses for the tank. The top curve shows the tank heat losses (without fittings) as a function of stored water temperature for a tank assuming heat loss from the top, bottom and sides. Under actual operating conditions the bottom losses will not be as high as predicted because of tank stratification. The lower curve shows the tank losses assuming no losses through the bottom. Added to both of these curves should be the fitting losses. For a conventional water heater (with five fittings) these losses are 85 Btu/hr(3). Using this value, the design would have a tank loss of 330 to 400 Btu per hour at 150°F. However, Amtrol had a tank tested and the data point is shown in Figure 5. This data although taken at a lower temperature, projects to be 300 Btu/hr at design conditions. This result was less than expected, but it had fewer than 5 fittings and some were attached to the bottom. This would explain some of the difference between the predicted and actual data. Thus, while the design analysis shows the tank might have higher than desired heat losses, the test results from Amtrol, show that the tank and fitting losses should meet the design goal.

3.3 Combustion System

The combustion system is comprised of three elements: the burner or flameholder, the gas injection and mixing system, and the pilot. The most important design requirements were:

- No electric connection allowed.
- High pilot energy recovery
- Compact flame with low emissions

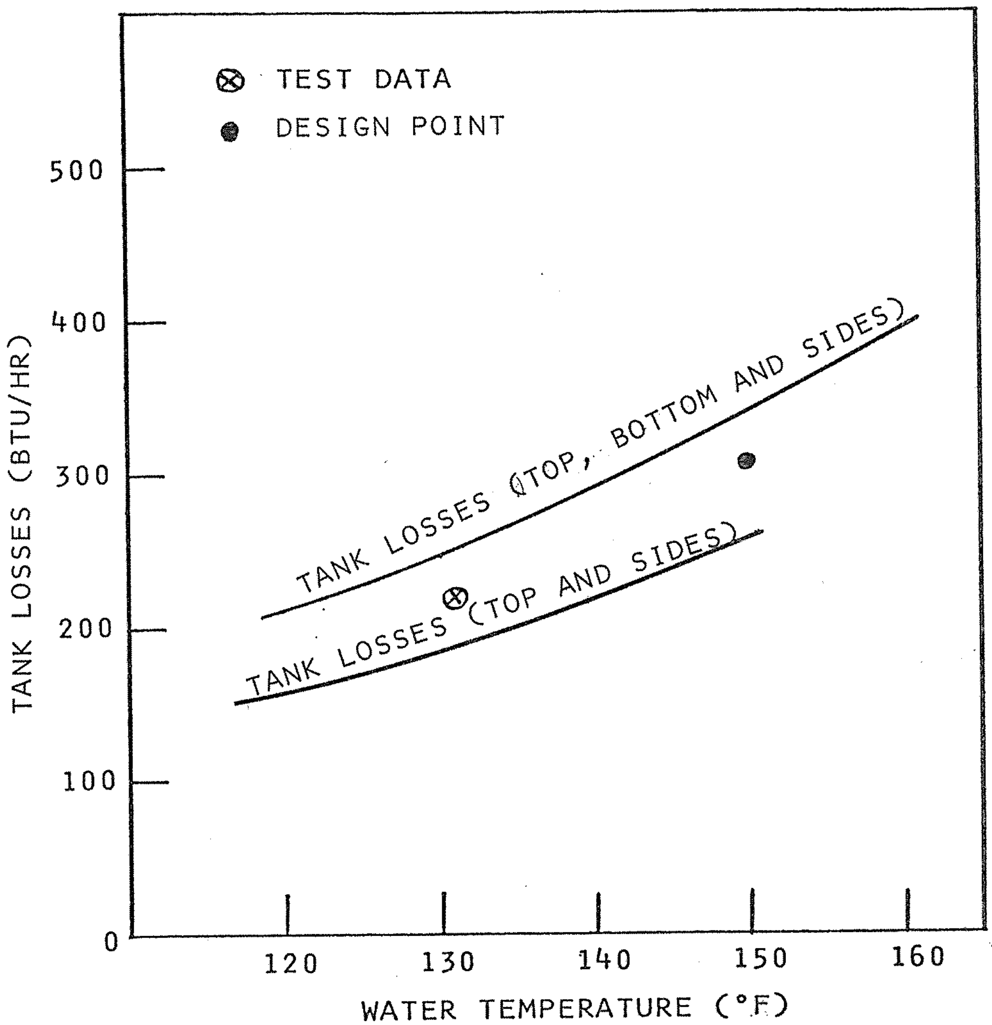


FIG. 5 TANK HEAT LOSSES

The selected approach uses pre-mixed combustion with a screen-type burner or flameholder. A gas pressure-driven air aspirator accomplishes mixing and supplements the stack draft in providing sufficient combustion air for operation of a sealed combustion system. A low gas input standing pilot is integrated with the burner.

3.3.1 Burner

The burner design was performed experimentally. Various flameholder configurations were bench-tested both with and without an aspirator, and the flameholding characteristics of the different burners were determined as a function of air/fuel ratio, geometry, etc. The most promising burner was further tested, and a final design was developed.

This process involved trade-offs between flameholder operating temperature, allowable flameholder pressure drop, and flame stability. The most crucial of these trade-offs versus the selection of a flameholder gas velocity low enough to avoid excessive pressure drop yet high enough to avoid excessive flameholder temperature. The end result of this trade-off is a conically shaped flameholder utilizing a perforated screen having approximately 39% open area and providing an unburned gas velocity of approximately 7.9 ft/sec through the screen.

3.3.2 Aspirator

The design of the aspirator is critical because it is the "pump" of the combustion air system. The main design goal was to maximize the pressure rise in the aspirator at the design flows, using only the gas line pressure (4 inches of water) as a power source. The aspirator consists of two basic parts, the mixing section, and the diffuser. The design analysis consisted of varying the mixer diameter and diffuser length, and selecting the combinations which maximized the pressure rise of the unit. Fig. 6 shows the calculated aspirator pressure rise as a function of mixer diameter for various loss assumptions. This was done for a design firing rate of 45,000 Btu/hr and an excess air rate of 50%. As can be seen, the optimum mixer diameter occurs at less than 1 inch if no losses were present. However, when losses are included in the model, the optimum diameter changes to about 1.75 inches and the curve becomes quite flat. Fig. 7 shows the final calculated aspirator performance for a mixer diameter of 1.75 inches. To produce this map, a conventional combination gas control is coupled with the aspirator to project a performance map of the aspirator operating with a conventional control regulator. The performance curves of Fig. 7 are equivalent to a fan curve for a powered combustion system.

3.3.3 Pilot

The design of the pilot burner has two primary design objectives. One is to provide an automatic and reliable ignition source for the main burner. The other is to enable a high pilot recovery efficiency to be achieved during standby. Achievement of the former objective is a relatively straightforward design exercise. The latter, however, involves rather complex interelationships between components of the system comprising the main burner, heat exchanger, intake/exhaust, and pilot burner. The design rationale for the pilot burner will be described below.

The pilot design principle is that of a gas jet which aspirates and mixes with much of its combustion air prior to combustion. The burner nozzle is placed upstream of the main burner flameholder and protrudes through the flameholder. In this manner, the pilot burner is kept out of the path of the combustion products from the main burner.

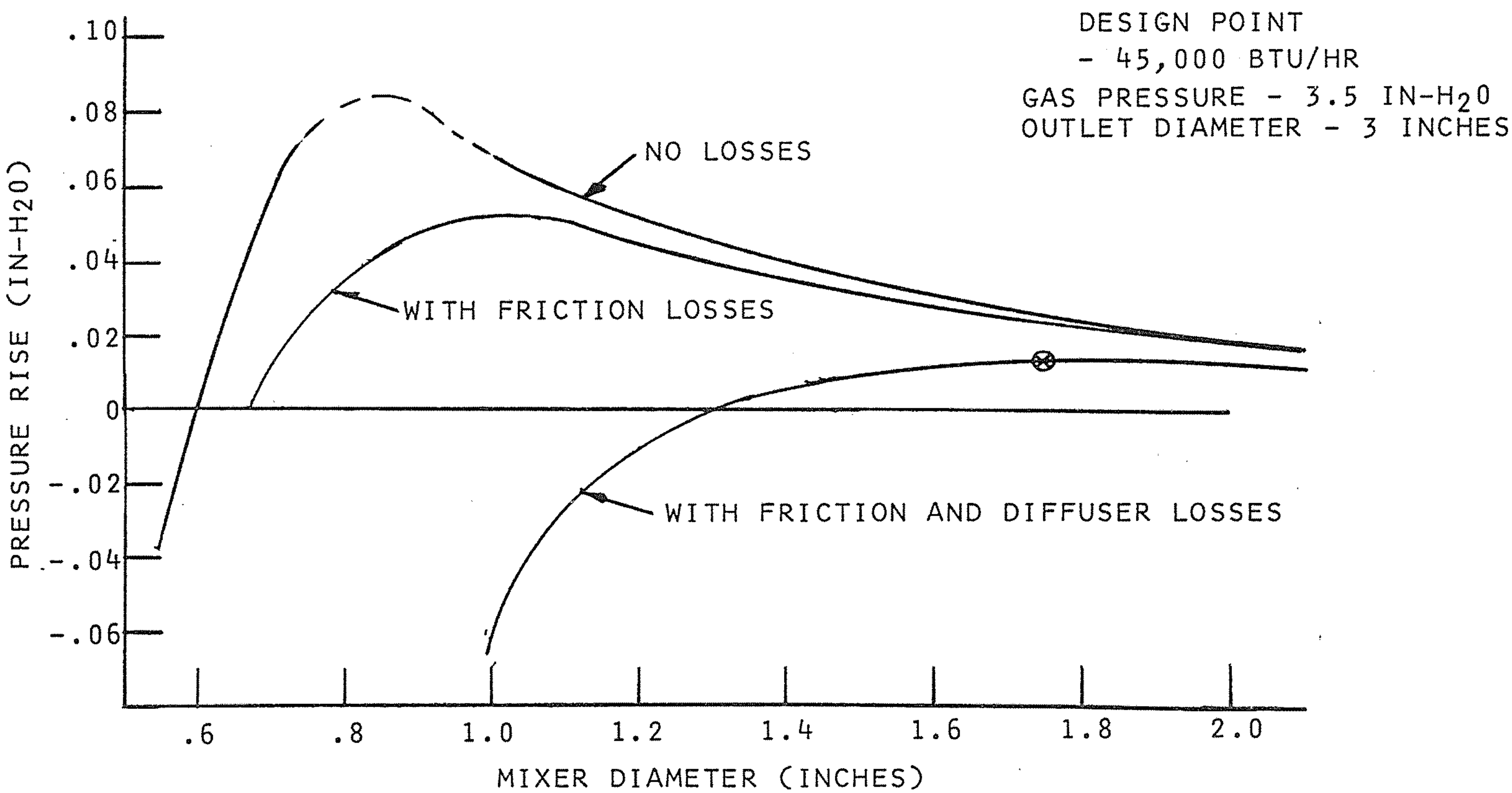


FIG. 6 GAS-AIR ASPIRATOR OPTIMIZATION (CALCULATED PERFORMANCE)

REGULATOR/ASPIRATOR PERFORMANCE

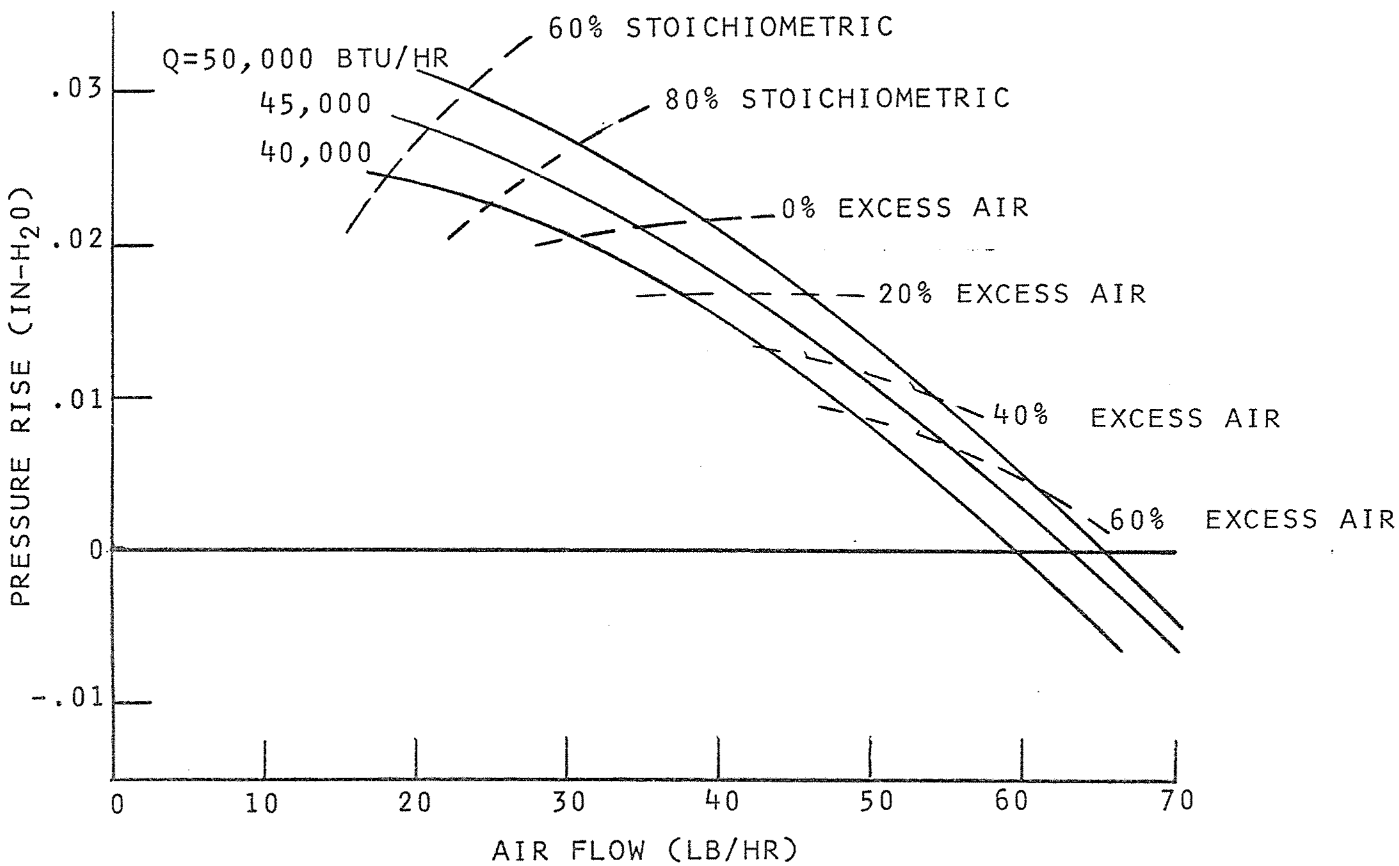


FIG. 7 CALCULATED REGULATOR/ASPIRATOR PERFORMANCE AT 4 INCHES OF WATER GAS PRESSURE

ADVANCED MECHANICAL TECHNOLOGY, INC.

The pilot flame impinges upon a flame-proving pilot thermocouple and a piezoelectric ignition electrode mounted downstream of the flameholder is used to ignite the pilot using the thermocouple as a ground. The piezoelectric ignition system is manually actuated and is used only for initial pilot burner ignition. It is, in essence, an electric match. This is employed to solve one of the major problems with sealed combustion; that is, the difficulty of obtaining access to the combustion chamber to light the pilot. Fig. 8 shows the current pilot burner configuration, including the ignition electrode.

With respect to recovery efficiency, the complexity of the processes involved makes it impractical to perform any quantitative design analysis. Rather, the design follows the qualitative precepts required by the stratified pilot concept. These are: 1) minimize mixing of the pilot products of combustion within the combustion chamber; 2) minimize convection through and mixing of outside air within the combustion chamber; and 3) attempt to promote natural convection of hotter fluid from the heat exchanger to the storage tank while minimizing gross circulation through the heat exchanger. At this stage, it is premature to determine to what extent these objectives have been met quantatively, however, the design does incorporate several features expected to enhance recovery. These are:

- Elimination of the center flue.
- Placing the pilot high in the combustion chamber.
- Use of concentric exhaust and air ducts to inhibit air flow during off-cycles.

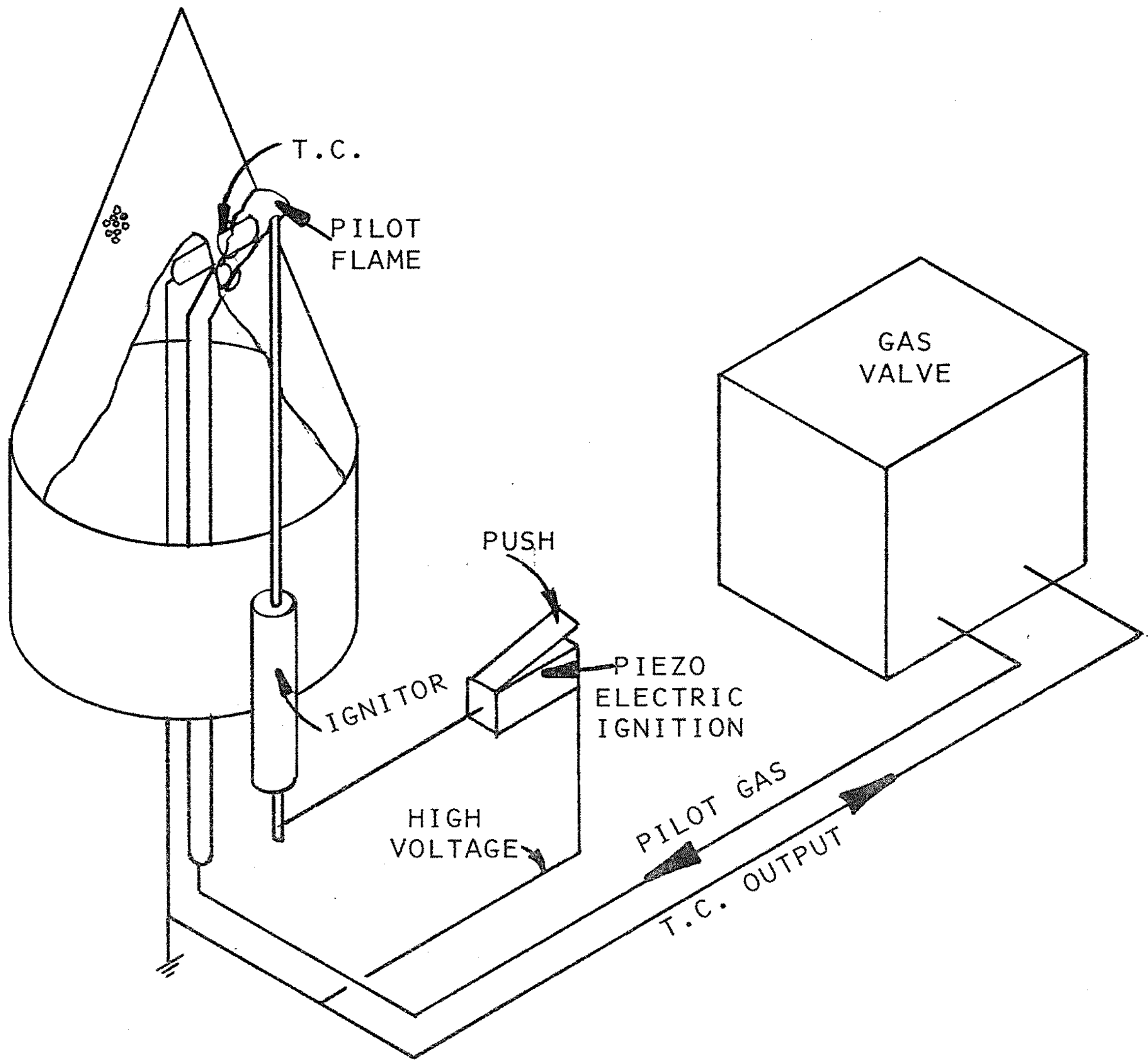


FIG. 8 PILOT IGNITION SYSTEM

ADVANCED MECHANICAL TECHNOLOGY, INC.

3.4 Sealed Combustion Stack

The basic designs that were analyzed consisted of concentric intake and exhaust passages with and without an internal draft diverter as shown in Fig. 9. In order to provide sufficient data, a vertical exhaust stack run of 45 inches was required. A 4 inch diameter exhaust duct was selected together with a 6 inch diameter air intake duct based on pressure drop requirements.

The use of an internal draft diverter and sealed combustion (Configuration C), resulted in additional stack height, requiring ducting to be supplied with the unit. Thus, the design that was selected consisted of a 45 inch vertical run, no draft diverter, and a short horizontal run to permit through-the-wall installation. Baffles are provided at the termination to keep the exhaust products from mixing with the incoming combustion air and to minimize the effects of wind. This is the case shown as Configuration A in Fig. 9. This case is the "worst condition" design. If the unit can be designed in this configuration then it can also be operated using Configuration B or C without any additional development. Actually, Configuration A and B are the most likely marketing options. Configuration A could be sold where sealed combustion venting was readily installed, or where sealed combustion was specified (mobile or manufactured homes). Configuration B could be sold to the replacement market were the existing unit vents to a chimney or there is no easy method of installing a sealed combustion system. The advantage of a concentric duct in preventing thermal syphoning are retained in the design of Configuration B by simply running the air intake duct concentric to the exhaust duct before letting the combustion air enter the burner.

3.5 Control System

The control concept needed for this water heater is shown in Fig. 10. This is the same as that required for conventional water heaters. The control consists of two gas valves in series. The first valve is a manual reset

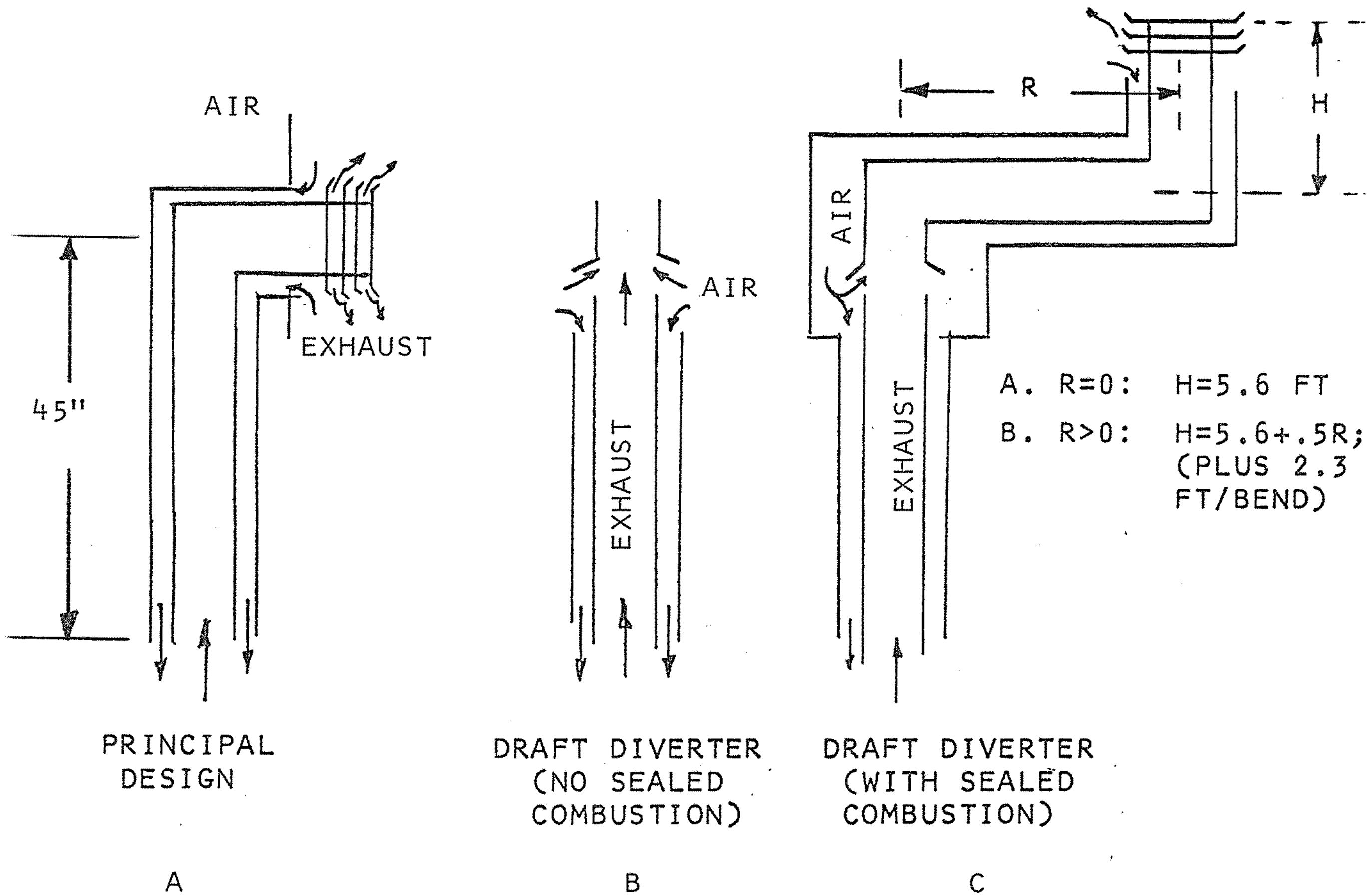


FIG. 9 STACK CONFIGURATIONS

ADVANCED MECHANICAL TECHNOLOGY, INC.

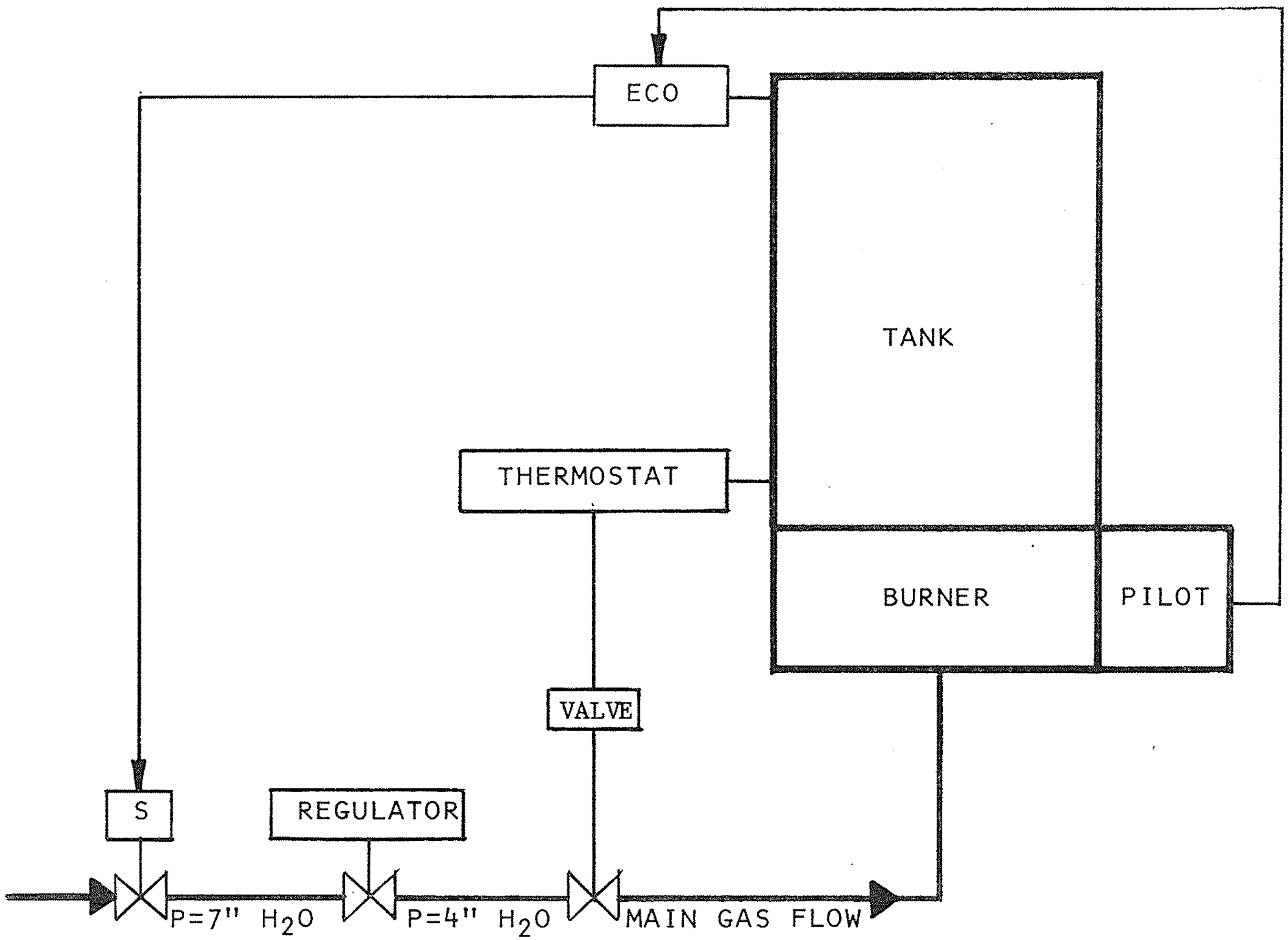


FIG. 10 WATER HEATER CONTROL

ADVANCED MECHANICAL TECHNOLOGY, INC.

type located upstream of the regulator. It is held open during operation by a solenoid coil energized by the output of a thermocouple being heated by the standing pilot. Any time the pilot is extinguished the valve closes. This first valve also has an additional safety feature which is really a high temperature shut off called an energy cut off (ECO). If the tank temperature exceeds 190°F, the first valve is closed. Anytime the first valve is closed, it cannot be reopened without manually resetting the valve.

The second valve is located downstream of the regulator and is normally controlled by an expanding/contracting bi-metallic rod which opens and closes the valve as the tank temperature rises and falls. The maximum control temperature is 160°F and the typical control band is 20°F. The regulator is built into the control valve with an output pressure of 4 inches of water for a regulator inlet pressure of 7 inches of water. This is at a nominal firing rate of 40,000 Btu/hr using natural gas. The initial development work will be done with this type control, using a Unitrol series water heater control made by Robertshaw Controls. As the project progresses a different control will be used because of packaging constraints required by Amtrol. The control vendor will provide a control with a remote bulb mounted on a flexible tube rather than a fixed solid rod. This will be done by using an expanding liquid rather than solid to operate the second valve. Other than this, the control functions will be the same. The control system is not expected to require significant effort in this development phase.

4. SYSTEM PERFORMANCE

There are two major concerns regarding the performance characteristics of the water heater system. The first is the performance of the combination of components and the second is the overall service efficiency of the unit.

4.1 Air Flow Characteristics

Calculated air flow characteristics for the system are shown in Fig. 11. The top curve shows the system pressure drop versus flow characteristic without stack draft (i.e., prior to combustion) and the lower curve shows the system curve with a stack draft at 300°F. Superimposed on these two curves is the pressure drop/flow characteristic of the aspirator (dashed line) which shows that at start-up a 15% excess air rate is obtained, and after start-up, a steady-state rate of 43% excess air is attained. The mixture can be easily ignited at start-up and 43% excess air at 45,000 Btu/hr is a good operating condition.

4.2 Service Efficiency

The water heater service efficiency can now be calculated for the design values used in the preceeding sections using the following equation:

$$E_s = \frac{G(T_w - T_o)C_g}{Q(t_m + t') + Q_p(24 - t_m - t') + EXF}$$

Where E_s - Service Efficiency (%)

G - Daily Hot Water Usage - 75 Gals/Day

T_w - Water Outlet Temperature - 150°F

T_o - Water Inlet Temperature - 60°F

C_g - Gallon Based Specified Heat - 8.25 Btu/Gal-°F

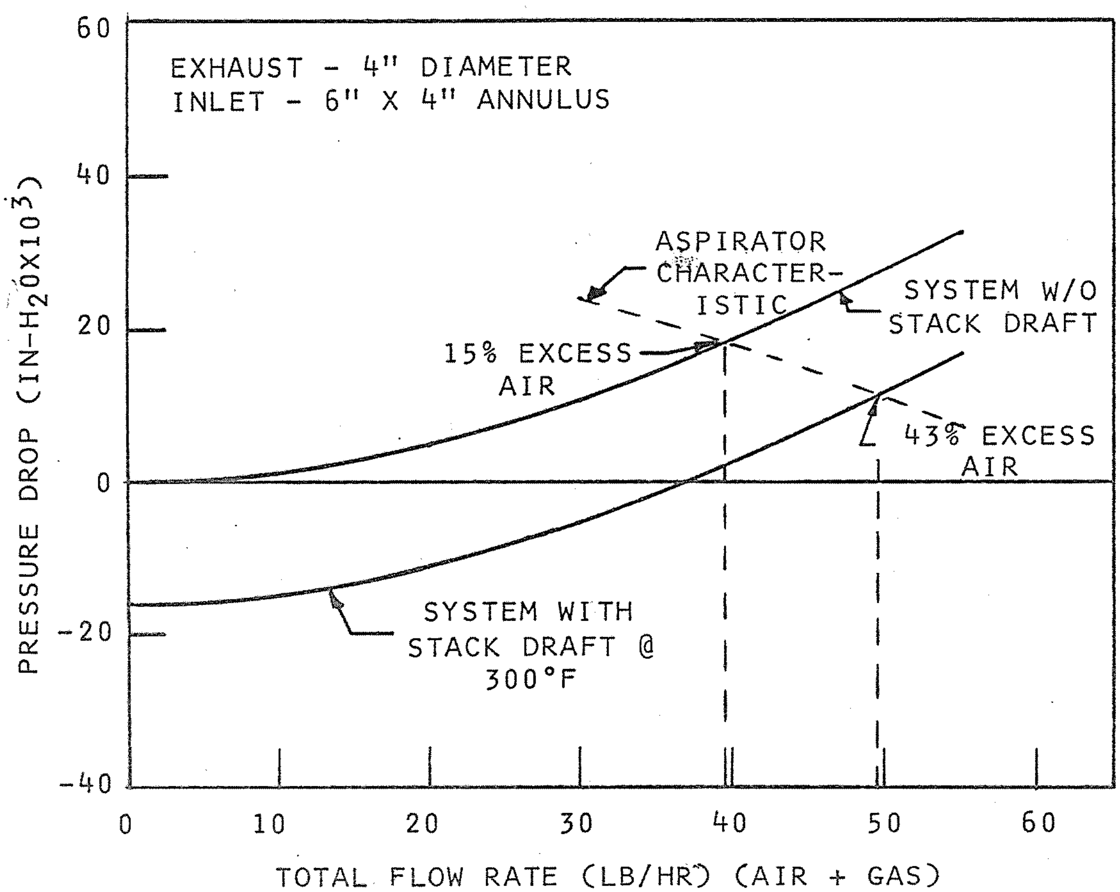


FIG. 11 SYSTEM AIR FLOW CHARACTERISTICS

$\dot{Q}$ - Burner Firing Rate - 45,000 Btu/Hr

$\dot{Q}_p$ - Pilot Firing Rate - 300 Btu/Hr

t_m - Main Burner on Time for Useful Heating - Hrs/Day

t' - Main Burner on Time to Makeup Heat Losses - Hrs/Day

EXF - Daily Exfiltration Loss - Btu/Day

This equation simply states that the service efficiency is equal to the daily useful water heating divided by the sum of the daily gas energy consumed by the main burner, the pilot and that attributed to exfiltration. The main burner on time for useful heating is:

$$t_m = \frac{G(T_w - T_o)C_g}{(E_r/100)\,\dot{Q}}$$

Where E_r - main burner energy recovery (%)

In order to obtain t', another equation is required which relates t' to the tank and fitting losses.

$$\dot{Q}_{TF}(24-t_m) = \dot{Q}(E_r/100)t' + \dot{Q}_p(E_{rp}/100)(24-t_m t')$$

Where $\dot{Q}_{TF}$ - Tank and Fitting Losses - Btu/Hr

E_{rp} - Pilot Energy Recovery (%)

This equation states that daily tank and fitting losses during standby are equal to the pilot energy recovered plus the burner energy input during standby. Rearranging the preceeding equation, t' can now be obtained:

$$t' = \frac{[\dot{Q}_{TF} - \dot{Q}_p(E_{rp}/100)]\ [24-t_m]}{\dot{Q}(E_r/100) - \dot{Q}_p(E_{rp}/100)}$$

The service efficiency can now be calculated using the design values. Table 4 shows the service efficiency for various performance options. Sealed combustion was assumed for all the computations, so the exfiltration term (EXF) was zero.

The first column of Table 4 shows a target service efficiency of 72.5% for the design values. The pilot recovery for this case was assumed equal to the main burner recovery. The last three columns of Table 4 shows the minimum acceptable component performance values which would still meet the project goal of a 70% service efficiency. As previously mentioned, all of the results assumed no exfiltration.

TABLE 4

SERVICE EFFICIENCY - SENSITIVITY ANALYSIS

Minimum Acceptable Performance	Target	Tank and Fittings	Burner/Heat Exchanger	Pilot
Tank and Fitting Losses (Btu/Hr)	300	390	300	300
Burner/Heat Exchanger Stack Efficiency (%)	84	84	80.8	84
Pilot Recovery Efficiency (%)	81.3	81.3	81.3	47.1
Service Efficiency	72.5%	70%	70%	70%

5. REFERENCES

1. "Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", Concept and Market Evaluation, Task 2 Report; AMTI, October 6, 1978.

2. "American National Standard for Gas Water Heaters", Vol. I, ANSI Z21.10. 1-1975, American Gas Association.

3. "Study of Energy-Saving Options for Refrigerators and Water Heaters", Vol. 2: Water Heaters; Arthur D. Little, Inc., May 1977.

4. "Program Plan for Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", AMTI, April 21, 1978.

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

RESEARCH AND DEVELOPMENT OF A HIGH EFFICIENCY GAS-FIRED WATER HEATER

PROTOTYPE WATER HEATER DEVELOPMENT

TASK 3.2 REPORT

January 1980

Prepared By:

Advanced Mechanical Technology, Inc.
141 California Street
Newton, Massachusetts 02158

Prepared under Subcontract 7381 for the

Oak Ridge National Laboratory
Oak Ridge, TN 37830
Operated By
Union Carbide Corporation
For The
U.S. Department of Energy
Contract No. W-7405-eng-26

ADVANCED MECHANICAL TECHNOLOGY, INC.

Table of Contents

List of Figures

List of Figures (con't.)

List of Tables

1. Introduction

This report describes the 13-month effort to develop a high efficiency gas-fired water heater. The project began with the development of individual components, with heavy emphasis on the development of the combustion system. The components were then combined to make up a pre-prototype water heater assembly, and a prototype water heater assembly. The pre-prototype tank had external insulation and a volume of 50 gallons, while the prototype tank had an internal plastic liner and internal insulation resulting in a volume of 40 gallons.

In this report the test facility that was used to test both the components and the water heater assemblies is described, together with the procedures used for testing the unit. These include tests for both performance and operating characteristics. Results from both component and system tests are described including the developmental work performed in order to attain the prototype configuration.

At the end of this report, the significance of the test results is discussed compared with project goals.

2. Water Heater Test Facility and Procedures

2.1 Test Facility

The facility for conducting all performance tests is shown in Figure 1. This figure illustrates the various components comprising the flow loop and associated instrumentation. Table 1 summarizes the instrumentation, including specific detailed information. The facility is capable of being run in one of three modes. It can be run as an open loop for "steady state" flow tests; it can be used for "heated volume" recovery tests; and it can be run in a standby mode for evaluating off-cycle losses.

Hot and cold inlet water were mixed to control inlet temperature to the water heater. All water flowrates were measured using three standard rotameters with ranges of 0-0.267,1.12 and 4.8 gal/min. For gravimetric tests, a low capacity (20 kg) and a high capacity (1000 lbs) balance-type scales were used. Water flowed through the water heater and was discharged. Prior to initiation of the testing, all the rotameters were calibrated using the timed-fill of a weigh tank.

Water heater tank volumes were determined by taking several weighings of the empty tank and the tank filled with water. All water pressures were measured with 0-100 psig Bourdon-tube pressure gages. Natural gas flow was measured using a standard displacement-type cumulative flow meter with resolution to 0.05 scf. The gas meter was checked at the Boston Gas Company calibration facility and found to be within it specification. All gas pressures were measured with Magnehelic gages calibrated in inches of water.

Copper-constantan (ANSI Type T) thermocouples were used to measure temperature. Where possible, commercial sheathed and grounded thermocouples were used. In all other cases thermocouples were formed by inert gas welding of 30 ga. wire. A Doric Model 415A-F digital temperature indicator was used in conjunction with a rotary thermocouple switch to measure individual temperatures during testing. This instrument was equipped with an internal reference junction and offered ±.5°F accuracy. During standby loss testing,

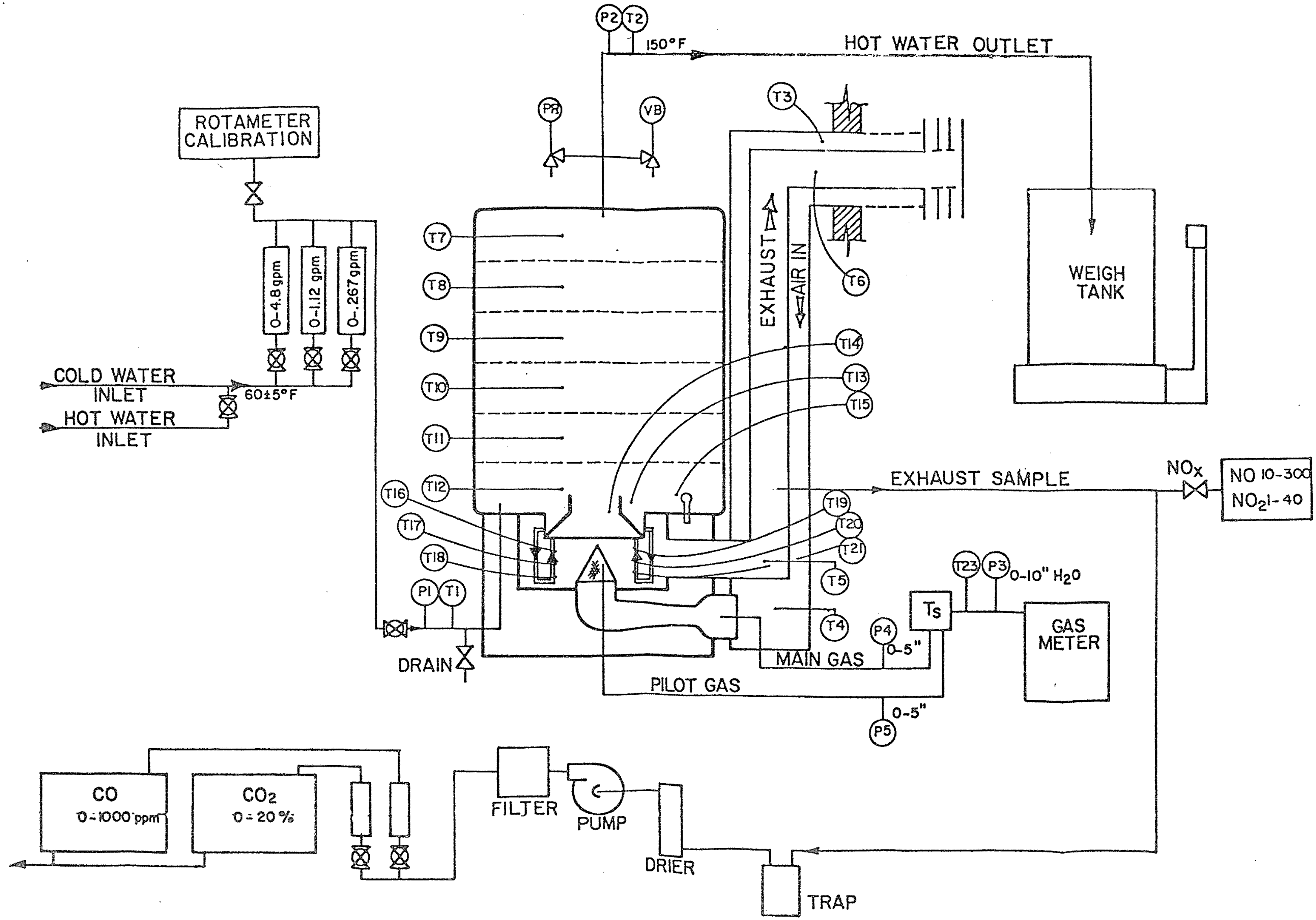


FIG. 1 GAS-FIRED WATER HEATER TEST LOOP SCHEMATIC

TABLE 1 Test Instrumentation

Instrument	Manufacturer	Model No.	Range	Resolution	Accuracy
Temperature					
Digital Temp. Indicator	Doric	415A	0-700°F	.1°F	.5°F
Temperature Recorder	Leeds & Northrup	250	0-200°C	.5°C	1°C
Pressure					
Water Pressure Gage	Ashcroft	-	0-60 psig	1 psig	-
Gas Pressure Gage	Helicoid	-	0-5 IN. W.C.	.05 IN W.C.	.1 IN W.C.
Flow					
Water Flowmeters	Fischer Porter	10A3555	0-4.8 GPM	1% FS	1% FS*
	Fischer Porter	10A3555	0-1.12 GPM	1% FS	1% FS*
Gas Flowmeter	Singer	AL-175	-	.05 FT^3	±2% of 1CF
Emissions					
CO_2 Analyzer	Beckman	864-23-3-6	0-20% 0-5%	1% FS	1% FS
CO Analyzer	Beckman	865-14-3-6	0-1000 ppm 0-100 ppm	1% FS	1% FS
NO_X Analyzer	Matheson/ Kitzgawa	8041	0-350 ppm	1 PPM	10 PPM*

* Calibrated

a 24 point chart recorder was used. This recorder provided a 0-200°C range with ±1°C accuracy.

Since the plastic-lined prototype tank did not allow penetration from the side for mounting standard thermocouples, a multiple junction thermocouple probe was constructed and inserted from a fitting at the top of the tank. The thermocouple probe was constructed of sections such as the one shown in Figure 2. All copper construction was employed in the area of the bead to provide a uniform temperature distribution. Six of these sections and several lengths of stainless steel tubing were joined together by compression fittings to locate the thermocouples at the desired tank level. The type 304 stainless steel provided rigidity and reduced axial conduction in the probe. This probe was calibrated in a flow rig pictured in Figure 3. With both hot and cold water the probe yielded consistent and repeatable temperature indication.

The lower part of Figure 1 shows the sample handling and measuring system used in analyzing the products of combustion. A continuous sample of combustion products was drawn from the exhaust flue by a diaphragm pump. The sample first passed through a cold trap to remove liquid water and then through a dessicant chamber to remove the remaining water. Downstream of the pump, the sample passed through a filter and then entered the CO and CO_2 analyzers. Finally, the sample was discharged from the analyzers into the room. Carbon dioxide analysis was accomplished using a Beckman Model 864 Infrared Analyzer with ranges of 0-5 and 0-20 percent CO_2. Carbon monoxide content was determined using a Beckman Model 865 Infrared Analyzer with ranges of 0-100 and 0-1000 ppm CO.

Nitorgen oxides content was analyzed in a different fashion. Since NO_2 is soluble in water, an error in measurement occurred if a sample was drawn through the cold trap which was partially filled with water. Consequently, samples for NO_X analysis were drawn.

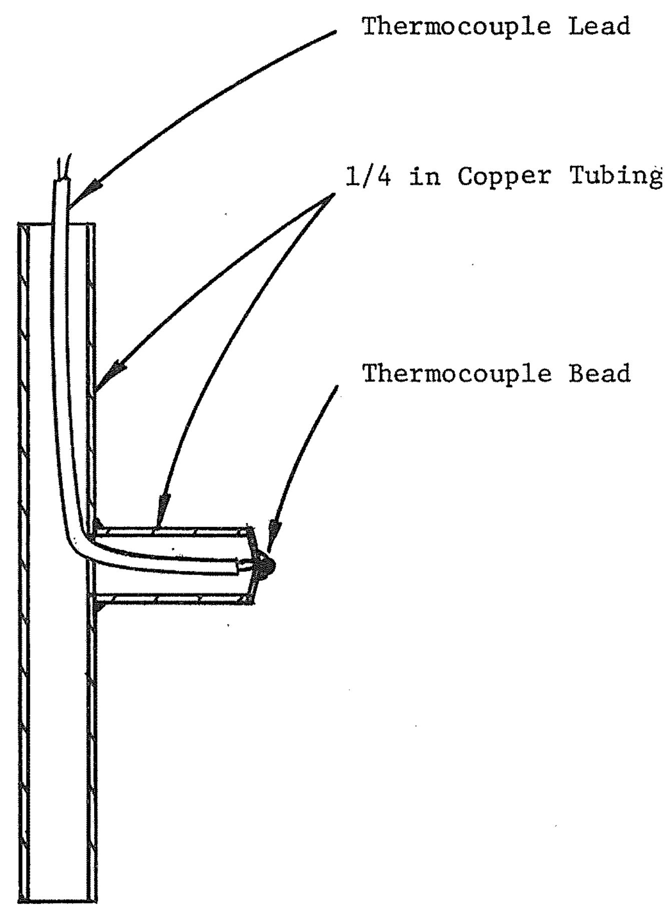


Figure 2: Detail of a Section of Thermocouple Probe

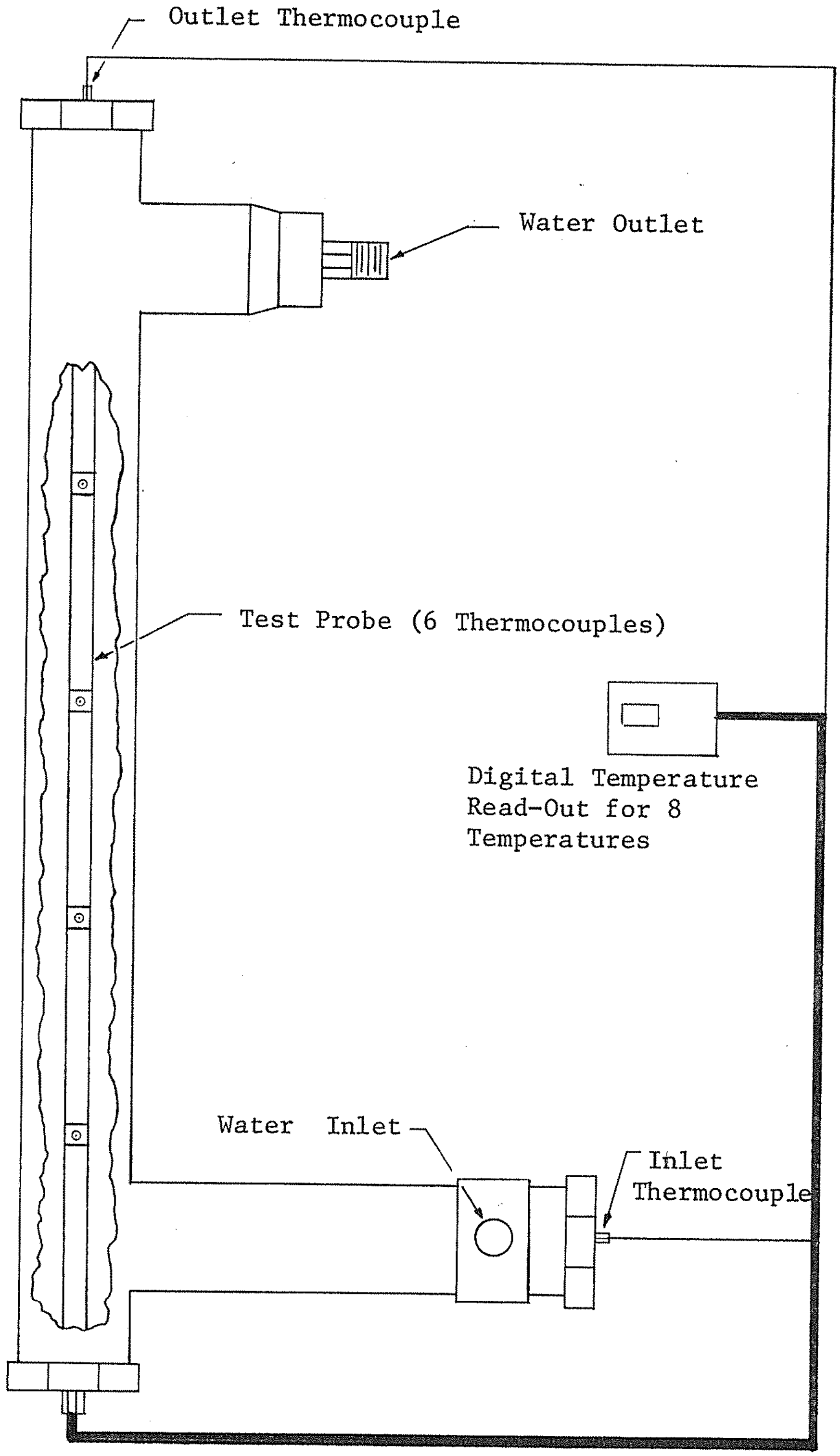


Figure 3: Thermocouple Probe Calibration Apparatus

directly from the exhaust flue with a hand pump into a plastic sample bag. Analysis was then performed with a Matheson Model 8041 NO_X sampling system in conjunction with NO/NO_2 chemical reagent tubes.

In all cases, calibration of analysis equipment was accomplished using "standard" gases. In the case of CO_2, a 9.8% mixture in nitrogen was used. For CO, a 250 ppm in air sample was used. For a zero point purified N_2 was used. The samples were either passed directly through the sample system or were placed into a sampling bag and then pumped through the analysis equipment. The CO and CO_2 analyzers were calibrated at least weekly during test periods and more frequently if it was necessary for a particular test.

Since the measured levels of NO and NO_2 were so minute ($\leq$ 20 ppm) it was essential to establish a region of confidence in the chemical reagent method. By repeated trials with the reagent tubes and calibration gases it appears that measurements within 10 ppm could be made. So, a confidence band of ±10 ppm should be used in interpreting any NO_X data.

2.2 Water Heater Testing Procedures

This section will briefly describe the test procedures used to obtain water heater performance in the area of recovery efficiency, standby losses, and capacity or usage. A more detailed description of the test procedures including data sheets and required calculations is given in the Appendix.

2.2.1 Recovery Efficiency Test Procedures

The bulk of the recovery efficiency data was taken by heating a constant volume of water through a 90°F temperature rise. This was determined using a probe capable of measuring the initial and final water temperature in six equal volume tank locations. The ratio of the heat absorbed by the water divided by the measured fuel consumed is the recovery efficiency. This test is common both to ANSI Z21.10-1975[1] and the D.O.E.[2] test procedure.

A second procedure using a steady-state flow test was attempted several times. Largely inconsistent and invalid results were obtained. Several factors were responsible for these results. First, the success of such a test depends on the achievement of truly steady-state conditions in the tank and system. Such long time constants are involved, if a storage volume is used, that achieving this condition was practically impossible. Second, maintaining a flowrate constant to the accuracy necessary for consistent results was very difficult. Third, maintaining a constant inlet temperature by mixing hot and cold water was also difficult since the hot water supply came from another standard water heater.

Since the constant volume recovery test worked the best, this method was selected for the testing.

2.2.2 Standby Loss Test Procedure

Two types of tests were performed to obtain water heater loss data. The first of these were cooldown tests which helped analyze component performance. The second was the standby loss determined with the water heater assembled and the burner operating off the thermostat.

In the cooldown test, the storage tank was filled with water at a controlled temperature and the tank was allowed to cool down over a period of time. Tank and room temperatures were measured at the beginning and end of the test period. By varying the length of cooldown time and the initial tank water temperature, a wide range of data was obtained defining heat loss as a function temperature difference between the tank and the room. These tests were run under several sets of conditions. In some cases only the tank was used without the heat exchanger or other fittings. This provided "tank only" losses. Other tests were performed with the tank, heat exchanger, and fittings attached. This yielded tank and fitting losses. This latter test was performed with and without pilot input, allowing determination of pilot energy recovery.

The second type of standby loss test conformed closely to the D.O.E. test procedure.(2) Water heater operation was initiated and when operating temperatures were reached, a chart recorder was turned on to obtain tank and room temperature histories during a 48 hour test period during which the water heater operated in the "standby" (no water draw) mode.

The temperature recordings were analyzed at 15 minute intervals and the average tank and air temperatures were determined. These were used in combination with the gas consumed during this test to determine standby loss (S-%/HR).

2.2.3 Capacity Tests

Two different types of capacity tests were completed. They were:

1. First Hour Draw Capacity Test
2. Test of the ability of the unit to deliver:
    a. 2 gal/min for 10 min
    b. 40 gal in 1 hr
    c. 80 gal in 4 hr
    d. Maintain a delivery temperature of 150°F in all of the above tests.

Test 1 above was intended to define the delivery capacity of the unit. The procedure given below follows as closely as possible the D.O.E. test specifications[(2)]

Test (2a) above was accomplished by establishing a flow of 2 gal/min at 150°±5°F and continuing to draw water for 10 min while recording outlet temperature. Tests (b) and (c) were accomplished by establishing a flow of .67 gal/min at 150°±5°F and continuing to draw at that rate for two hours. This resulted in an accrued volume of 40 gal in one hour and 80 gal in less than four hours.

3. Component Development and Testing

The basic components of the water heater are the aspirator, the burner or flameholder, pilot, tank, heat exchanger, the exhaust system, including the stack and the control system including the flame safety and ignitor. Figure 4 shows the component parts of the water heater while the burner, pilot, and control system are shown in more detail in Figure 5.

A brief description of water heater operation is described here to provide an understanding of the relationship between components. Water heater operation is initiated when the thermostat senses a temperature below the set point. This causes the gas valve to open admitting gas to the aspirator. The gas entrains air which mixes with the gas in the aspirator and is ignited at the surface of the burner screen by the pilot. The hot combustion products pass over the heat exchanger surfaces heating the water and creating natural circulation of the water through the heat exchanger and back into the tank. When the tank reaches the thermostat cut-out setting, the gas valve is closed. Exhaust gases are collected in a shroud which surrounds the heat exchanger and directs the exhaust into the stack.

Flame safety is accomplished by having the pilot heat a thermocouple. The thermocouple output keeps a solenoid valve open, allowing gas to enter the main gas valve which is controlled by the thermostat. If the pilot extinguishes, the solenoid valve closes and water heater operation ceases. The pilot is ignited using a piezoelectric ignition system which produces a high voltage spark between an electrode and the thermocouple sheath.

3.1 Aspirator Development

The main development goal set for the aspirator was to entrain sufficient air for a firing rate of about 40,000 BTU/HR using the jet formed by the gas at normal pressure regulator setting. The only additional assist was the stack draft produced in a 42 inch stack at an exhaust temperature of 300°F. A secondary goal was that the gas/air mixture delivered to the burner be well mixed so that complete combustion and low carbon monoxide emissions could be attained. During the course of the project, low oxides of nitrogen emissions were added to the goal.

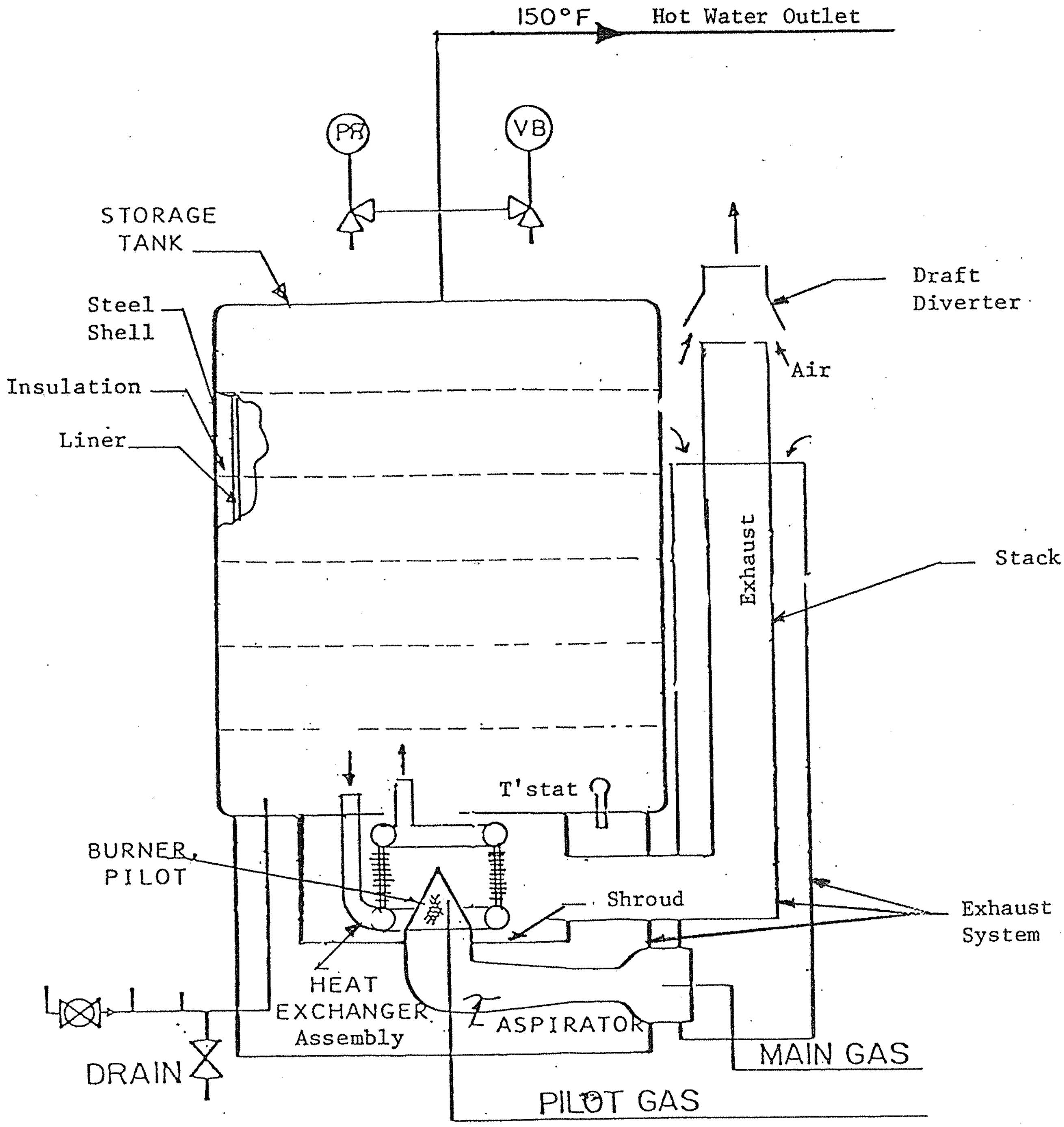


FIGURE 4. SCHEMATIC OF WATER HEATER AND COMPONENTS

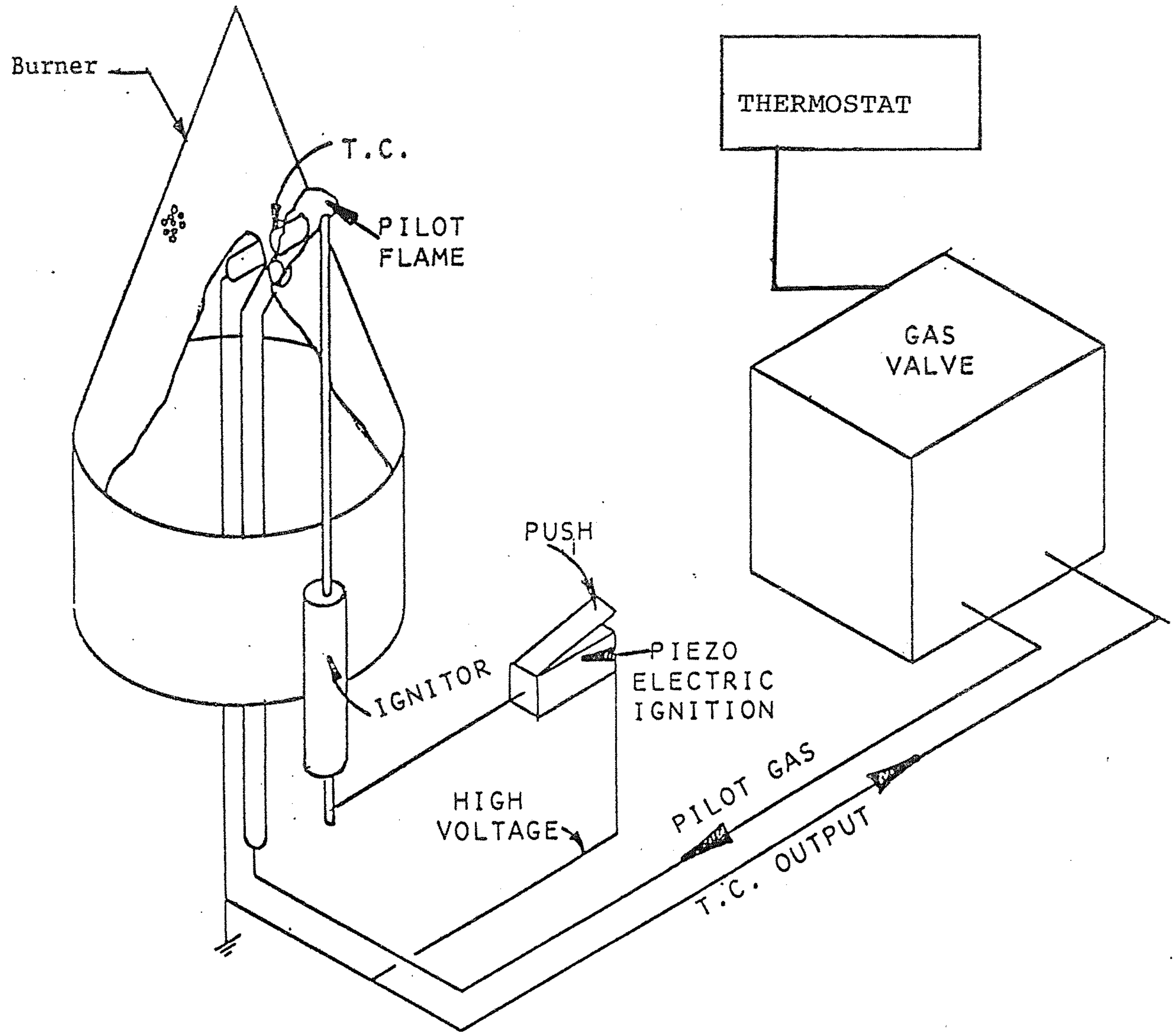
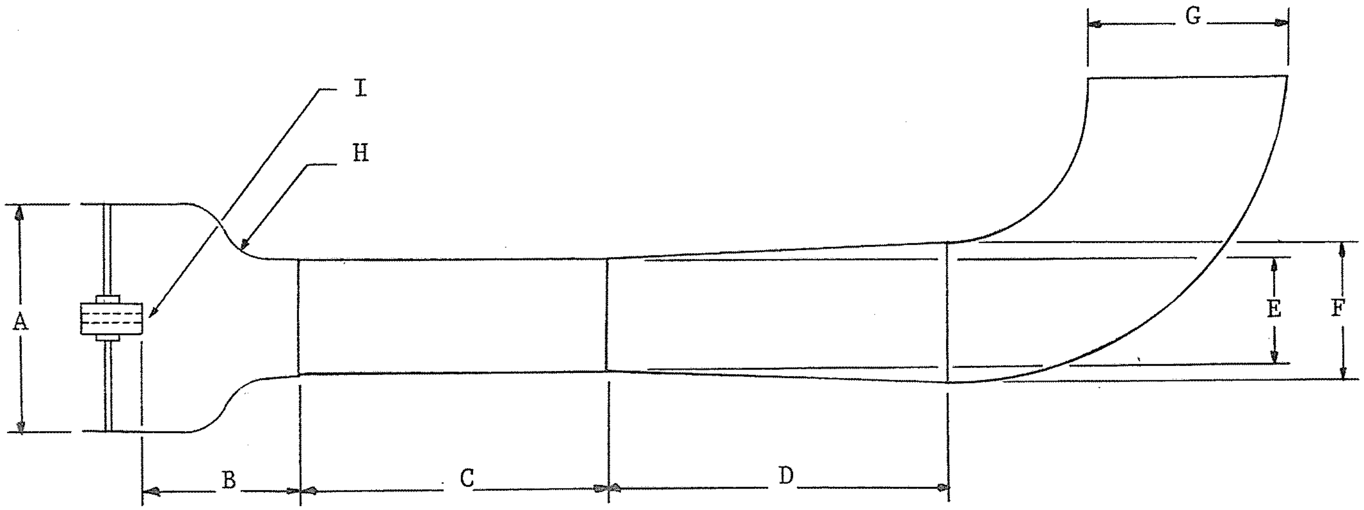


FIGURE 5. Pilot/Burner Configuration

Figure 6 presents the various aspirator configurations tested. Initial calculations indicated that high system pressure drops would not permit 100% air aspiration. The first configuration tested was that shown in Figure 7(a). This was done to provide a low impedance path by which stack draft would directly draw room air around the aspirator. This configuration was tested at several firing rates from 30,000 BTU/HR to 45,000 BTU/HR, yielding unstable and inconsistent results. It employed a commercially available aspirator illustrated in Figure 6(a). Since the configuration was extremely draft-dependent, it was necessary to begin with either hot water in the tank or an extremely tall stack. After several minutes of very lean burning, the airflow would begin to decrease. Soon loud acoustic oscillations would occur and operation would end in flash-back. Though this arrangement occasionally displayed acceptable operation, its instabilities and high noise levels demanded investigations of other configurations.

The next aspirator arrangement involved placing the burner screen directly on the outlet of the same aspirator as shown in Figure 7(b). This arrangement involved using the aspirator to drive 100% of combustion-air without the annular flow path of Figure 7(a). Initially this arrangement was bench tested with several screen geometries (see "Burner Screen" section for detailed results), resulting in the selection of a 60° cylindrical cone with 39% open area. This aspirator and burner combination produced a firing rate of up to 33,000 BTU/HR with 80% excess air (maximum pumping power) and 20 ppm CO at 40% excess air (design condition) as indicated in Table 2. This arrangement proved satisfactory for all firing rates less than 35,000 BTU/HR. However, at low excess air an audible acoustic oscillation of ~ 300 Hz occasionally occurred. Though this noise was unacceptably loud, it did not seem to affect combustion. Also, this aspirator geometry would not produce satisfactory air aspiration at firing rates higher than 35,000 BTU/HR.

The next configuration tested used a commercially-available, cast-iron aspirator with dimensions presented in Figure 6(b). At firing rates of 42,000 and 33,000 BTU/HR this aspirator would not sustain stable operation as shown in Table 2. Audible oscillations would initiate upon start-up and continue, with no operating point having long-term stability.



CASE	A	B	C	D	E	F	G	H	I
a	3.3	1.7	3.7	5.7	1.2	2.3+	3.0	>1	*
b	3.9	2.25	0	10.0	1.5	2.9+	3.0	>1	*
c	4.0	2.25	3.0	6.5	1.75	2.5+	3.0	>1	*
d	4.0	2.25	4.0	11.5	1.4	2.5+	3.0	>1	*
e	4.0	2.25	5.0	6	1.6	2.5	3.0	>1	*
f	4.0	2.25	5.0	11.5	1.6	2.5	3.0	>1	*

* Variable Orifice Diameter
\+ Diffuser Discharged Into a 3" x 3" Elbow

Figure 6: Aspirator Geometries

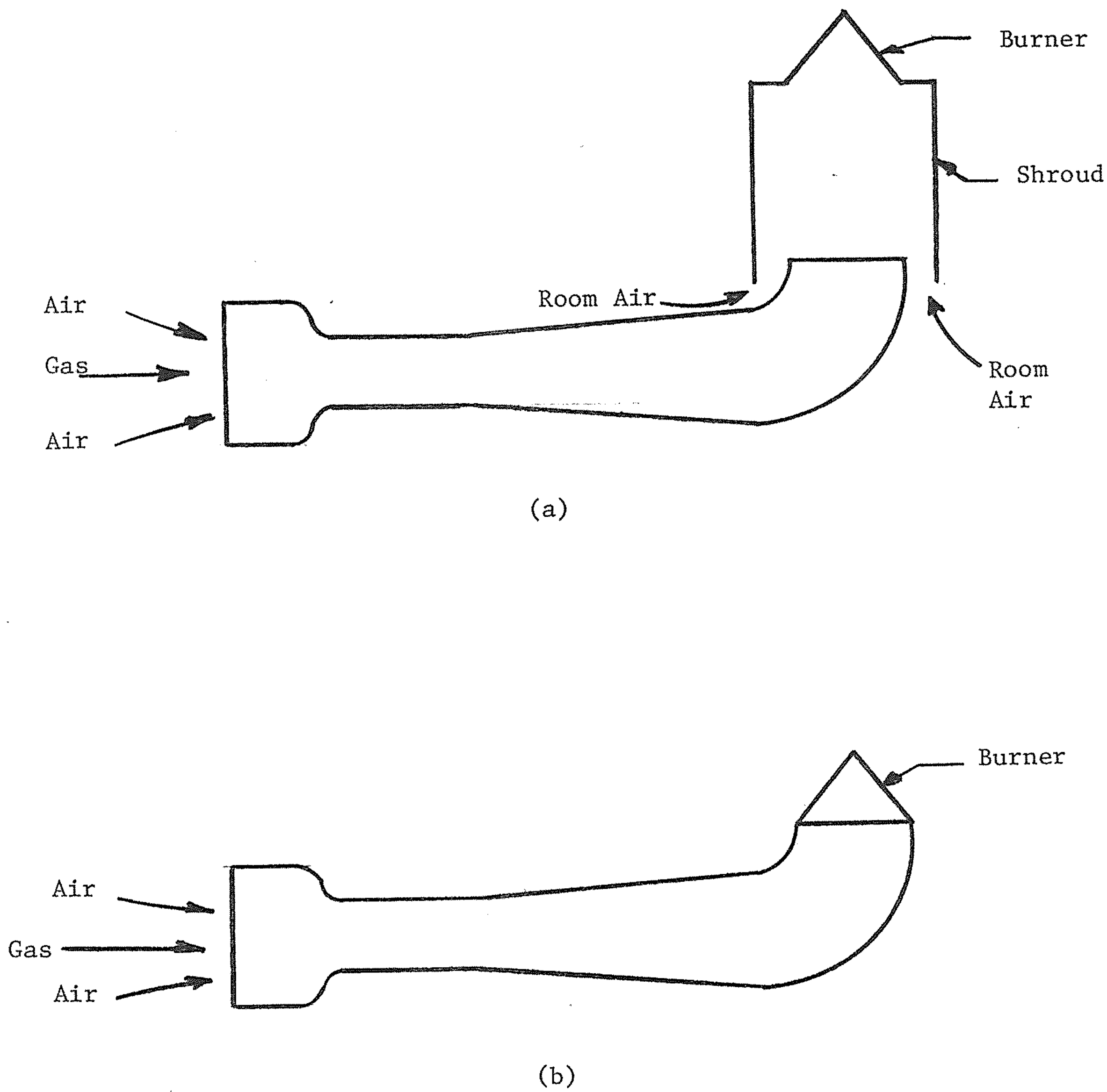


Figure 7: Burner/Aspirator Interface Configurations

Table 2. Summary of Aspirator Performance

ASPIRATOR REFERENCE	FIRING RATE[1] (Btu/hr)	MAX. ATTAINED EXCESS AIR (%)	CO EMISSIONS AT 40% EXCESS AIR (PPM)	COMBUSTION CHARACTERISTICS
Fig. 6(a)	33000	80	20	-Stable operation; noisy below 30% excess air
	42600	15	>1000	-Flameholder overheats
Fig. 6(b)	33000	-[2]	-[2]	-[2]
	42600	-[2]	-[2]	-[2]
Fig. 6(c)	31900	80	-	-Not as stable as 6(a)
	42600	-[2]	-[2]	-[2]
Fig. 6(d)	45300	50	50	-Stable, low emissions, noisy below 35% excess air
Fig. 6(e)	42000	100	29	-Excellent stability, low emissions, noisy below 35% excess air
Fig. 6(f)	42000	98	29	-Same as 6(e)

(1) At 4.3" H_2O Gas Regulator Output Press.

(2) Not Operable At These Conditions

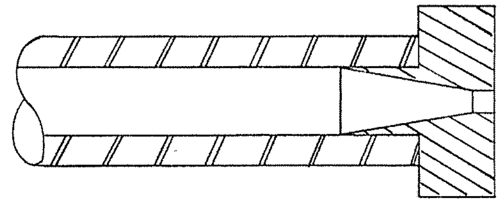
The aspirator shown in Figure 6(c) was then constructed. The design of this unit was based on a flow analysis to produce optimum pressure recovery at design conditions. However, this unit did not perform at firing rates higher than 32,000. Following this unit, the aspirator shown in Figure 6(a) was scaled-up experimentally until that shown in Figure 6(d) was obtained. As shown in Table 2. this was an improvement over the previous units but the excess air levels attained with this unit were still lower than desired.

In an attempt to improve performance, the effect of different gas nozzles and the nozzle-to-throat spacing (dimension B in Figure 6) was investigated. Figure 8(a) shows the standard "spud type" gas orifice used normally with the aspirator. The investigation of nozzle-to-throat spacing showed that a wide range of spacings were acceptable. Minimum and maximum values were defined for acceptable operation with a range of ±.5 in of the dimensions shown in Figure 6. However, qualitative observation noted that concentricity of jet and throat and parallelism of jet and throat axes were much more sensitive parameters.

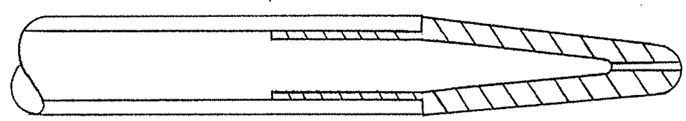
The tapered nozzle (Figure 8b) was tried to see if nozzle blockage was creating a problem. A two stage aspirator was attempted by using the nozzle shown in Figure 8(c). In order to improve the efficiency of the aspirator by improving mixing, the multi-hole orifice shown in Figure 8(d) was used. However, none of these nozzles proved better than the standard nozzle.

At this point, an extensive aspirator development program funded by Amtrol was undertaken to try and further optimize the aspirator design. This resulted in the aspirators shown in Figure 6(e) and (f) which had firing rates of 45,000 BTU/HR at 100% excess air.

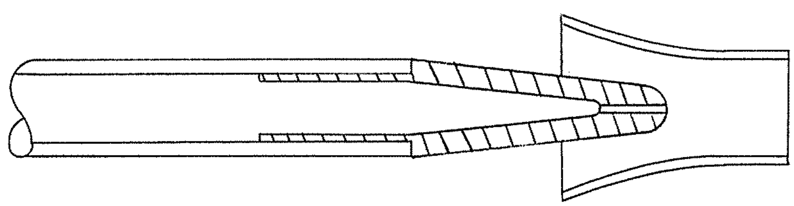
The performance of these units as shown in Table 2 (e and f) was equal when a sweep elbow (diffusing) was used at the exit of the diffuser. When a standard 3" elbow was used the performance of the aspirator shown in Figure 6(e) deteriorated. This was attributed to pressure recovery still occurring in the elbow. Because of installation problems, a diffusing elbow could not be used. Thus the aspirator shown in Figure 6(f) was chosen for installation in the prototype unit.



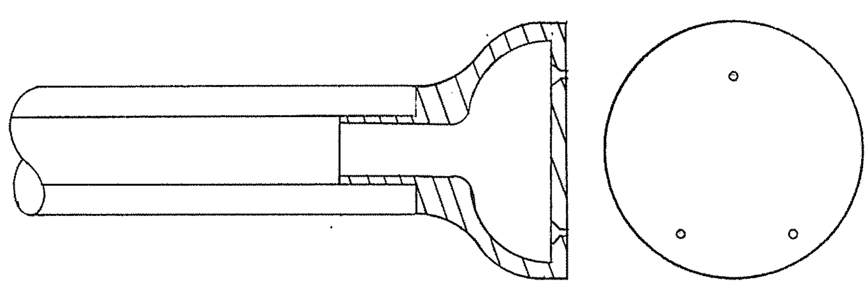
a) Standard "Spud"-type Orifice



b) Tapered Nozzle



c) Tapered Nozzle With Small Aspirator



d) Three-Holed Orifice

Figure 8: Gas Injection Configurations

During the course of this Amtrol funded study, the cause of the 300 Hz acoustic oscillation at low excess air was discovered. The mechanism for oscillatory behavior was the "Rayleigh phenomenon"(3) in which an oscillating rate of heat release was acoustically tuned to the column of air/gas mixture upstream of the burner screen. The result was that 35% excess air conditions were such that a continuing acoustic oscillation of the air column occurred. This phenomenon was verified by placing a Helmholtz resonator on the aspirator, which effectively "detuned" the air column from the oscillation and suppressed the noise. Even though it was demonstrated that noise could be suppressed using a properly constructed resonator, a superior solution was to assure that air-fuel ratio stayed above 40%, thereby eliminating the "tuned" conditions which produced acoustic oscillations.

When the prototype unit was fitted with the aspirator shown in Figure 6(f) and tested, it was found that an oscillation of magnitude sufficient to extinguish the flame existed at a frequency much lower than the 300 Hz oscillation described in this section. It was discovered that this noise occurred when the exhaust system was very tightly sealed and that it was not a function of aspirator performance. The elimination of this oscillation is described in section 3.6. In addition, the aspirator would only produce 50% excess air at 42,000 Btu/hr. This was less than the 100% excess air expected based on the test results in Table 2. This lower air flow was due to a higher system pressure drop for the prototype unit when compared to the bench test system used to obtain the results reported in Table 2. This higher pressure drop was due to differences in the heat exchangers used in the two units. The heat exchanger is shown in Figure 14 and construction details are given in Table 5. The bench test system used the heat exchanger described in Table 5(a) while the prototype used that in Table 5(b). While they should have been dimensionally similar, in brazing the assembly, the tube spacing in 5(b) decreased which increased the pressure drop resulting in a reduced prototype system flow as compared to the bench test system. In addition, the prototype heat exchanger had a higher effectiveness due to the closer tube spacing which decreased the stack temperature and consequently the stack draft. This caused a further decrease in system flow.

3.2 Flameholder (Burner) Development

Figure 9 illustrates the shapes of various burners tested. Initial work employed the cylindrical shape shown in 9(a). Though this burner dis-

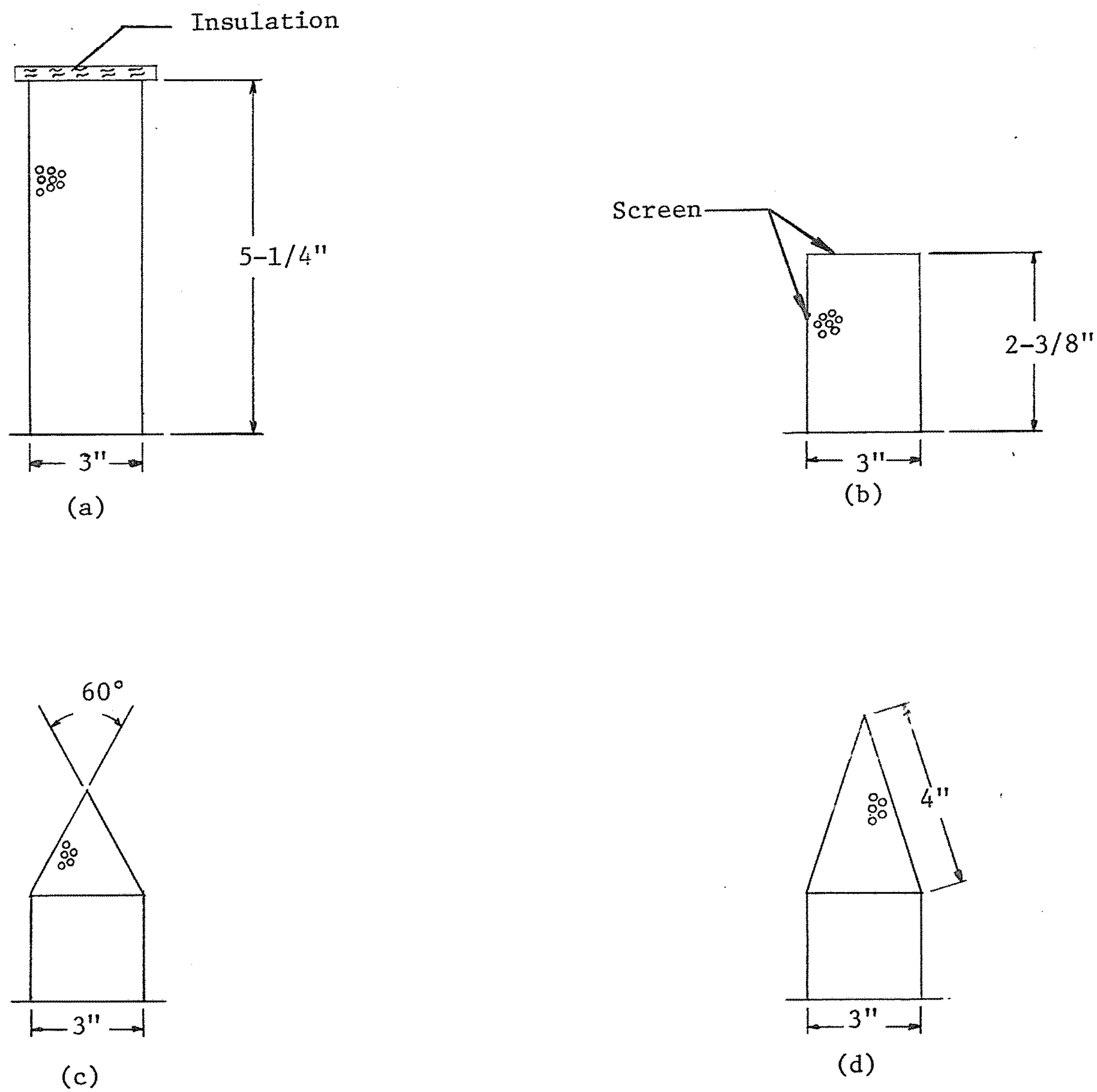


Figure 9: Flameholder Geometries

played reasonable flameholding properties, overheating of the flameholder occurred. It was suspected that the top overheated first because it was solid, and then conducted heat over the test of the flameholder. The top was insulated in order to eliminate the overheating, but the results were inconclusive. The flameholders shown in Figures 9(b and c) were also tested with unsuccessful results. All of these tests were done with the burner/aspirator configuration shown in Figure 7(a) installed in a heat exchanger. It was difficult to evaluate burners in this configuration because of the early system problems encountered with this aspirator/burner coupling configuration. For this reason, a second set of tests were performed with the configuration shown in Figure 7(b) in open air (no heat exchanger) with the burners shown in Figure 9(a to c). The short cone (Figure 9c) ran at 32,000 BTU/HR without overheating. All of the others overheated at this firing rate.

A third set of tests were performed using the apparatus pictured in Figure 10. This was done to decouple the aspirator performance from the burner. In this facility, a well-mixed air-gas mixture of known proportions could be supplied to the burner and its flameholding characteristics could be observed. Again the short cone (Figure 9c) performed best, but at firing rates greater than 32,000 BTU/HR, the flame lifted. This was corrected by increasing the cone height to that shown in Figure 9(d). The flame was still a little "lifty", but it was felt that this would be eliminated when it was installed in the heat exchanger. The flameholder temperature would be higher under these conditions and for this reason there would be less of a tendency for the flame to lift.

Finally, each cone was tested in the heat exchanger for actual system performance. In both cases, the flame appeared less "lifty" in the heat exchanger than the same air-fuel ratio case in the open-air combustion tests. In addition, the tall cone continued to show greater stability, less lift-off at higher air-fuel ratios, and lower carbon monoxide levels. Therefore, the large-cone geometry was selected for all further testing.

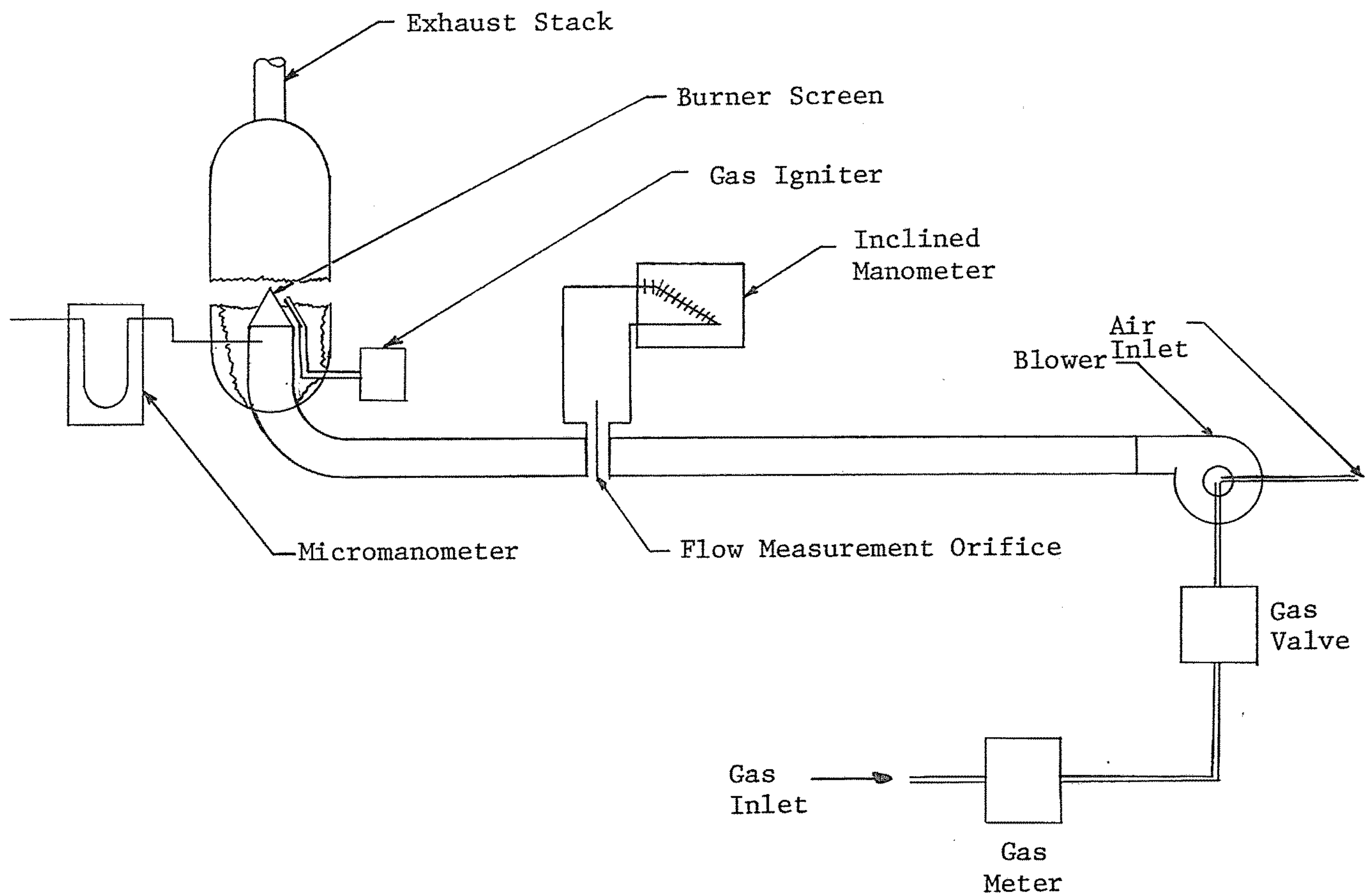


Figure 10: Forced Combustion Test Apparatus

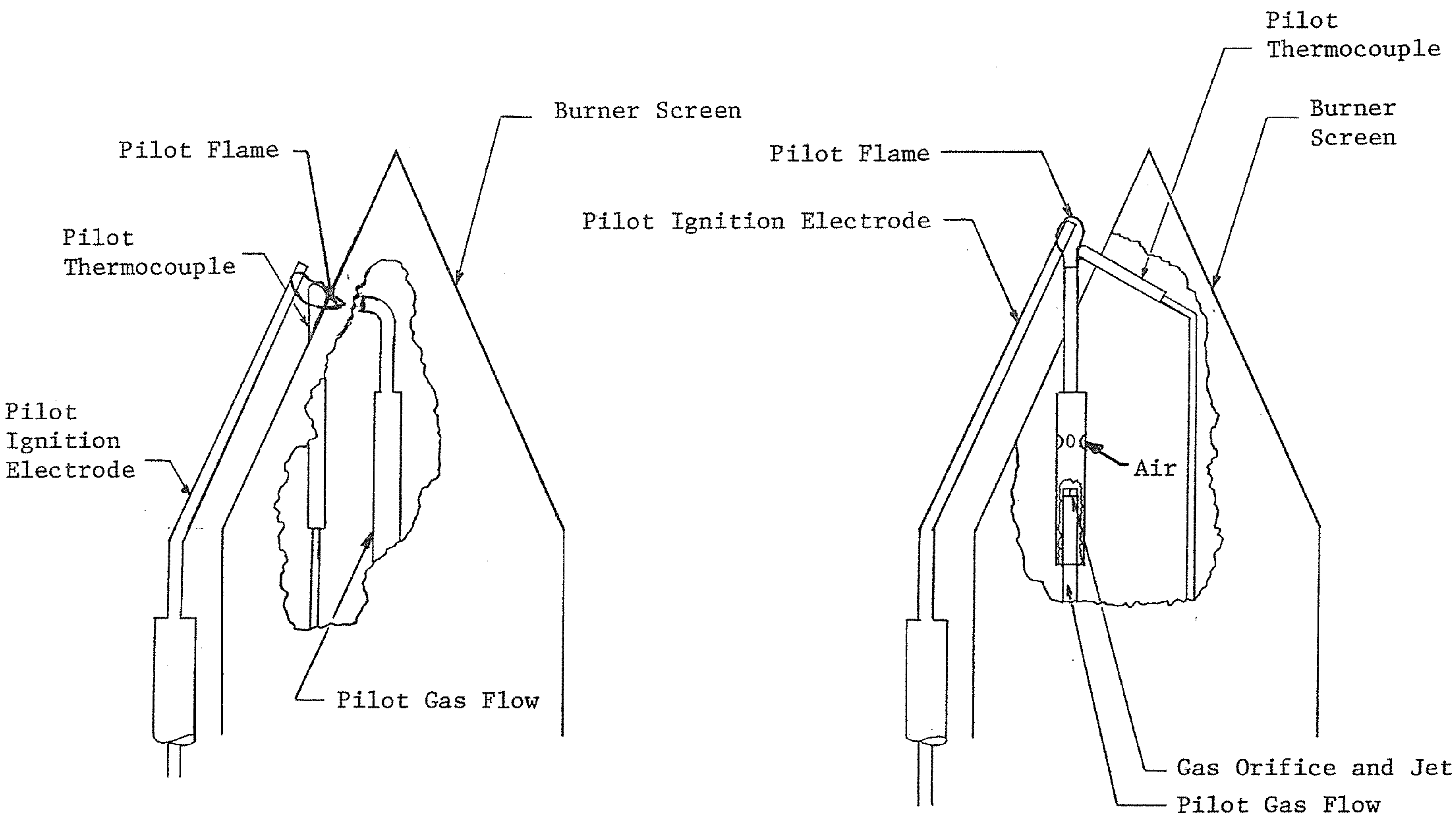
During later aspirator testing a larger cone was constructed from a slotted perforated material. The slots were arranged in a straight row pattern with 31% open area. The cone was constructed to yield the same flow area as the 39% open area large cone. This slot pattern provided a well-seated flame. The CO levels were generally lower than those at corresponding air-fuel ratios with the round-hole screens. However, since the slotted cone was much taller, it displayed a tendancy toward flow maldistribution, with tip overheating and a slight lift-off at the base. Overlapping a band of screen at the base provided improved flow distribution. Since the round-pattern cone was more completely tested and performance more well defined, further work with the slotted screen was curtailed until a further date and the burner shown in Figure 6(d) was used in both the pre-prototype and prototype tests.

3.3 Pilot Development

Figure 11 illustrates the two pilot designs used for testing. Design (a) employed an orifice drilled in a blanked-off tube. The pilot jet used the burner screen for flameholding and entrained air for combustion between the pilot tip and the screen. A stable flame occurred only on the outside of the screen and enveloped the tip of the pilot thermocouple. However, since the jet diameter was of the same order as the screen hole diameter, this design was extremely sensitive to the position of the gas jet relative to the screen hole pattern. The resulting flame was inconsistent and difficult to ignite.

To avoid these problems, the design pictured in Figure 11(b) was constructed. This pilot featured venturi-type partial primary air aspiration. This pilot operated at flows down to 220 BTU/HR and was not dependent on screen geometry. The flame could be directed at the thermocouple and provided sufficient heat to hold the gas valve open at a pilot input of 220 BTU/HR.

The pilot flame was located nearly half-way up the side of the cone. In all cases, good ignition of the main burner flame occurred with no excessive amount of combustible mixture building up prior to ignition. Ignition was smooth and flame spread evenly over the cone surface.



(a) (b)

Figure 11: Pilot Configurations

Pilot recovery efficiency was determined using the procedures described in Section 4.1. Final pilot recovery efficiency fell somewhere from 30-40%. Though this did not satisfy the design criterion, further improvement of the pilot heat recovery system was postponed to later development efforts.

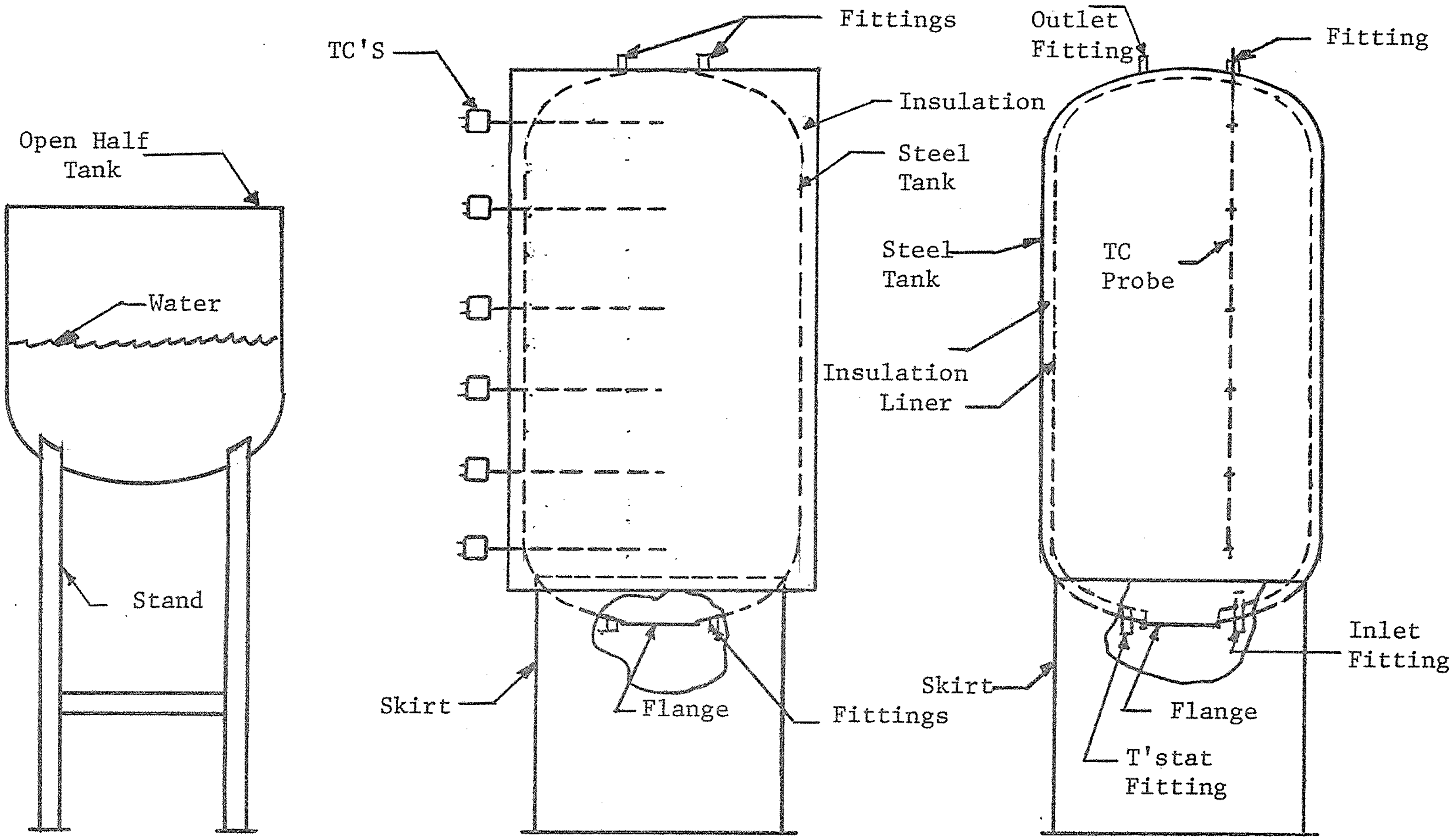
3.4 Storage Tank Description

Three different types of tanks were used for testing as pictured in Figure 12(a-c). "Proof-of-Concept" testing used an open, uninsulated tank to facilitate direct observation of water circulation. This arrangement proved useful for testing of burners, aspirators and heat exchangers.

The second was a pre-prototype tank employing the actual steel tank shell to be used in the final prototype configuration. However, this tank did not have either a plastic liner or internal insulation. Instead, the tank was coated inside with an epoxy-based primer and overcoat to prevent internal corrosion. The resulting tank volume was 50 gallons. One inch of rigid polyurethane pipe insulation was applied to the tank sides, with 3-1/2 inches of fiberglass insulation on the top and bottom. All thermocouples penetrated the side walls and extended to the middle of the tank. Water inlet and outlet connections were located at the bottom and top respectively.

The prototype tank employed both internal insulation and molded polyethylene liner. The internal insulation measured 0.75 inches on the sides with some thinning out of the insulation at the top. This tank had a storage volume of 40.8 gallons. The thermocouple probe (described in Section 2) was mounted in one of the upper penetrations and extended downward into the tank.

Heat loss testing was performed on the pre-prototype tank with the heat exchanger installed. The tank was filled with hot water and allowed to cool overnight. Tank and room temperatures were measured at the beginning and end of each test. Values for the data obtained are presented in Table 3, along with a description of system conditions. Since the tank configuration was quite different from that intended for the prototype, these results



(a) (b) (c)

Figure 12: Storage Tank Test Configurations

Table 3: Pre-Prototype Tank & Fitting Cooldown Test Results

TEST NO.	TANK TEMPERATURE INITIAL - FINAL (°F)	AIR TEMPERATURE INITIAL - FINAL (°F)	FLUE CONDITIONS	TANK AND FITTING LOSS (Btu/hr)
2D0312	157 - 139	74.4 - 71.1	Open, Shroud Not Insulated	460
2D0320	162.1 - 143.7	72.8 - 70.4	Blocked, Shroud Insulated	514
1D0326	154.4 - 137.7	69.5 - 59.3	Blocked	487
1D0405	155.2 - 137.9	72.1 - 71.1	Open	495
1D0406	152.4 - 135.8	67.8 - 71.9	Blocked, (Shutter Closed)	450
3D0411	157.6 - 140.9	75.9 - 71.7	Blocked, (Shutter Closed)	450
2D0417	161 - 143.1	74.8 - 69.2	Blocked, (Shutter Closed)	491
1D0419	154.6 - 137.6	75.4 - 70.0	(Shutter Open)	458
3D0507	155.6 - 136.4	75.4 - 74.8	Sealed Combustion	483
1D0510	156.1 - 141.3	91.2 - 75.8	Sealed Combustion	407

were not significant in an absolute sense. They did, however, provide two important pieces of data. The first was that the flue configuration seemed to have little effect as is evidenced in Table 3. Various flue conditions were tested including completely blocked, open, and sealed combustion. Any effect this had was less than the scatter in the data. The second result was the use of the data to obtain pilot recovery. The pre-prototype tank was tested with and without a pilot which allowed the determination of pilot recovery efficiency. This analysis is included in Section 4.1 where the pre-prototype system testing is described.

The prototype tank was tested in two ways: as a separate component and as part of the system. For the first case, the tank was filled with hot water and allowed to cool for a period of time. Tank and room temperatures were measured at the beginning and end of the time period. Room-to-tank temperature difference and time durations were varied. The results of these tests are presented in Figure 13 and listed in Table 4(a). These represent tank losses without fittings. Also shown in Figure 13 is a range of predicted values for the tank losses with 0.75 inches of insulation. The top boundary of the predicted values represents total heat losses from the top, sides, and bottom of the tank. The lower band does not include losses from the bottom. It was felt that the actual values would fall between these two lines because temperature stratification would favor lower bottom heat losses.

The actual losses were higher than expected. While the cause of this is not certain, it is thought that the insulation is less than 0.75 inches at the top and that the conductivity is higher than that used in the analysis (k =0.015 BTU/HR-FT-°F). The tank could not be cut apart for analysis because it was the only one available for testing. New tanks will have slightly thicker insulation at the top and an improved chemical composition. It is hoped that the new tank will have heat losses closer to the predicted values.

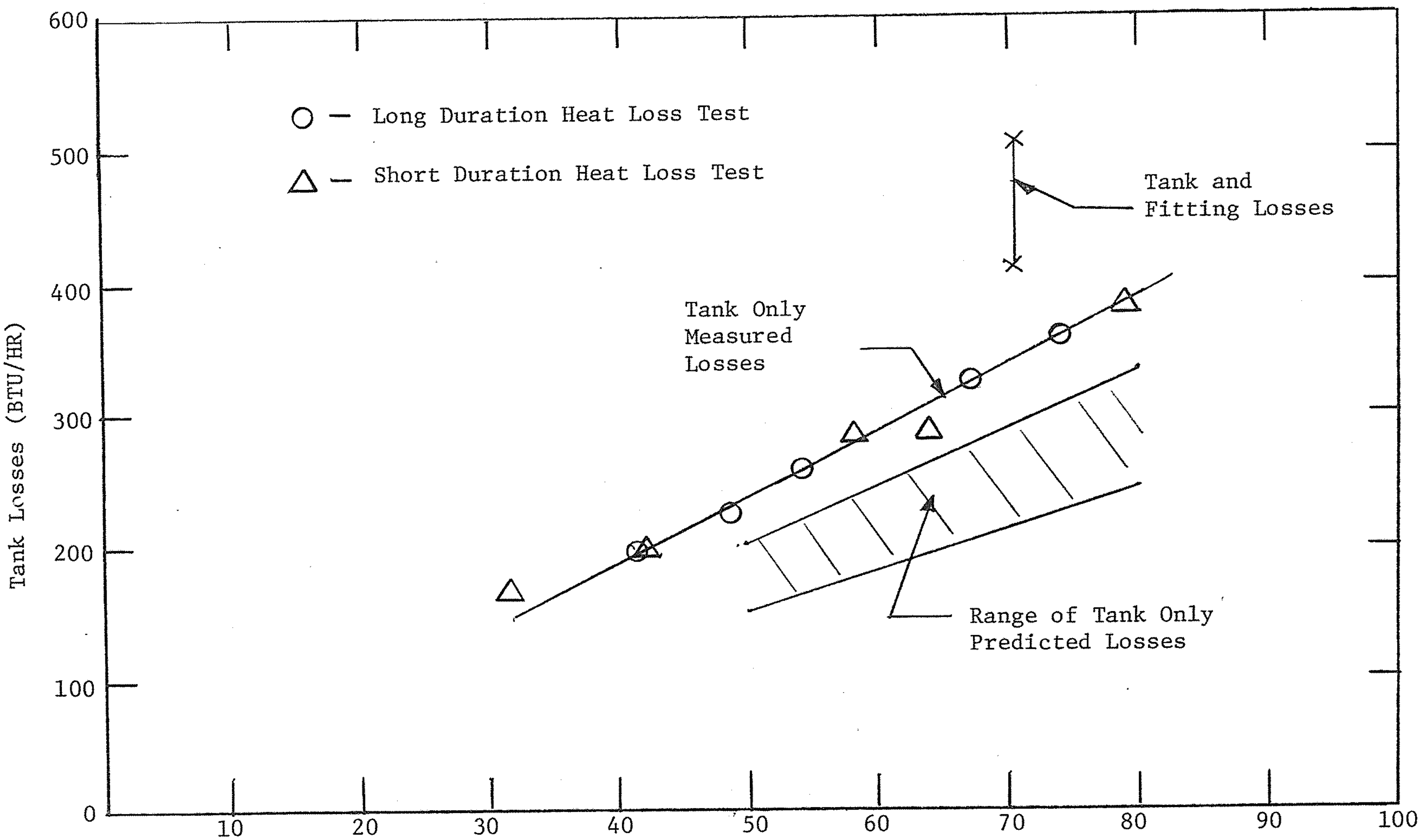


Figure 13: Prototype Tank Heat Losses

Table 4: Prototype Tank Cooldown Test Results

Table 4(a) Prototype Tank Only Heat Losses

Type of Test	Time (hrs)	Average Tank to Air Temp. Difference (°F)	Initial Tank Temp. (°F)	Heat Loss (Btu/hr)
Long Duration	15.1	74	155	361
Long Duration	17.2	67	150	326
Long Duration	15.6	58	142	282
Long Duration	15.9	54	132	258
Long Duration	16.5	49	125	225
Long Duration	14.1	41	120	198
Short Duration	4.7	79	156	381
Short Duration	4.6	64	147	285
Short Duration	5.5	54	130	256
Short Duration	5.0	42	121	195
Short Duration	4.5	31	109	169

Table 4(b) Prototype Tank and Fitting Heat Losses

Long Duration	17.4	71	163	411
Long Duration	16.9	70	162	463
Long Duration	14.3	72	165	512

The prototype tank was also tested as part of the overall water heater system (with tank and fitting losses). These tests were performed both as cool-down tests similar to those performed on the tank alone and as standby-loss tests with burner input. The results from the cool-down tests for tank and fitting losses are shown in Table 4(b) and are plotted in Figure 13. The standby-loss tests with burner input are described in the prototype system tests which can be found in Section 4.2.

3.5 Heat Exchanger Development

Figure 14 illustrates the basic design of the heat exchanger used in all water heater testing. In all cases the basic geometry remained constant, with the number and diameter of fintubes and the header, riser and downcomer material changing. Four variations were tested and the key design details and performance results are shown in Table 5. All of the units were fabricated from Amtrol manufactured copper integral-finned tubing. For heat exchanger A and B the 7/8 inch O.D. fin tubing was used. The headers used in design A were stainless steel while cooper headers were used in design B. Heat exchangers C and D had a different number of 3/4 inch O.D. finned tubes. Table 5 shows three sets of values for the thermal performance of these units. This is done to simulate actual heat exchanger operation with a cold tank temperature, an intermediate temperature, and a high water temperature. The three important test results shown in Table 5 are the exhaust temperature, thermal or stack efficiency, and maximum tube wall temperature (measured). The design goals for these parameters were a 300°F exhaust temperature, an 84% thermal efficiency, and a non-boiling (T_{WALL} <270°F @ 40 psig) wall temperature.

Heat exchanger A, the first version, was tested with an open tank configuration ("proof-of-concept"). Thermally, the unit performed well and met all of the performance criteria. One problem with this design is that the stainless steel headers are expensive and are too large to accomodate the pilot ignition system. In addition, for manufacturing considerations, Amtrol requested that the heat exchanger should use 3/4" fin O.D. tubing rather than 7/8" O.D. This resulted in the design and testing

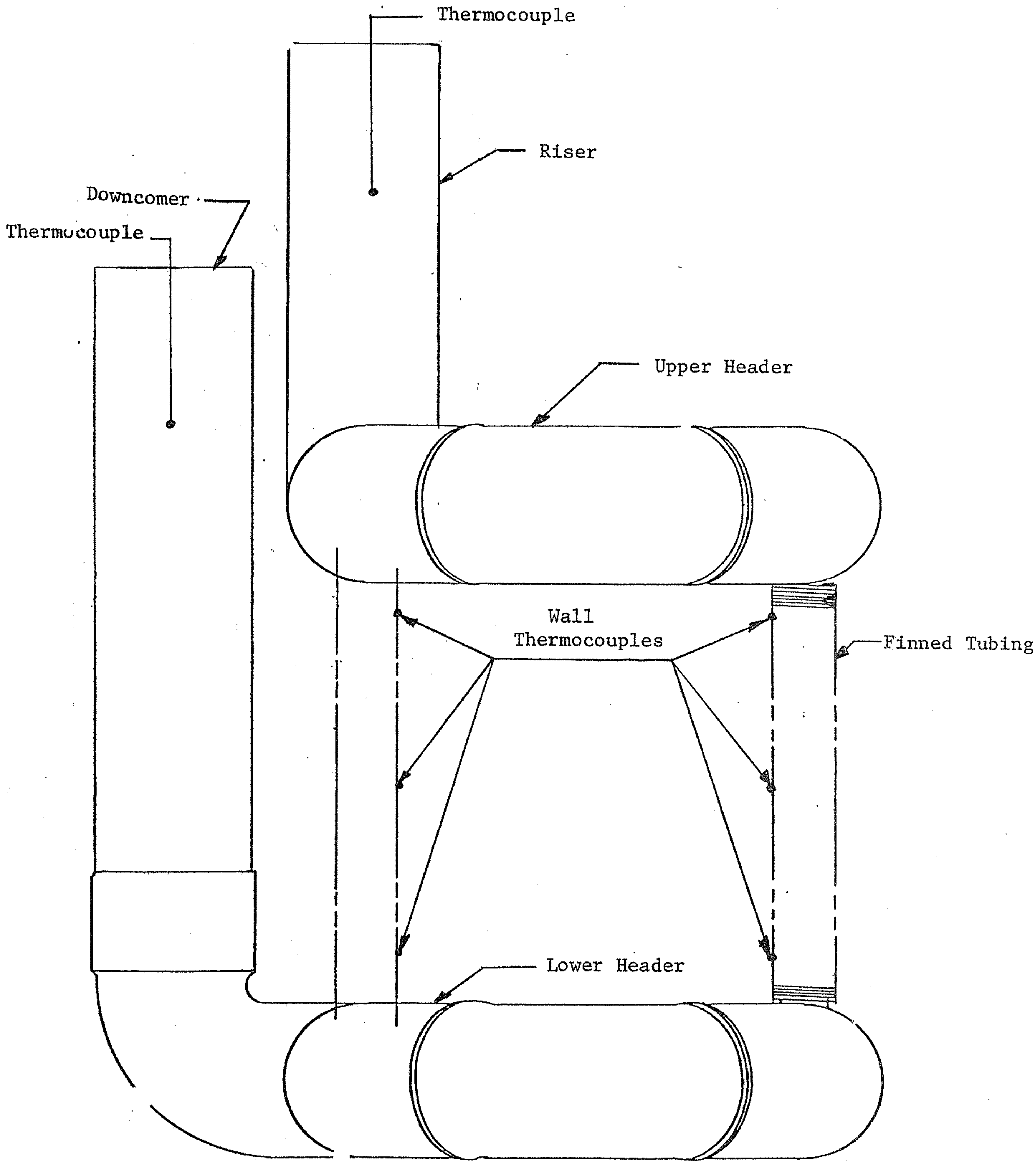


Figure 14: Heat Exchanger Configuration

Table 5: Heat Exchanger Performance Test Results

	CONFIGURATION											
	A			B			C			D		
Header Material	304 Stainless Steel			Copper			Copper			Copper		
Fin Tube O.D.	.875			.875			.75			.75		
No. Tubes	21			21			25			24		
Operating Temp.	LOW	MED	HI	LOW	MED	HI	LOW	MED	HI	LOW	MED	HI
Firing Rate (BTU/HR)	45300			42000			31000			32000		
Excess Air (%)	40			48			46			40		
Water Inlet Temp. (°F)	75	133	180	68	100	139	72	104	137	76	115	152
Water Outlet Temp. (°F)	104	151	198	104	129	170	102	130	159	104	140	173
Exhaust Temp. (°F)	260	293	310	222	241	256	192	212	226	288	299	316
Thermal Stack Eff.	.84	.84	.84	.87	.87	.86	.89	.88	.88	.84	.84	.83
Effectiveness	.94	.94	.95	.95	.95	.96	.96	.96	.97	.93	.94	.94
Water Flow (LB/HR)	1300	2000	-	990	1250	1170	890	1030	1170	950	1070	1280
Max. Tube Wall Temp. (°F)	205	235	238	171	187	209	190	194	222	-	-	-

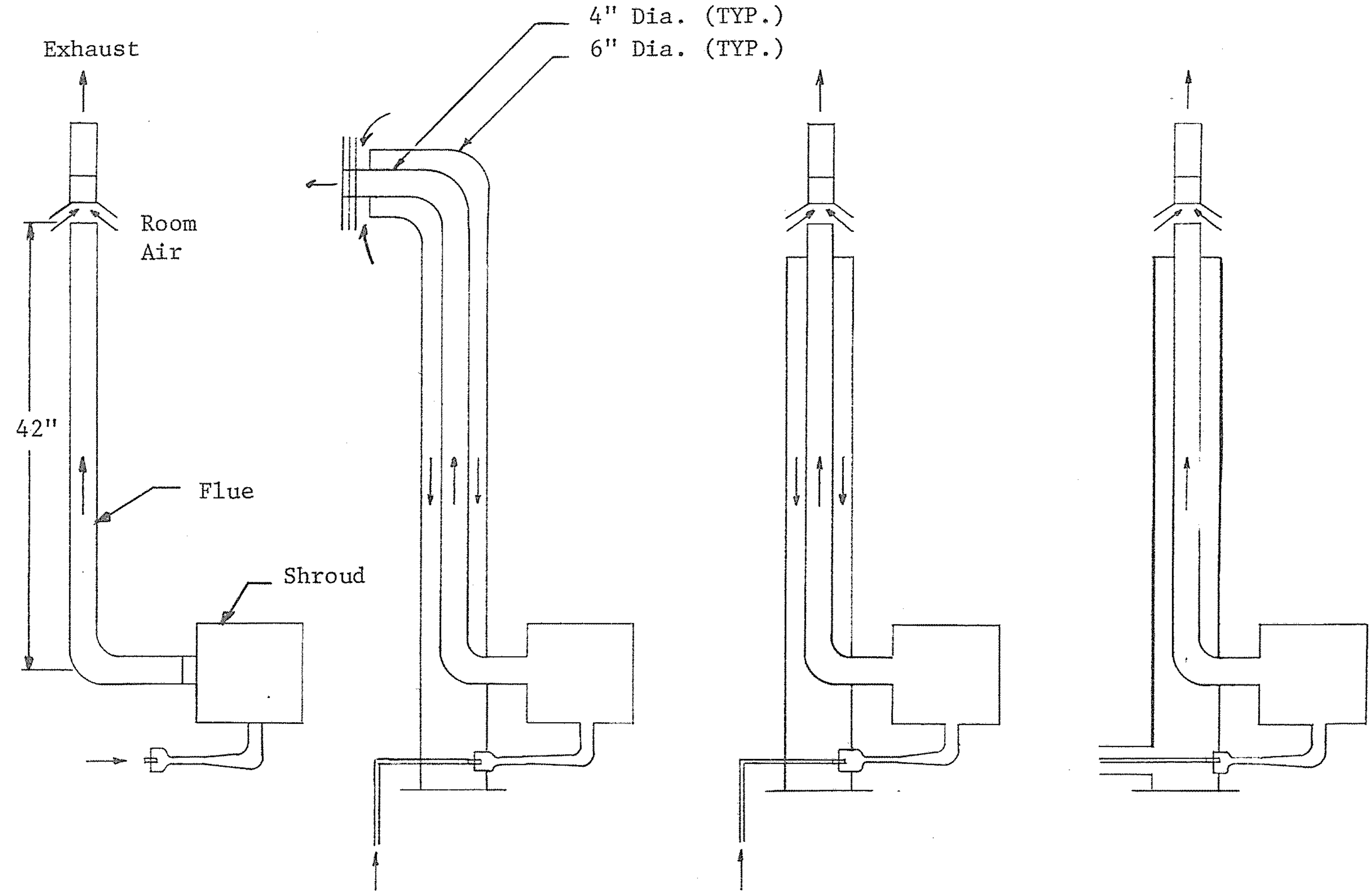
of exchanger C in the pre-prototype configuration. This unit met all design goals but proved too effective and resulted in too low a stack temperature. To correct this, heat exchanger D was built with one less tube than C. The results for this unit in Table 5 are for a firing rate of 32,000. At this firing rate, this would be a good design. However, at higher firing rates the stack temperature of this unit would be higher than desired.

For the prototype unit, it was decided that the heat exchanger should have the thermal performance of A with the header design used in exchangers C and D. Thus, heat exchanger B was constructed for the prototype. The unit should have had a thermal performance similar to A. However, the as-built tube spacing was slightly lower than that of A, resulting in a higher effectiveness and lower stack temperature. The results presented in Table 5(b) reflect heat exchanger performance with some exhaust gas bypassing the heat exchanger (passing from the combustion chamber directly to the exhaust). This arrangement was used in order to keep exhaust temperature high enough to prevent condensation and to provide adequate draft. These results establish the fact that control of minimum fin-tip spacing is important to the proper functioning of the water heater, and will have to be well controlled in manufacturing.

3.6 Exhaust System Development

Four different systems for exhausting combustion products were tested as shown in Figure 15. Each was employed for a different application.

The standard system (a) was used for early open-tank testing and much of the pre-prototype and prototype testing. A stack height of at least 42 inches was used in almost all styles to provide the proper draft. On occasion shorter stacks were employed for brief times, which resulted in lower air flowrates. This configuration worked well in all installations. Configuration (b), sealed combustion, was employed to eliminate exfiltration losses and provide some exhaust-to-inlet thermal regeneration. It consisted of two concentric ducts with the hot exhaust products in the center flue and the inlet air in the annulus surrounding the stack. Sealed combustion,



(a) Standard exhaust with draft diverter

(b) Sealed Combustion

(c) Partially ducted air inlet

(d) Protected stack

Figure 15: Exhaust System Configurations

was only tested on the pre-prototype unit. With sealed combustion, it was found that the pre-prototype unit would not operate above firing rates of 33,800 BTU/HR. This was below the design firing rate of 45,000 BTU/HR. Table 6 summarizes the performance of the sealed combustion system. As indicated about 14% of the energy in the exhaust was transferred to the inlet air. However, accompanying this regeneration was an increase in system flow resistance. The annular inlet flow duct caused increased friction pressure drop. In addition, the lower stack temperature resulted in reduced stack draft. The net result of these effects was to limit the unit to running at less than 34,000 BTU/HR. Sealed combustion was not tested on the prototype unit with the improved aspirator.

Configuration (c) employed a partially-ducted air inlet to provide temperature equalization within the concentric ducts to reduce natural circulation through the unit during standby. It was tested on both the pre-prototype and prototype units. This exhaust system exhibited identical behavior to that described with sealed combustion; that is, operation at the design firing rate of 45,000 BTU/HR would not be attained.

The last configuration (d) was a modified version of (c) which allowed the unit to operate at the design conditions. Its performance was identical to that shown in Figure 15(a). However, it serves the additional function of shielding the hot exhaust pipe and may offer some benefits in reducing off-cycle heat exchanger losses. This was the exhaust configuration used in the prototype tests.

Each of these exhaust systems contained two common elements: the exhaust shroud and the flue. The exhaust shroud was tested in the various forms indicated in Figure 16. Configuration (a) used in the proof-of-concept model placed the heat exchanger downcomer outside the shroud. This resulted in the smallest shroud and one which could be formed cylindrically. The disadvantages of this design were the heat loss from the downcomer during burner operation and the requirement of a complicated sealing arrangement where the downcomer entered the shroud.

Table 6: Sealed Combustion Operating Conditions

Test - 1D0507

Firing Rate - 33800

Recovery Rate - 86.4%

	TEST CONDITION		
Temperature (°F)	A	B	C
Heat Exchanger Water Inlet	71.6	112.8	144.8
Heat Exchanger Water Outlet	103	140.0	169.5
Air Inlet (Ambient)	75.6	77.1	80.5
Air Inlet (Combustor)	85.2	105.3	109
Exhaust Gas (Exchanger Outlet)	208.6	235.1	253.7
Exhaust Gas (Vent)	145.	161.9	172.4
Excess Air	40	40	40
Net Heat Recovery*	5.8%	14.4%	13.3%

* Expressed as a percentage of stack heat loss referenced to ambient conditions.

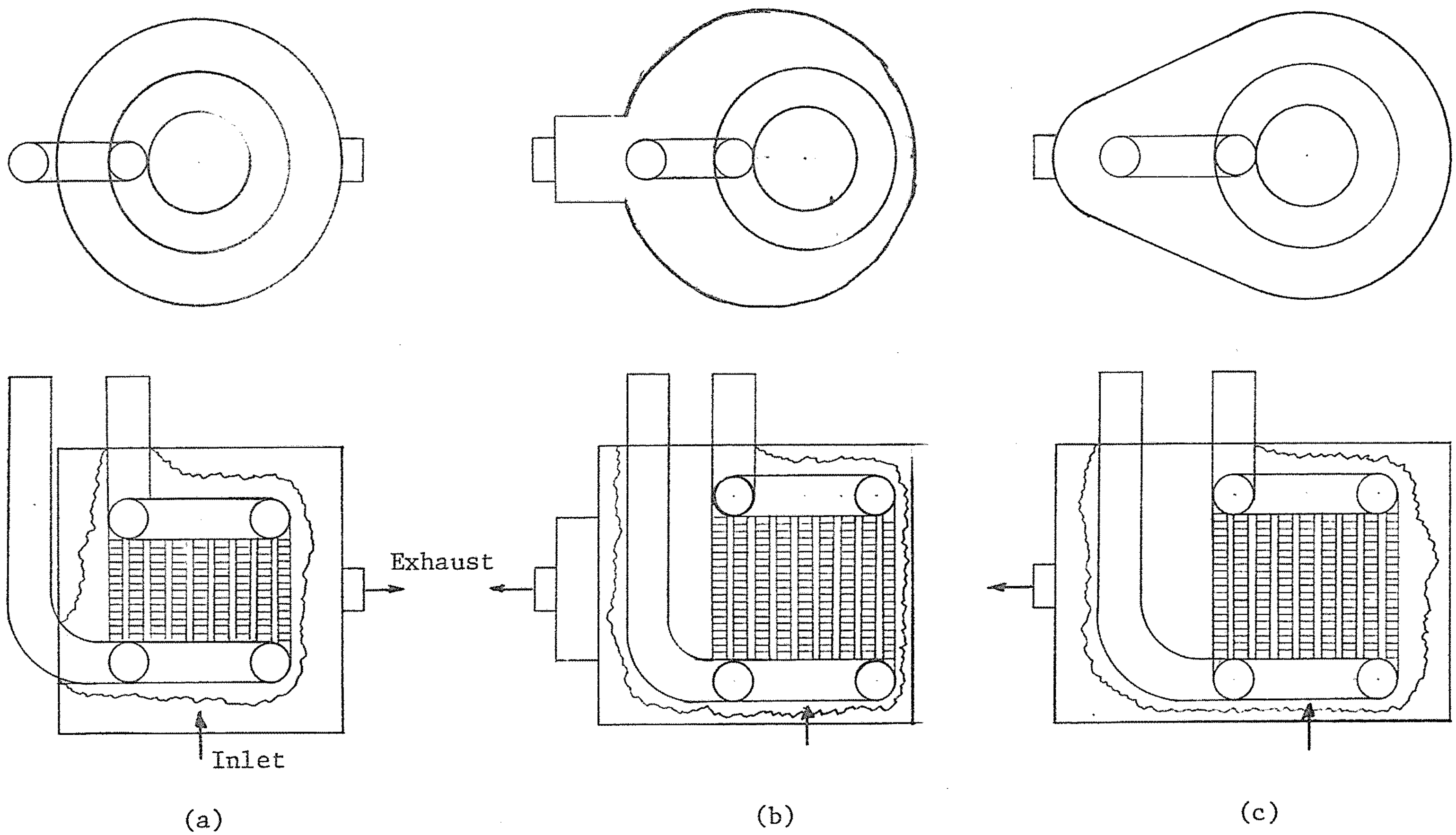


Figure 16: Exhaust Shroud Configurations

Configuration B was designed to overcome the disadvantage of the previous shroud. It was initially constructed with the 4" exhaust teed directly off the shroud. Later, it was modified to include the enlarged discharge when it was suspected that there might be insufficient flow area near the exhaust discharge. This was the shroud used in all the pre-prototype tests. Configuration (c) was a "tear drop" shape which was designed to have ample discharge flow area, simple construction, and minimum volume. This was the version used in the prototype design.

Exhaust/Combustion System Instability

In the section discussing the aspirator development, an oscillatory instability at about 300 Hz was described. In this section a much lower frequency (~50 Hz) oscillation is described which became apparent in the prototype unit. When the exhaust system was made more leak-tight than conventional practice, an oscillation occurred which had amplitude sufficient to extinguish the flame at the design air/fuel ratio. At high rates of excess air (>60%) this behaviour was not generally observed. However, in the region between 30-60% excess air, the oscillations were present. Units such as the pre-prototype and "proof-of-concept" which originally did not exhibit this behavior were tested after being thoroughly sealed and also showed this instability. It is discussed here because the suppression technique employed involved a modification to the exhaust system.

When the instability was confirmed, a variety of different techniques were tested to investigate the source of the instability and its suppression. At present the exact mechanism of oscillation remains unknown. However, as indicated below, an effective method of suppression was discovered. Holes drilled in the exhaust shroud (2-.375 in dia) shortened the acoustic length of the system and thereby decoupled the apparent resonator (stack) from the unidentified source. With the holes no audible oscillations or accompanying high CO levels were detected at any firing rate. If the holes were plugged an oscillation of magnitude sufficient to extinguish the flame began. Thus, even though the exact source was undetermined, the holes functioned as an effective suppression device. The small amount of in-leakage flow from the atmosphere was not sufficient to dilute the hot flue gases nor to destroy the chimney draft. In addition, since internal exhaust pressure was always negative with respect to the atmosphere, no out-leakage of exhaust could occur. Further work may uncover the mechanism for instability and/or more effective suppression techniques.

3.7 Gas Control Valve, Flame Safety and Igniter

Gas Valve and Temperature Control

Figure 5 shows the essential elements of the water heater control system. The gas valve/pilot operation is illustrated in Figure 17.

Two standard commercial gas valves were employed for all testing as pictured in Figure 18. Type (a), a standard Robertshaw Unitrol R110RT control for domestic water heater, was used for all proof-of-concept and pre-prototype testing. Since the prototype tank did not permit mounting a control from the side, a valve using a remote, hydraulically-actuated temperature sensor was used in all testing on that unit. The Robertshaw 7000-ASR control used was a space heating control with a special temperature sensing bulb calibrated for the hot water temperature ranges. Both units delivered sufficient gas flow at an adequate and constant manifold pressure, allowed independent adjustment of pilot flowrates, and operated well with a low-flow (230-270 BTU/HR) pilot.

The major difference between the two controls lay in the water temperature control band. Unit (a), the standard control, operated on a 37°F differential, while unit (b) operated on a nominal 10°F differential with its bulb directly immersed in water and 34°F when installed in a well.

For final standby loss testing, the temperature probe shown in Figure 18(b) was directly immersed in water about 11 in from the tank bottom. The operating band width in this configuration was 5-10°F, based on average tank temperature. In order to determine the effect of this narrow temperature band an analysis was performed. The main standby loss due to a narrower control temperature band was the higher cooldown losses in the heat exchanger due to the increased number of cycles. When this effect was taken into

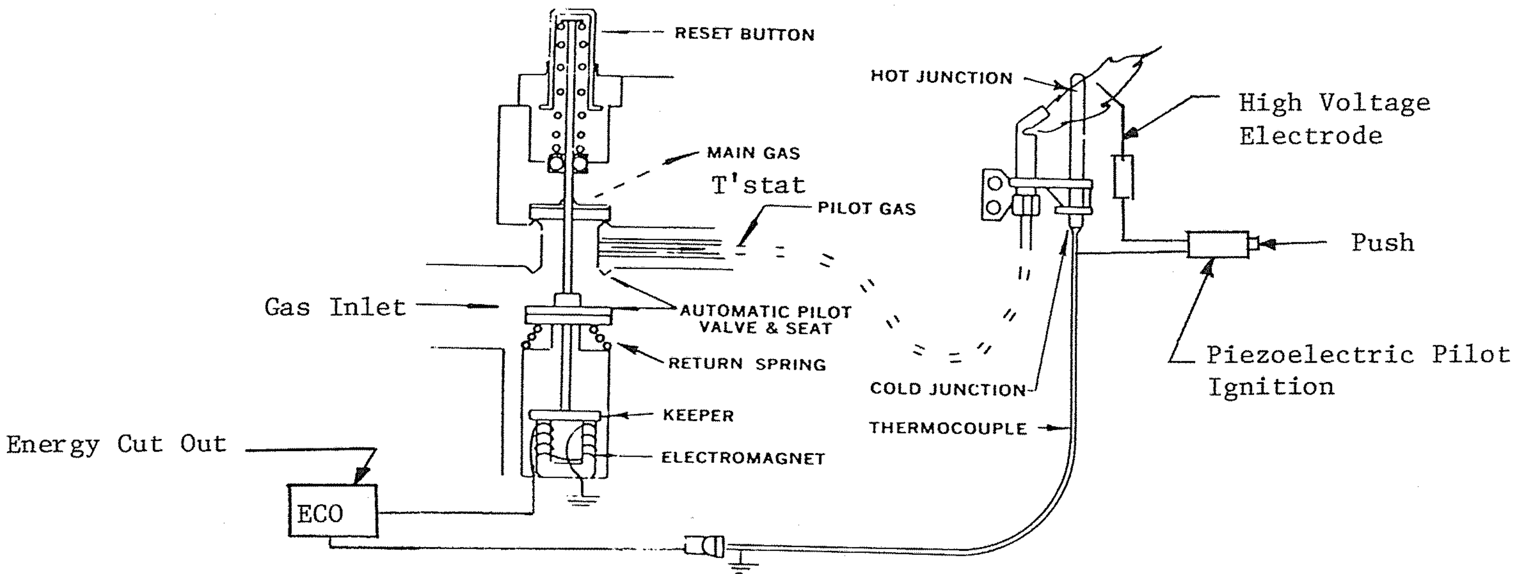
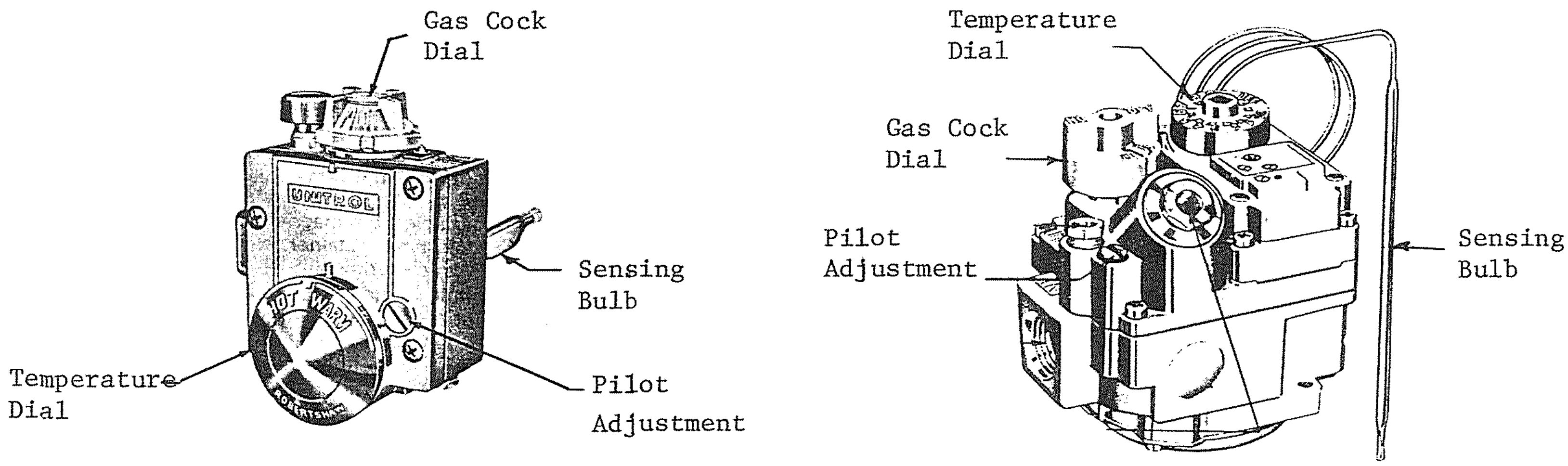


Figure 17: Gas Control Valve and Pilot Operation



(a)

(b)

Figure 18: Water Heater Controls

account, the standby losses decreased by only 3.4% when the control temperature band was varied from 5°F to 30°F. Based on these results, the effect of temperature control band was found to be negligible.

Flame Safety

Proof that the pilot was lit was accomplished with a standard pilot thermocouple arrangement, as pictured in Figures 5 and 17. Pilot firing rates varied from 230-275 BTU/HR. In all cases the pilot produced enough heat to hold open the gas valve via the thermocouple-powered relay. Since direct observation of the flame is very difficult, the thermocouple and a special 0-16 mV voltmeter were used to indicate pilot flame. This meter had sufficiently high internal resistance to minimize loading of the thermocouple.

Igniter

A piezoelectric spark generator was used to ignite the pilot flame. Different models of spark generators were tested and found to be equal in performance, varying only in reliability. The difficulty in implementing this ignition system lay in providing a well-insulated electrode to carry the high-voltage to the arc location. However, given an adequately insulated electrode, the piezoelectric system proved to be an effective method for pilot ignition.

4. Pre-Prototype and Prototype System Tests

The water heater system tests consisted of recovery efficiency, standby loss, and water delivery capacity. The test procedures are described in Section 2.2. For the early development system, a pre-prototype water heater was tested which did not include an internally insulated and lined tank. At that time, the internally insulated and lined tank was not yet available. The system tests that were performed with this unit were recovery efficiency, cool-down loss and pilot recovery tests. Standby loss testing with burner heat input was not performed, nor were water delivery tests. When the prototype tank became available it was installed and the test unit became the prototype water heater. The full complement of tests were performed on this unit and the results from these tests are the ones used to report the final prototype performance and project service efficiency. Table 7 lists the components which were used in both the pre-prototype and prototype systems.

4.1 Pre-Prototype System Tests

The instrumented pre-prototype water heater is shown in Figure 19. The tank consisted of a 50 gallon steel shell (with internal insulation and liner this would become a 40 gallon tank) which was epoxy painted inside and insulated with 1" of foam insulation on the outside. Thermocouples were placed inside the tank using side penetrations as can be seen in Figure 19. One other difference between the pre-prototype and prototype was the type of control used. Both are water heater controls, however, the pre-prototype control uses the thermal expansion of a bimetallic rod to operate the gas valve while the prototype control uses the thermal expansion of a liquid. The remainder of the pre-prototype components were similar to the ones used with the prototype.

The pre-prototype water heater is shown being tested in Figure 20. The test facilities consisted of a flow and temperature measuring module and emission testing equipment. These are also pictured in Figure 20 and are described in more detail in Section 2.1.

During the testing of this unit the burner subassembly had not been developed to the point of operating consistently at 40,000 BTU/HR and con-

Table 7: Components Used In The Pre-Prototype and Prototype System

Component Figure References

	Component	Pre-Prototype	Prototype
1.	Aspirator	Figure 6(d)	Figure 6(f)
2.	Gas Orifice	Figure 8(a)	Figure 8(a)
3.	Burner	Figure 9(c and d)	Figure 9(d)
4.	Pilot	Figure 11 (a and b)	Figure 11(b)
5.	Tank	Figure 12(b)	Figure 12(c)
6.	Heat Exchanger	Table 5(c)	Table 5(b)
7.	Exhaust System	Figure 15 (a,b and c)	Figure 15(d)
8.	Exhaust Shroud	Figure 16(b)	Figure 16(c)
9.	Gas Control Valve	Figure 18(a)	Figure 18(b)

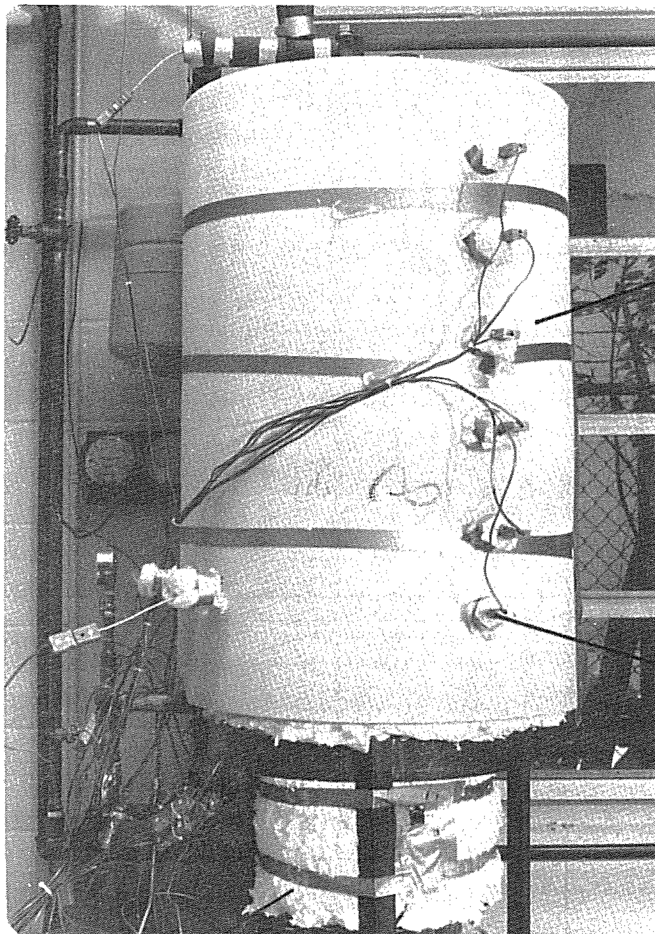


Figure 19: Instrumented Pre-Prototype Tank

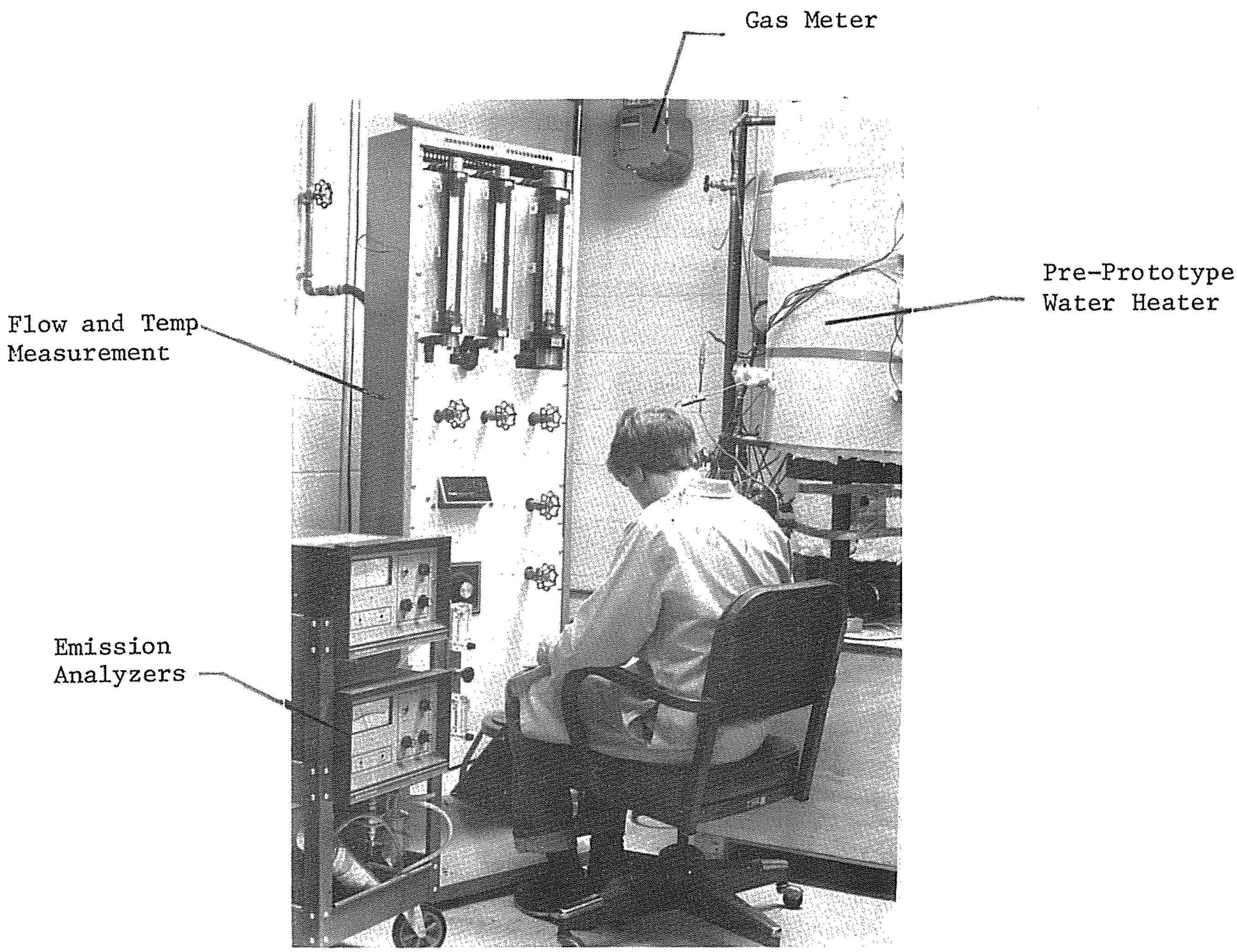


Figure 20 Pre-Prototype Water Heater Installed in Test Facility

sequently much of the testing done on this unit was for a firing rate of 32,000 BTU/HR. Some testing was done at 40,000 BTU/HR both using natural draft and using forced combustion. The forced combustion tests were run with the test rig shown in Figure 10 to provide a well-mixed air-gas mixture to the burner in order to examine mixing effects. Cool-down loss tests were performed with and without the pilot to measure pilot recovery. Actual tank and fitting loss measurements with this unit had little significance because the tank configuration was so different from the prototype unit. The pre-prototype test results are described below.

Pre-Prototype Recovery Efficiency

The recovery efficiency for the pre-prototype unit are shown in Table 8. As can be seen in this table the recovery efficiencies represent a wide range of operating conditions and configurations. In Figure 21 these recovery efficiencies are plotted versus excess air. The firing rate for each point is represented using different symbols and the points representing sealed combustion are highlighted. As can be seen from the figure, all of the points are correlated using excess air versus recovery efficiency within a band of ±2%. Other parameters such as firing rate, sealed combustion, natural draft versus forced draft seem to have an influence less than the scatter. This is not to say that they have no effect, but that the effects were indistinguishable in this series of tests. From the figure, the recovery efficiency was well above the design goal of 82%. This was mainly due to the heat exchanger module being more effective than desired and is not considered a problem.

The temperature distribution of the tank during operation with the heat exchanger/burner module during a recovery test is quite good as can be seen in Figure 22. The temperature field at different time intervals is shown as a function of position. The temperature distribution is relatively even with no stacking at the top (position 6). There is a higher than average temperature at position 2. This is near the discharge plane of the heat exchanger and this region is always hotter (when the burner is on) than the average tank temperature,

Table 8: Pre-Prototype System Recovery Tests

Test No.	Excess Air (%)	Firing Rate (BTU/HR)	Energy Recovery (%)	Test Condition
1D0320	50-75	34000	.80	(1)(2)
1D0321	11-17	36200	.85	(1)(2)
1F0326	48	44600	.82	(2)(3)
2F0326	53-64	42600	.83	(2)(3)
1F0328	42	42500	.86	(2)(3)
1D0405	50	30600	.85	(1)(2)
1D0410	50	39300	.85	(1)(2)
1D0411	40	45300	.84	(1)(2)
2D0411	40	44600	.88	(1)(4)
1D0502	30-40	33800	.86	(1)(2)(5)
1D0507	40	33800	.86	(1)(2)(5)
2D0507	30	33800	.87	(1)(2)(5)
1D0523	42	32000	.84	(1)(2)(5)
1D0531	25	33300	.86	(1)(2)(5)
2D0531	25	35800	.86	(1)(2)(5)

(1) Natural Draft

(2) Heated Volume Recovery Test

(3) Forced Combustion Test Rig Used

(4) Steady-State Flow Recovery Test

(5) Sealed Combustion

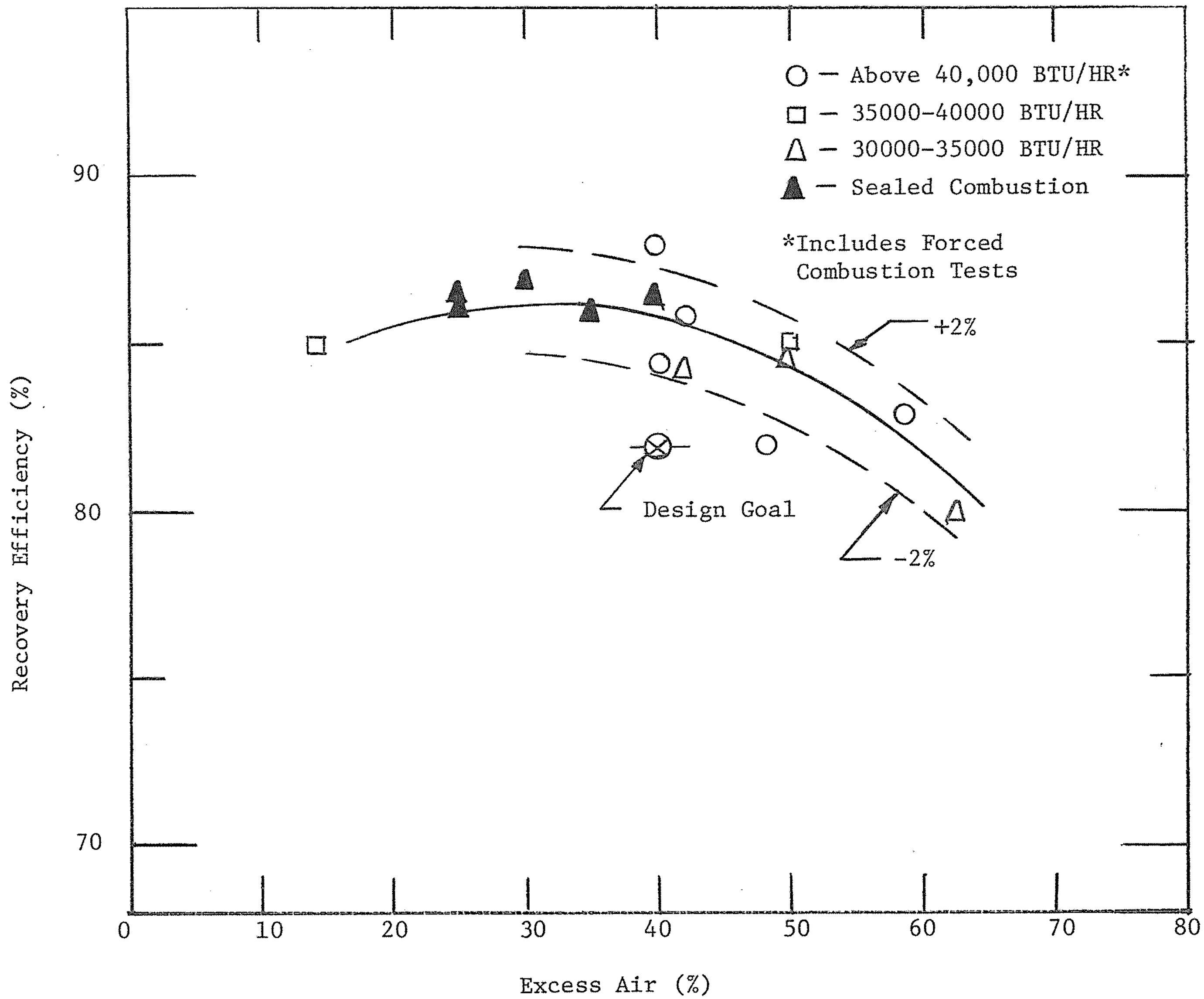


Figure 21: Pre-Prototype Recovery Efficiency versus Excess Air

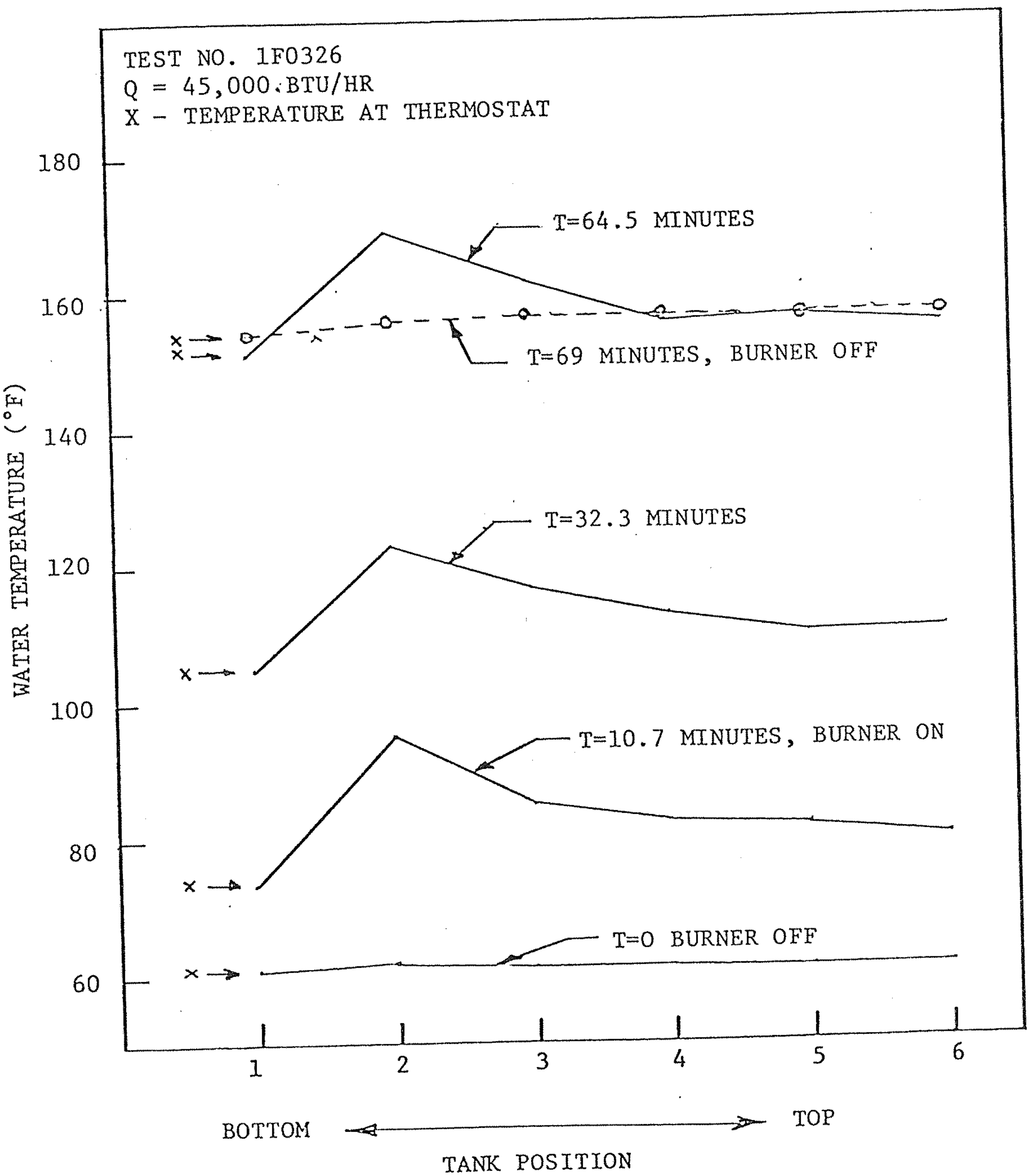


FIG. 22 TANK TEMPERATURES DURING RECOVERY TESTS

as expected. If the top most curve (burner off) is examined, it can be seen that the entire tank is close to the thermostat setting at the end of a heating cycle. Thus, there was no evidence of stacking during this test.

Pilot Energy Recovery

As explained previously, this tank was not prototypic and because of early developmental problems with the burner, unattended burner operation was not attempted. Tests were run, however, to obtain the pilot recovery efficiency. The heat exchanger configuration for the prototype was similar to the pre-prototype, so that pilot recovery data would be meaningful. First the tank and fitting losses were measured by a cool-down test of stored hot water, with the results as shown in Table 3. This was done with the pilot burner turned off. The tests were then repeated with the pilot operating near the design heat input. These results together with those of Table 3 are shown plotted in Figure 23. The absolute level of losses for the tanks is not significant for determination of pilot energy recovery, however the difference between the two conditions is the net heat gain due to the pilot. As can be seen from the figure, this was from 75 to 100 BTU/HR for a 275 BTU/HR pilot. This results in a pilot recovery efficiency of 30-36%. Since there is some scatter to the data it was decided to assume the lower limit of pilot efficiency of 30% for any energy projections requiring a pilot efficiency.

4.2 Prototype Water Heater System Tests

The prototype water heater tank and skirt without the burner/heat exchanger module installed is shown in Figure 24. This unit is shown assembled and on test in Figure 25. The testing for the prototype unit was done in the same facility described in earlier sections. The prototype was a complete operational unit so testing centered more on defining the system performance as opposed to component evaluation. The main testing for the prototype unit consisted of recovery tests and standby loss tests which followed closely the DOE test procedures for water heaters(2). The test plan(4) was followed for capacity or usage tests. In addition, the DOE test for the first hour rating (capacity) for the water heater was also performed.

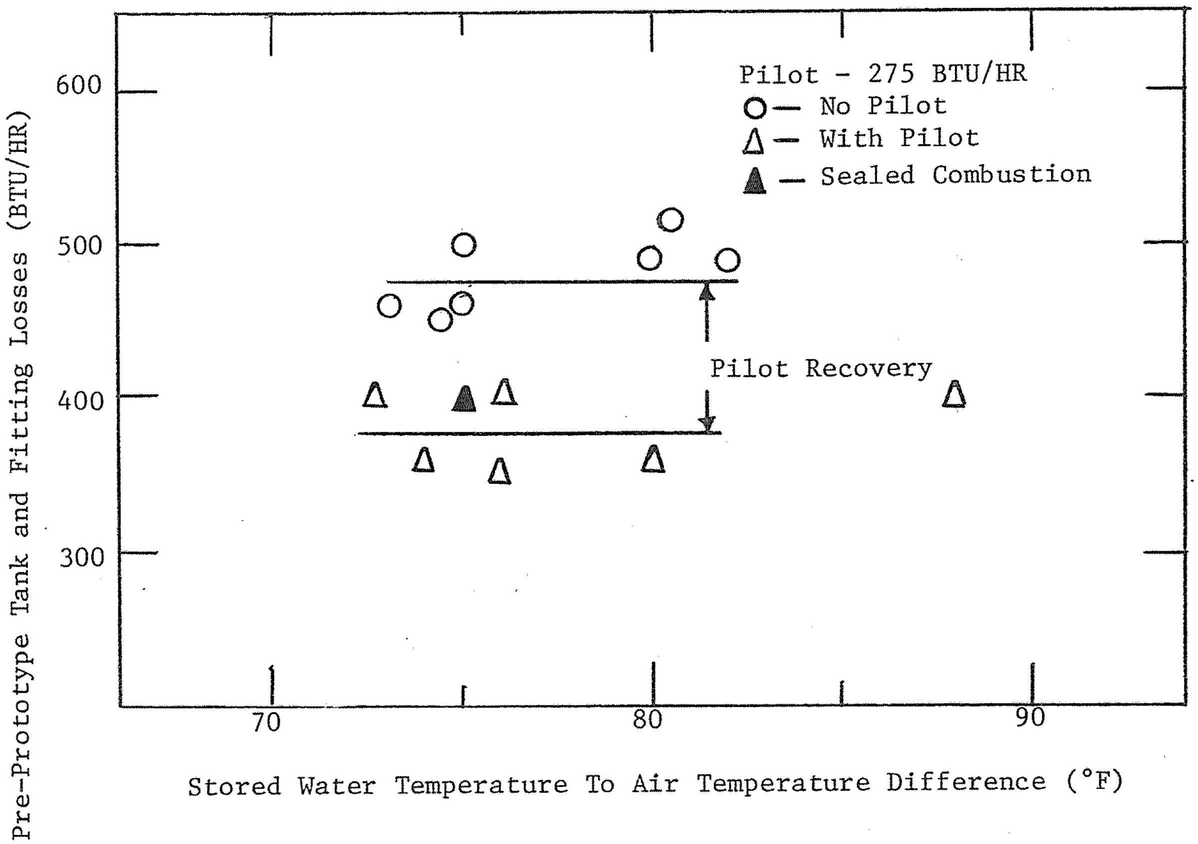


Figure 23: Pre-Prototype Tank and Fitting Losses With and Without Pilot

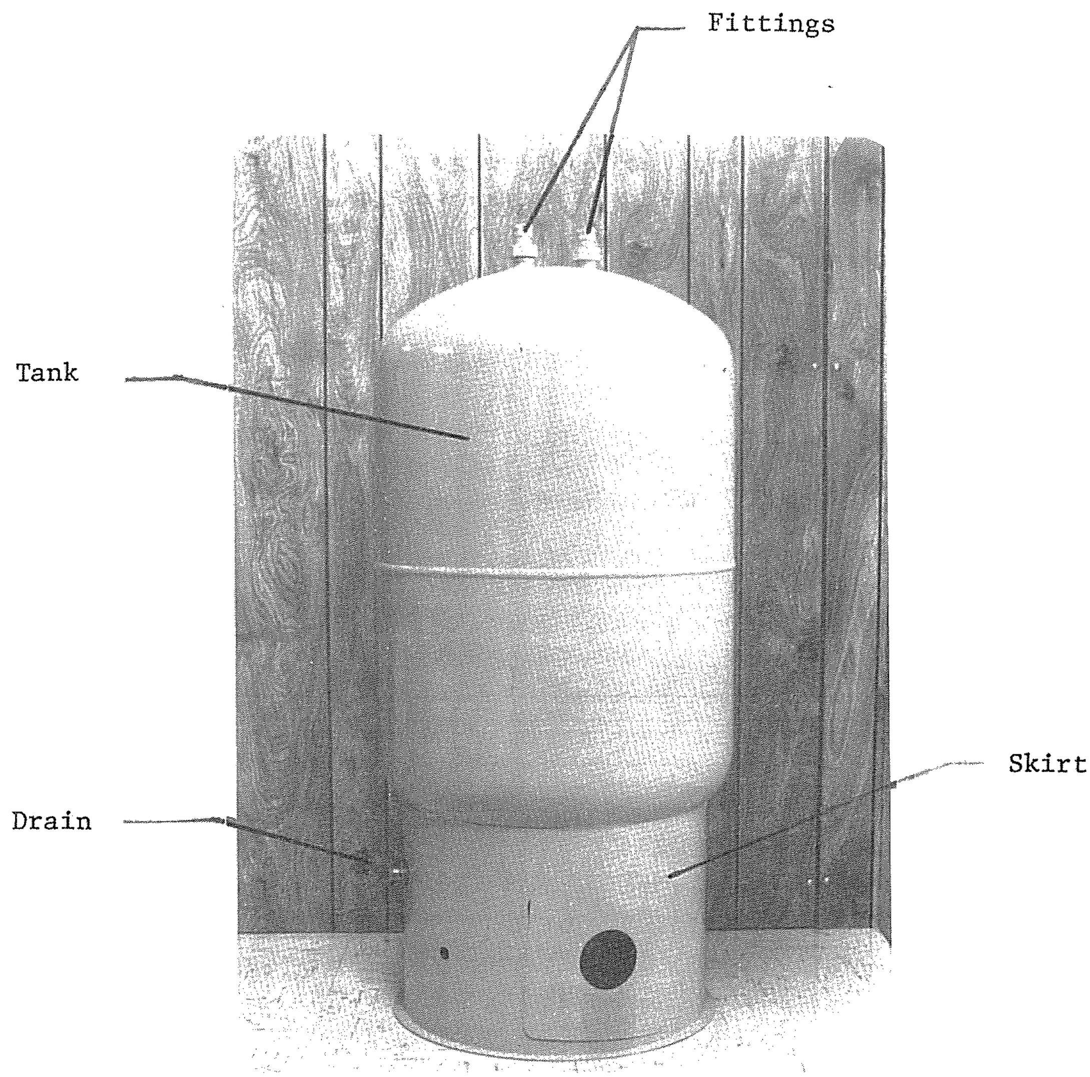
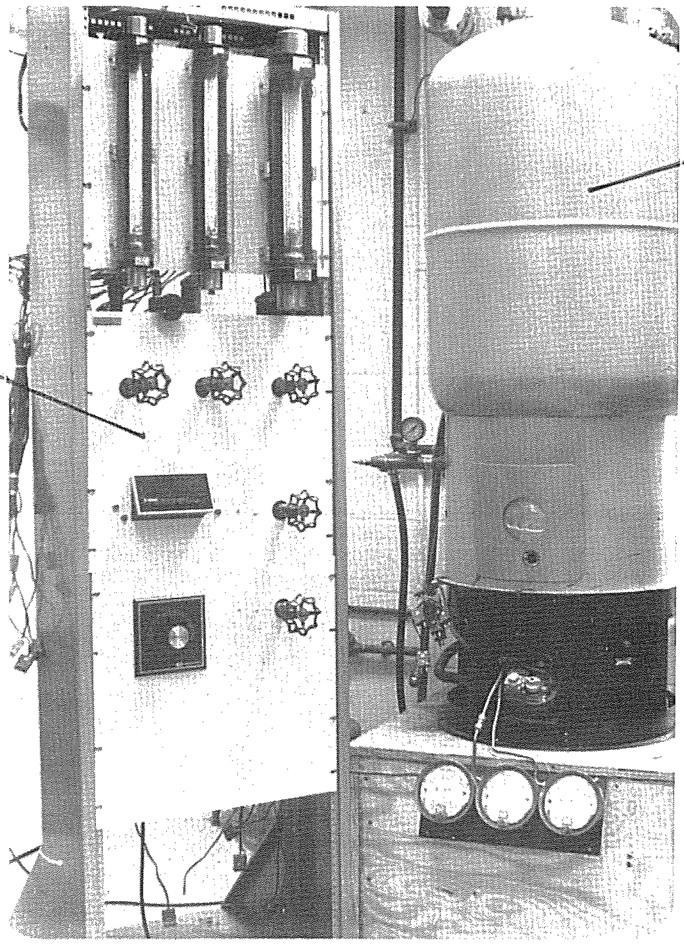


Figure 24: Prototype Storage Tank

Water and
Temperature
Instrumentation



Prototype
Water Heater
Assembly

Figure 25: Prototype Water Heater Installed In Test Facility

While tank and fitting loss tests similar to those specified in the test plan were performed, that is, a cool-down type test, it was felt that the DOE standby loss test was more valid. This was because it included all the losses and directly measured the gas consumption during standby as opposed to measuring the losses separately and then combining them to calculate the standby loss. The recovery efficiency test described in the test plan[4] was not used. This was due mainly to problems in maintaining a steady-state condition with the large volume of water stored in this water heater.

Prototype Water Heater Recovery Tests

The recovery efficiency tests performed on the prototype water heater are shown in Table 9. These were all performed at the design firing rate and with the heat exchanger shown in Table 5(b).

All of these tests were performed with a draft diverter (no sealed combustion). The stack temperature shown in the table is the value measured at the end of the recovery test before burner operation stopped. Variables such as carbon monoxide and excess air vary during the test, and the range of values encountered are shown in the table. The data points numbered 1, 2 and 7 encountered unstable combustion during the tests, as indicated by the high CO values. The final water temperature in tests 3 and 4 was below 150°F, which caused higher than normal recovery efficiency. The remaining tests (5, 6, 8, 9, 10) result in an average recovery efficiency of 82%. Tests 8, 9 and 10 are more indicative of the final prototype unit performing properly as most of the combustion problems had been remedied by this time. This would indicate that a recovery efficiency higher than 82% might be expected. However, the stack temperature for these tests was still a little low, and when the design temperature is achieved, the recovery efficiency will be closer to 82%.

Standby Losses

The standby losses were measured and calculated as described in the Appendix. Installation of the unit was similar to that described in the DOE test procedure for water heaters[2], that is, the inlet and outlet

Table 9: Prototype System Recovery Efficiency Tests

NO.	TEST NO.	FIRING RATE (BTU/HR)	EXCESS AIR (%)	CO (PPM)	STACK TEMP. (MAX.-°F)	WATER TEMP. (°F) INITIAL	WATER TEMP. (°F) FINAL	ENERGY RECOVERY (%)
1	1D1016	40100	43-53	140-850	259	66	155	82
2	1D1017	39200	47-57	100-250	263	65	155	82
3	1D1022	39100	25-40	23-61	240	64	144	87
4	1D1023	41500	25-40	23-63	265	63	146	84
5	3D1024	42000	43-47	23-34	260	65	157	81
6	2D1024	41900	47-50	64-160	270	63	156	80
7	1D1024	41800	40-50	74-290	269	63	157	79
8	1R1112	42500	45-48	51-74	261	63	161	85
9	2R1112	42000	47-51	36-76	256	63	151	84
10	1R1114	40900	45-53	53-95	254	61	151	83

connections had heat traps installed and the lines were insulated. Two 48 hour standby loss tests were run with the unit. These tests resulted in standby losses of 2.7% per hour for both tests. Table 10 shows some of the details of these tests.

Capacity Tests

The test plan[4] for this project included water heater draw tests of 2 gallons per minute for 10 minutes, 40 gallons in one hour, 80 gallons in 4 hours, all while maintaining a 150°F delivery temperature. In addition, the DOE one hour recovery rating for the water heater was performed[5].

Figure 26 shows the water outlet temperature and the water temperature at 6 locations in the tank during a 2 gallon per minute draw. As can be seen from the figure, the hot water outlet stayed above 150°F for 12 minutes and, in fact, was still close to 150°F after 14 minutes. The temperature did start dropping at this point, because at 40,000 BTU/HR with an 82% efficiency recovery, the draw rate required to keep delivery temperature constant was .67 gpm. The temperature distribution within the tank remains stratified during the draw, which shows that the cold water intake was effectively dispersed at the bottom of the tank.

The requirement of a 40 gallon and 80 gallon draw in one and four hours respectively was satisfied by setting a draw rate of 0.67 gallons per minute and letting the unit operate with the thermostat. As can be seen from Figure 27, the unit could have operated continuously in this mode, that is, 40 gallons in 1 hour, 80 gallons in 2 hours, etc. The temperature did droop below 150°F at the 22 minute point and at the 90 minute point. This was the result of a control action and was not due to any recovery limitation. The control could have been reset higher and the test rerun but this was not considered serious enough to run the test again.

The last of the capacity tests run was that required for the one hour rating according to the amended DOE test procedures for water heaters[5].

Table 10: Prototype Standby Loss Test Results

	Test Number	
	2S111S	3S1119
Standby Loss (S-%/HR)	2.7	2.7
Tank Volume (GAL)	40.8	40.8
Average Water Temp. (°F)	144	144
Average Air Temp. (°F)	71	72
Water Temperature Control Range (°F)	140-150	140-150
Air Temperature Range (°F)	69-73	69-74
Test Duration (HRS)	48.1	48

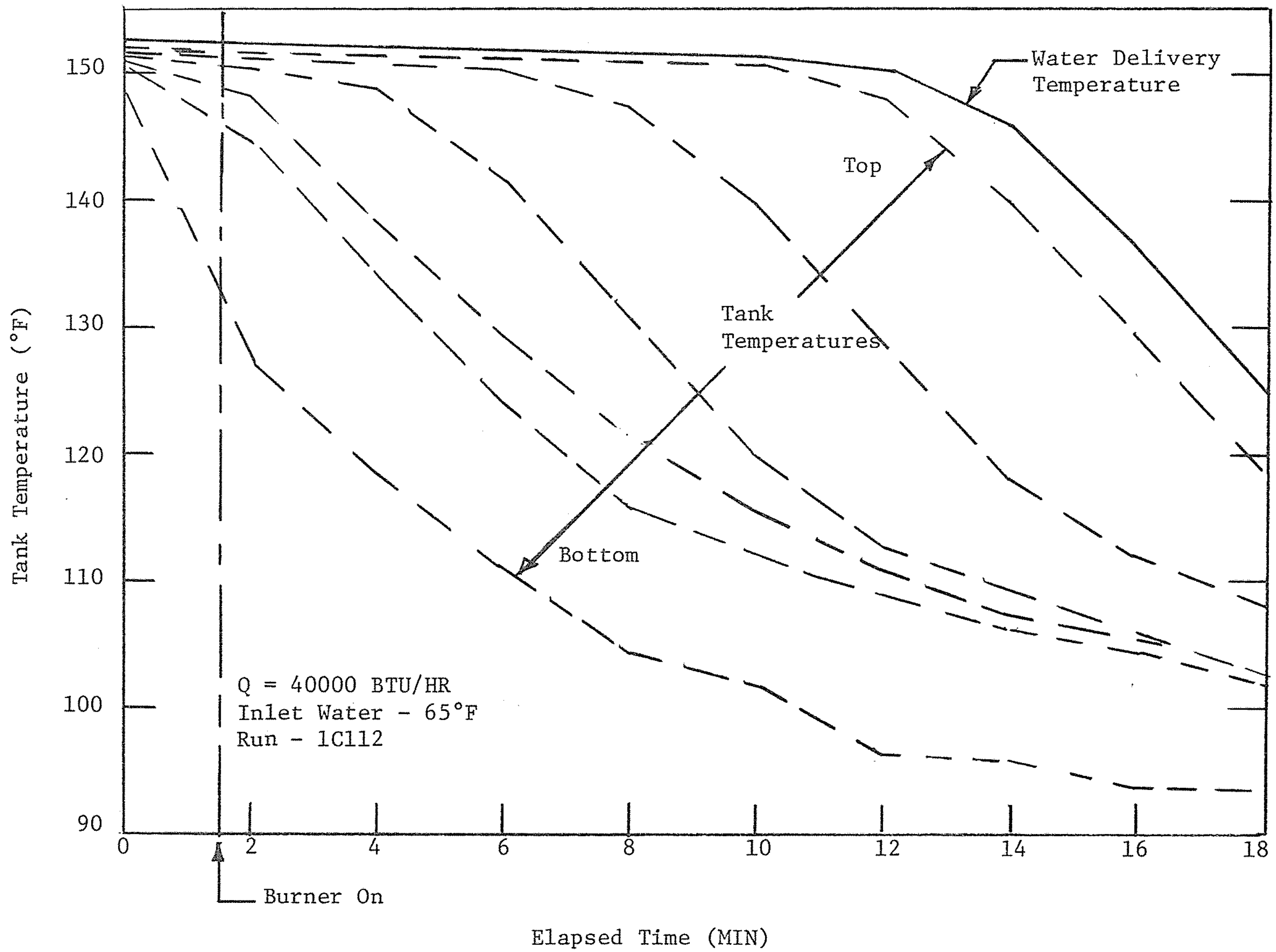


Figure 26: Delivery and Tank Temperature During 2 GPM Draw

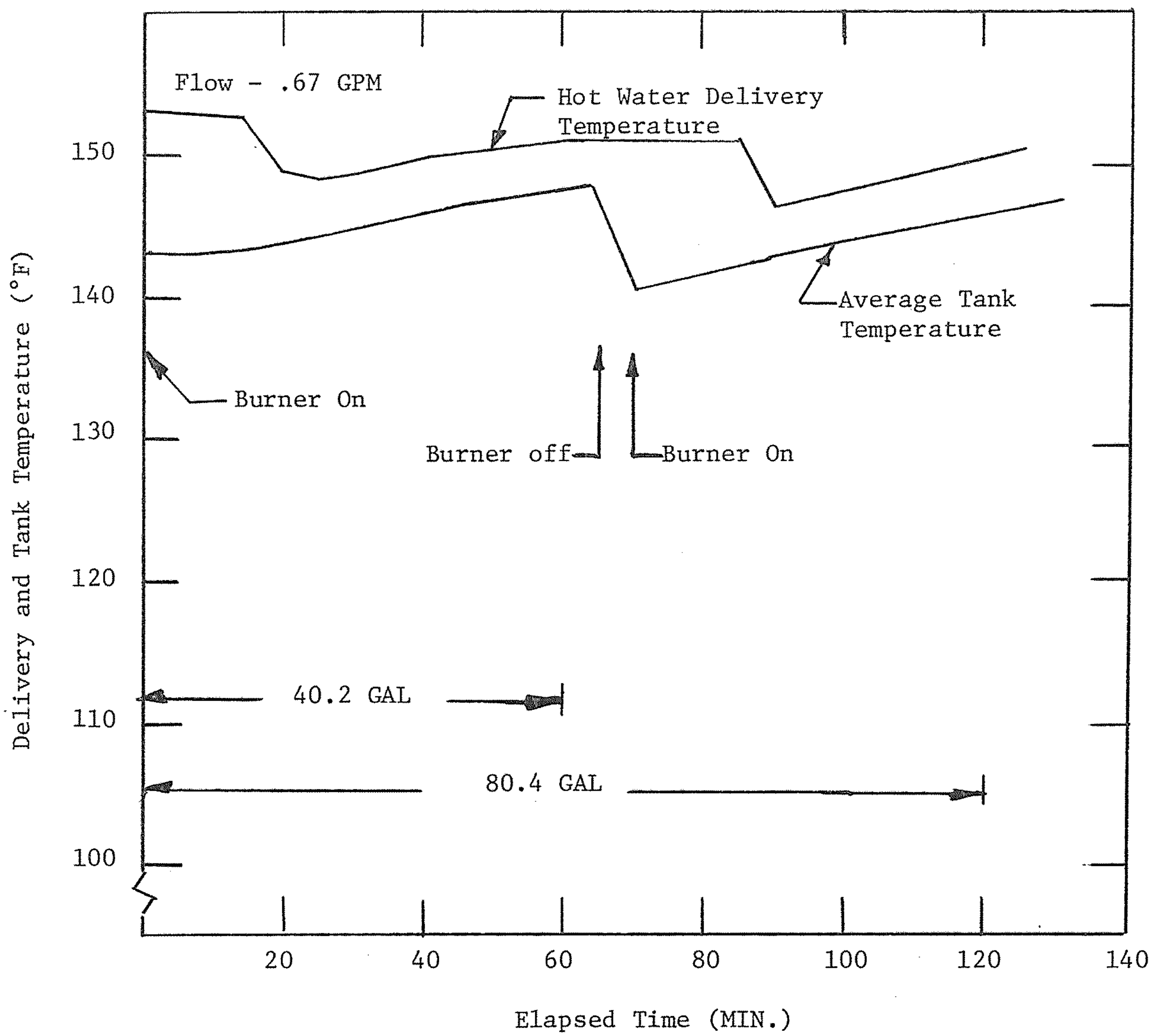


Figure 27: Draw Test At .67 GPM

In this test, water is drawn from the unit at a rate of 5 gallons per minute and the time required for the delivery temperature to drop 40°F below the initial temperature is determined. For the prototype water heater this was 6.2 minutes as can be seen in Figure 28. Using this result with the burner firing rate and recovery efficiency, the water heater had a one-hour draw capacity of 70.6 gallons based on the DOE test procedure (See Appendix for calculation procedure).

At this time, data from conventional water heaters is not available for comparison with the project water heater with regards to draw capacity. Since the labelling law will be in effect in May 1980, the project water heater draw capacity can then be compared with conventional units. It is expected that it will be better than conventional 40 gallon heaters since the burner input is the same and recovery is higher. In addition, the one-hour draw rating should be higher still than the current high efficiency units since they have a lower burner input (typically 30,000 BTU/HR) and a lower recovery than the project water heater.

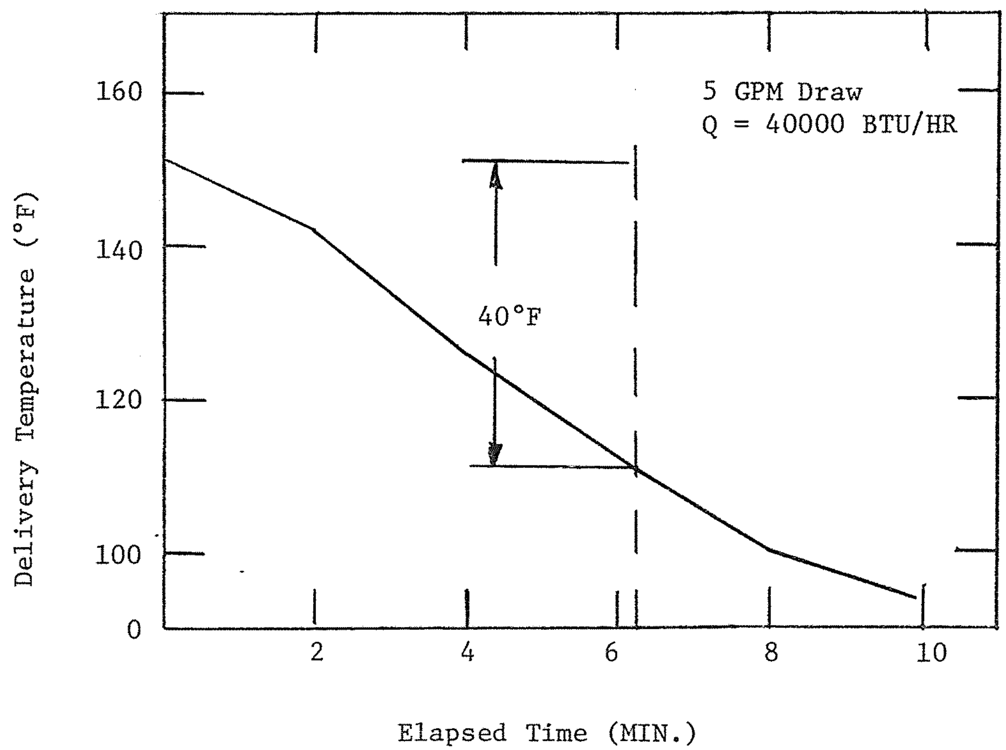


Figure 28: Water Delivery Temperature During 5 GPM Draw

5. Service Efficiency Projections and Emission Test Results

5.1 Service Efficiency

The service efficiency results presented in this section will apply to the prototype unit. The service efficiency is based on a 75 gallon daily draw, a water outlet temperature of 150°F, and a water inlet temperature of 60°F, and an ambient of 70°F. The project goal is a service efficiency of 70% including the effect of exfiltration. For reference, a comparison of these conditions and the DOE test conditions is shown in Table 11. The tests described in this report use the Program Plan(4) test conditions and the DOE testing procedures(2). Had the DOE test conditions been used, the service efficiencies would be lower than those reported in this section.

The service efficiency is defined as follows:

$$E_s = \frac{Q_{NET}}{Q_{TOT}}$$

Q_{NET} - net heat required for daily water heating (BTU/DAY)

Q_{TOT} - total daily energy required for daily water heating (BTU/DAY)

where $Q_{NET} = G x k x \Delta T_1$

G - Daily Water Usage (GPD)

k - Volume Based Specific Heat ($8.25 \frac{BTU}{°F\text{-}GAL}$)

ΔT_1 - Water Temperature Rise (°F)

and $Q_{TOT} = Q_{NET}/(E_r/100) + S \times \Delta T_2 \times V \times k \times t$

E_r - Recovery Efficiency of the Water Heater (%)

S - Standby Loss (%/HR)

ΔT_2 - Temperature Difference Between Stored Water and Room Temperature (°F)

V - Water Heater Tank Volume (GALS)

t - Daily Time at Standby Operation (HRS)

$$t = 24 - Q_{NET}/[(E_{r}/100)(\dot{Q})]$$

where $\dot{Q}$ is the burner input (BTU/HR)

Table 11: Comparison of Program Plan and D.O.E. Test Conditions For Water Heaters

Parameter	Program Plan	D.O.E.
1. Water Usage	75 GPD	64.3 GPD
2. Water Temperature Rise	90°F	90°F
3. Water to Air Temp. Difference For Standby Loss	80°F	90°F
4. Stored Hot Water Temp.	150°F	160°F
5. Exfiltration Considered	Yes	No

Figure 29 shows this equation plotted as service efficiency versus recovery efficiency for various standby losses. This figure does not include the effects of exfiltration. Exfiltration is accounted for by increasing the project goal from 70% (with exfiltration) to 78% (without exfiltration). This increase in efficiency was based on a 9600 Btu/day penalty for exfiltration using a simple model[6] which was part of the program plan requirement[4]. More recent work[9] indicates that this model may predict twice the actual exfiltration loss making a goal of 74% (without exfiltration) more realistic. In order to be consistent with previous analyses, however, the current model is used and the service efficiency goal excluding exfiltration is 78%.

Shown in Figure 29 is the project goal of 78% and the measured prototype result of 66.4%. For reference, a conventional water heater with a service efficiency of 51.3% and a current (high efficiency) unit with a service efficiency of 61% are shown. As can be seen, the project water heater falls short of the project goal by 11.6 percentage points. Further, while the unit meets the energy recovery goal, the standby losses of 2.7% per hour are above the value needed to reach the efficiency goal. Thus, the deficiency in service efficiency of the prototype is due to higher standby losses than expected and the elimination of sealed combustion as a design feature.

In regards to sealed combustion, the prototype configuration did not include this option because the use of sealed combustion at firing rates above 30,000 BTU/HR was found difficult to achieve as described in Section 3. Consideration of the relative importance of sealed combustion led to its temporary shelving until satisfactory performance could be demonstrated. Thus, based on sealed combustion tests with the pre-prototype, the prototype could have been developed with sealed combustion at a firing rate of about 30,000 BTU/HR in which case the service efficiency of the unit including exfiltration would be 66.4% versus a project goal of 70%. This would fall short of the project goal by 3.6%.

Figure 30 shows the standby loss as a function of tank and fitting losses and pilot energy recovery. As can be seen in the figure, the tank

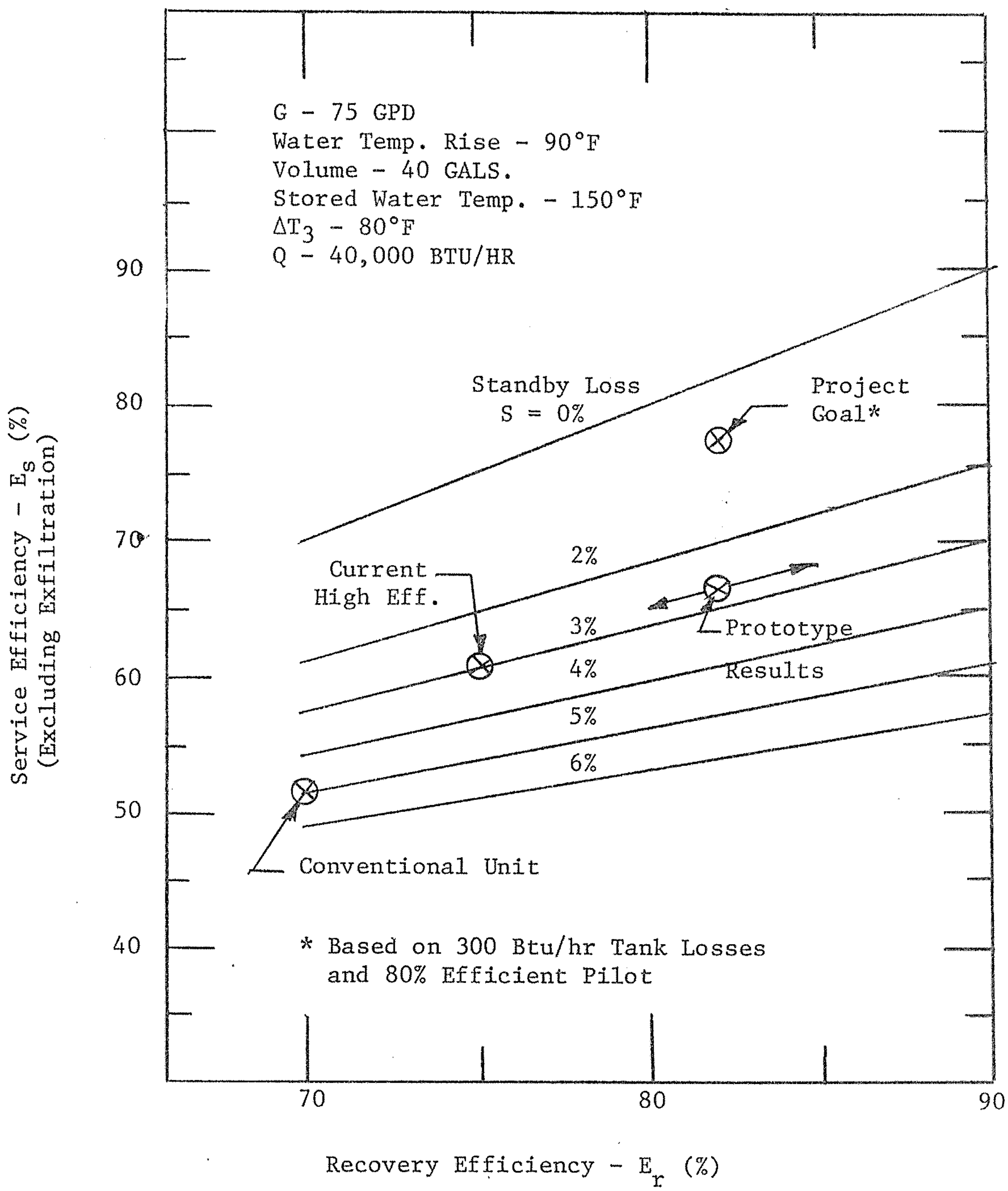


Figure 29: Service Efficiency Versus Recovery Efficiency at Various Standby Losses

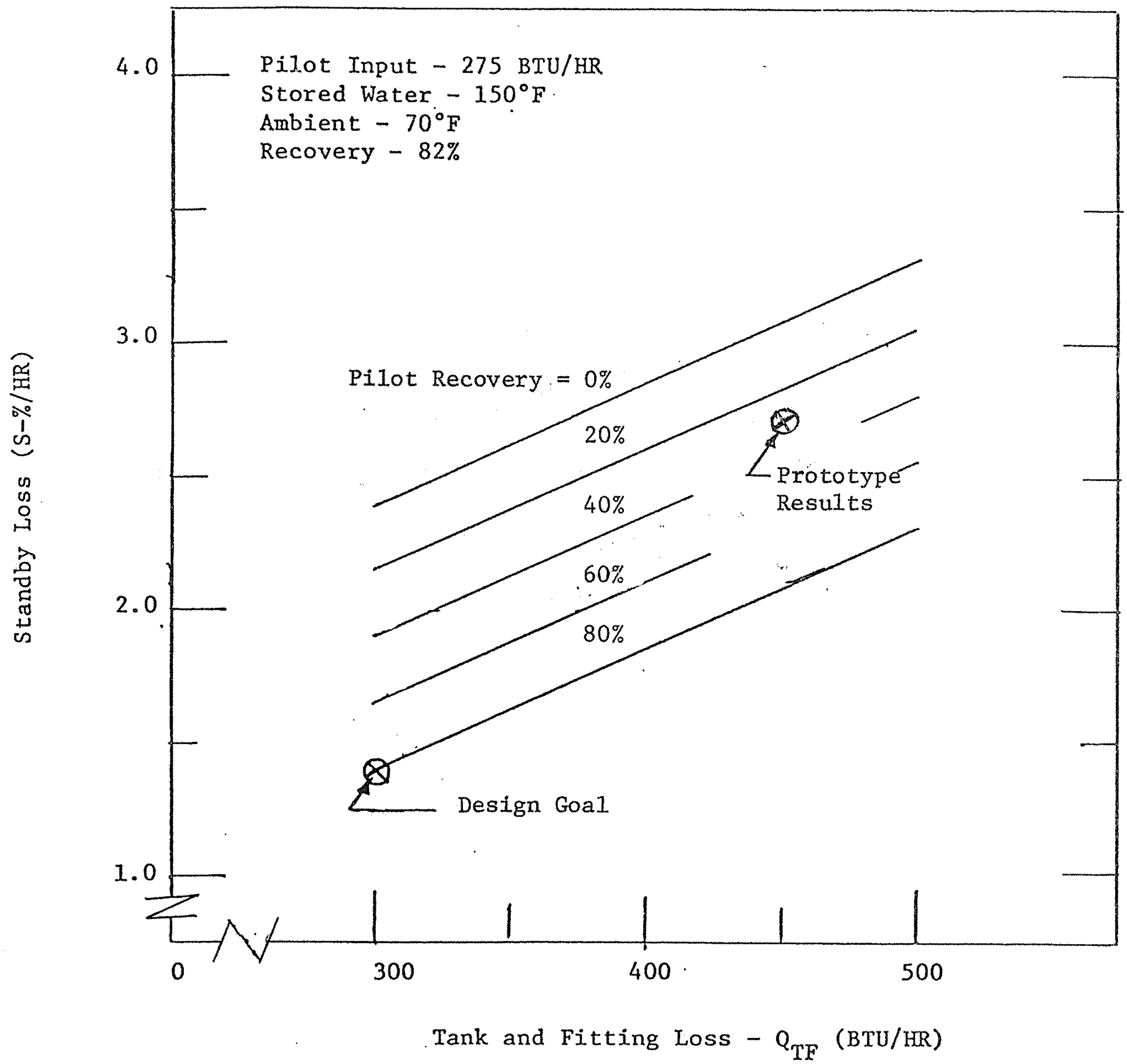


Figure 30: Standby Loss as a Function of Tank and Fitting Losses and Pilot Recovery

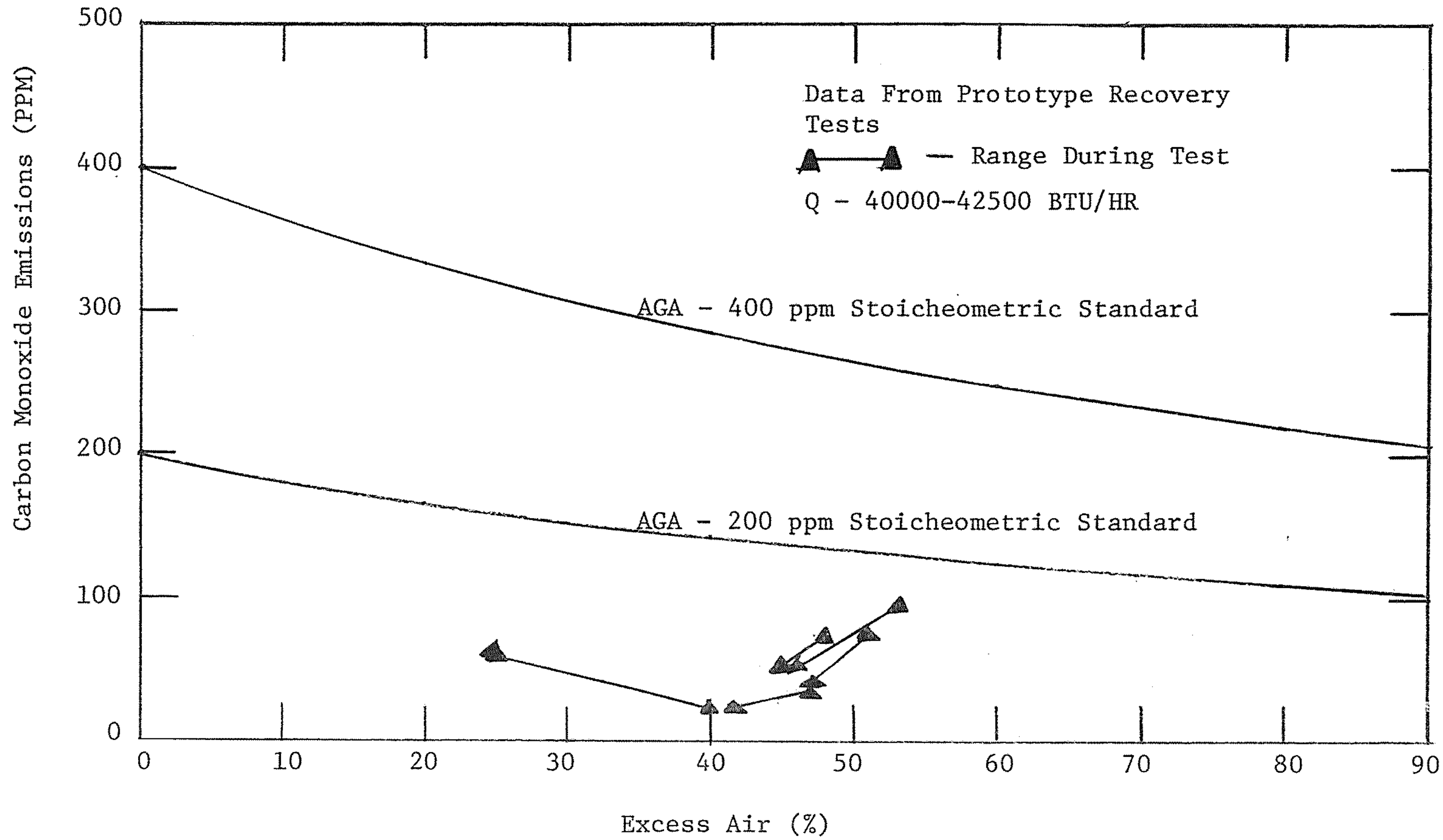


Figure 31: Water Heater Carbon Monoxide Emissions

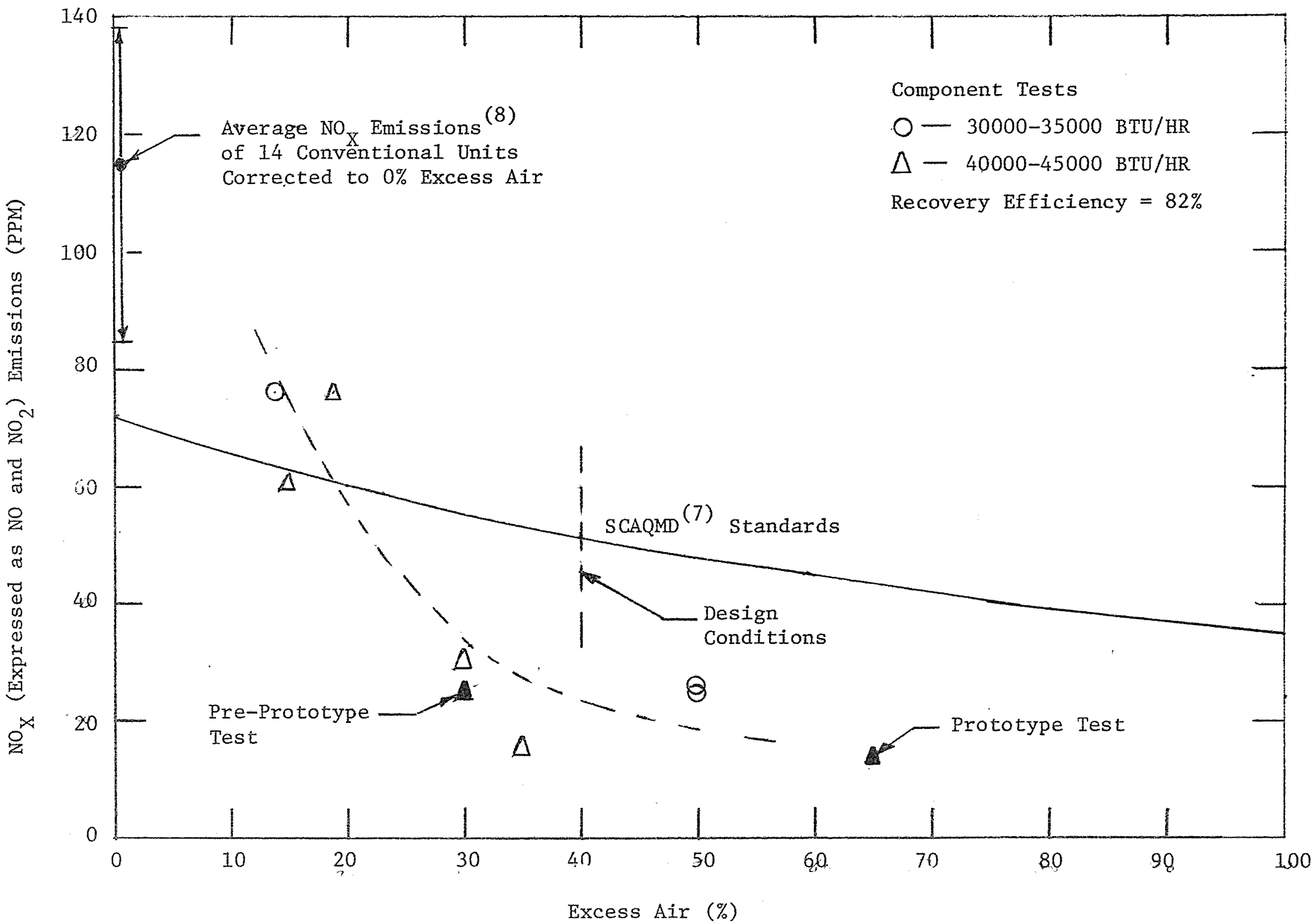


Figure 32: Water Heater NO_X Emissions

6. References

1. "American National Standard for Gas Water Heaters", Vol. I, ANSI Z21.10.1-1975, American Gas Association.

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

3. "Combustion-Driven Oscillations in Industry", Abbott A. Putnam, BMI, American Elsevier Publishing Company, Inc., New York, 1971.

4. "Program Plan for Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", AMTI, April 21, 1978.

5. "Energy Conservation Program for Appliances: Ammended Test Procedures for Water Heaters", Federal Register, May 9, 1979.

6. "Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", Concept and Market Evaluation, Task 2 Report, AMTI, October 6, 1978.

7. 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.

8. "Evaluation of the Pollutant Emissions From Gas-Fired Water Heaters", American Gas Association Laboratories, Report No. 1507.

9. "An Assessment of Retrofit Automatic Vent Dampers for Residential Heating System", Arthur D. Little, Inc., November 1977.

and fitting losses were 450 BTU/HR versus a goal of 300 BTU/HR and the pilot recovery was 30%-36% versus a goal of 80%. The tank and fitting losses should not be considered final values because the tank is still undergoing development at Amtrol. The new tank will have a different insulation composition and the thickness at the top will be slightly increased. This should decrease the tank and fitting losses slightly.

Because of developmental problems with the combustion system, extensive development of pilot energy recovery was not attempted. The pilot system was debugged to the point that it was operational and the pilot efficiency was measured. There was no attempt to increase its efficiency.

5.2 Emission Test Results

Emissions, specifically CO and NO_X, were measured for the water heater during the entire development effort. These measurements were made to determine prototype compliance with code requirements.

The ANSI code for water heaters requires that the unit emit less than 200 ppm CO during low test gas pressure tests and less than 400 ppm CO at gas pressure 12% above normal. These values are corrected to zero excess air. In addition there are tests with gases other than natural gas at the same values. The AGA combustion tests were not performed with the project water heater, but CO emissions were constantly monitored and are shown compared to these standards in Figure 31. The results shown were obtained during the prototype recovery tests. These are typical for values measured during the project and are well below specifications.

The code requirements for oxides of nitrogen are set by the South Coast Air Quality Management District (SCAQMD)[7] and only apply to Southern California after December 31, 1982. The code requirements are shown in Figure 32 together with various data collected on the project water heater. As can be seen, oxides of nitrogen emissions were well below the standard in component tests and system tests. Emissions from conventional water heaters[8] are also plotted (corrected for excess air) in Figure 32. The actual excess air rates were not given for these tests, but they were probably run at about 40% excess air. In addition, they should be increased by about 25% to account for recovery efficiency[8]. Thus, the project water heater emits about one half the code requirements for NO_X, while conventional water heaters emit 60% higher NO_X emissions than the code allows.

Appendix - Project Test Procedure for Water Heaters

A. Recovery Efficiency

B. Standby Loss

C. First Hour Draw Capacity Test

A. Recovery Efficiency Determination Test

DATA SHEET: Recovery Efficiency Test Data Sheet

I. Procedure: Experimental

A. Verify that all instrumentation is functioning properly and that the storage tank is filled with water with all air vented.

B. Verify that the tank thermostat is set to control at an average tank temperature nature of 150°±5°F.

C. Fill the tank with water at a temperature of 60°±5°F and allow to reach steady temperatures.

D. Record all temperatures and meter readings required by data sheet.

E. Place water heater in normal operation (ON position) and allow to run to cut-out. Record required operational parameters.

F. Allow tank temperatures to reach steady state and record all readings required by data sheet.

II. Procedure: Calculations

Calculate:

A. Average initial and final tank temperatures

B. Determine gas consumption in cubic feet

C. Calculate recovery efficiency from the following formula:

$$E_r = \frac{(V)(C_g)(\overline{T}_f - \overline{T}_i)}{(Q_{ng})(HHV)} \times 100$$

where

V	=	Total tank volume,	gal
C_g	=	Specific heat of water	BTU/gal-°F
$\overline{T}_f$	=	Average final tank temperature	°F
$\overline{T}_i$	=	Average initial tank temperature	°F
Q_{ng}	=	Gas Consumption	ft^3
HHV	=	Higher heating volume of natural gas	BTU/ft^3

ADVANCED MECHANICAL TECHNOLOGY, INC

Test No: ____________
Performed By: ____________
Date: ____________

Recovery Efficiency Test Data Sheet

Parameter	Initial	Final
Time of Day	____________	____________
Tank Inlet Temp.	____________	____________
Tank Outlet Temp.	____________	____________
T1 (Tank Temperatures)	____________	____________
T2	____________	____________
T3	____________	____________
T4	____________	____________
T5	____________	____________
T6	____________	____________
Exhaust Temp.	____________	____________
Room Temp.	____________	____________
Gas Consumption		____________ ft^3
Elapsed Time		____________

Range During Test

Excess Air: ____________%

CO: ____________ppm

Gas Outlet Press.: ____________in H_2O

Exhaust Temp.: ____________°F

NO: ____________ppm

NO_2: ____________ppm

ADVANCED MECHANICAL TECHNOLOGY, INC

B. Standby Loss Determination Test

I. Procedure: Experimental

A. Connect all tank thermocouples to the chart recorder.

B. Verify that all instrumentation is functioning properly and that the storage tank is filled with water with all air vented.

C. Verify that tank thermostat is set to control average tank temperature at 150°±5°F.

D. Place water heater in normal operation (ON position) and allow water to heat up to cut-out.

E. Immediately following cut-out initiate operation of chart recorder and record gas meter reading.

F. Allow test to continue for 48 hours.

G. At the end of 48 hours, terminate operation of chart recorder and record gas meter reading. If the burner is on, allow operation to continue to cut-out, and tank temperatures to settle prior to reading gas meter.

II. Procedure: Calculations

A. Determine and record average tank temperatures and room temperature at 15 min. intervals during the 48 hour test.

B. Calculate the following parameters:

1. $\overline{T}_t$ Average tank temperature during test °F

2. $\overline{T}_{rm}$ Average room temperature during test °F

3. ΔT_3 $\overline{T}_t - \overline{T}_{rm}$ °F

4. $\overline{T}_i$ Initial average tank temperature °F

5. $\overline{T}_f$ Final average tank temperature °F

6. ΔT_4 $\overline{T}_i - \overline{T}_f$ °F

7. Q_{ng} Total gas consumption ft^3

8. t Total time duration hr

C. Calculate standby loss using the following formula:

$$S\ (hr^{-1}) = \frac{(Q_{ng})(HHV)}{(C_g)(V)(\Delta T_3)(t)} + \frac{(\Delta T_4)}{(\Delta T_3)(t)(E_r)}$$

where:

HHV	=	Higher heating value of natural gas	BTU/ft^3
C_g	=	Specific heat of water	
V	=	Total tank volume	BTU/gal-°F
E_r	=	Unit recovery efficiency	(dim.)

C. First Hour Draw Capacity Test

I. Procedure: Experimental

A. Verify that the tank is full of water with all air vented and that all instrumentation is functioning properly.

B. Initiate burner operation and allow tank to heat up to cut-out at 150°±5°F.

C. After cut-out initiate water draw at 5 gal/min. Record water outlet temperature at two-minute intervals.

D. Continue test until water outlet temperature falls to less than 40°F below initial delivery temperature.

II. Procedure: Calculations

A. Plot water delivery temperature vs. time and determine the time at which water delivery temperature fell below 40°F less than initial delivery temperature.

B. Determine the following parameters:

1.	P	Unit firing rate	BTU/HR
2.	E_r	Unit recovery efficiency	(-)
3.	C_g	Specific heat of water	Btu/gal-°F
4.	ΔT_s	Temperature rise of water	90°F
5.	Q	Draw rate	gal/min
6.	t_f	Time duration determined in A above	min

C. Calculate:

1. $G \text{ (gal)} = Q \times t_f$

2. $R \text{ (gal/hr)} = \frac{P \times E_r}{K \times \Delta T_s}$

   where K = 8.25 Btu/gal-°F

3. First hour draw rating (GALS.)

   $F = G + (R \times (1 - t_f))$

RESEARCH AND DEVELOPMENT OF A HIGH EFFICIENCY GAS-FIRED WATER HEATER

FIELD TEST PLAN

TASK 4 REPORT

January 1980

Prepared By:

Advanced Mechanical Technology, Inc.
141 California Street
Newton, Massachusetts 02158

Prepared under Subcontract 7381 for the

Oak Ridge National Laboratory
Oak Ridge, TN 37830
Operated By
Union Carbide Corporation
For The
U.S. Department of Energy
Contract No. W-7405-eng-26

Task 1.4 - Plan Field Test Program

Table of Contents

1.0 INTRODUCTION AND SUMMARY

The Phase 2 program plan comprises the design, fabrication, and field-testing of production-like water heaters. This plan also includes endurance testing of the water heater and its components. It is felt that this will provide a more highly-developed field-test unit and will obtain greater reliability, both of which will insure a more successful field test.

Figure 1 shows the timing planned for Phase 2. Phase 2 comprises two main tasks. The first task consists of the construction of 10 prototypes by Amtrol (manufacturing subcontractor) to AMTI's (contractor) design. These units will be basically the same as the prototype unit developed in Phase 1. Once the units are operational, they will be evaluated by both Amtrol and AMTI. Amtrol will use its units to familiarize its personnel with the water heater, to evaluate its manufacturability, and to conduct independent tests. AMTI will set up a unit for endurance testing and will use another for advanced developmental work. Current plans, which are contingent on development status and scheduling, are to submit one of the preliminary prototypes to AGA's research laboratory for early evaluation of the design.

The second task consists of the design, construction, and field testing of the production design. Based on inputs from the first task, a production protytype will be designed by AMTI and 30 units will be built by Amtrol. Twenty of these will be used for field testing and the remainder will be used for AGA certification, laboratory testing, demonstration, and spare parts. The field testing will emphasize demonstration of energy savings and will include comparisons with "high efficiency" units currently being sold. At the end of the field tests, the results will be disseminated through as many channels as possible to create public awareness of the unit. This will serve to generate interest in the technology and aid in its introduction to the marketplace.

EXHIBIT I

MODIFIED PROGRAM SCHEDULE - PHASE 2

TASK NO.	TASK DESCRIPTION
2.1	Prototype Manufacture & Test
2.1.1	Prototype Construction
2.1.2	Design Evaluation and Refinement
2.1.3	Manufacturer's Evaluation
2.1.4	Endurance Testing
2.1.5	AGA Design Review
2.1.6	Task 2.1 Draft Report
2.1.7	Task 2.1 Final Report
2.2	Manufacture and Field Test
2.2.1	Advanced Development
2.2.2	Pre- Production Design
2.2.3	Pre-Production Prototype Fabrication
2.2.4	Lab Efficiency & Field Test
2.2.5	AGA Certification
2.2.6	Water Heater Evaluation
2.2.7	Disseminate Results
2.2.8	Dissemin. Material
2.2.9	Task 2.2 Draft Rep.
2.2.10	Task 2.2 Final Rep.
2.3	Final Report
2.3.1	Final Report Draft (2.3D)
2.3.2	Final Report (2.3F)

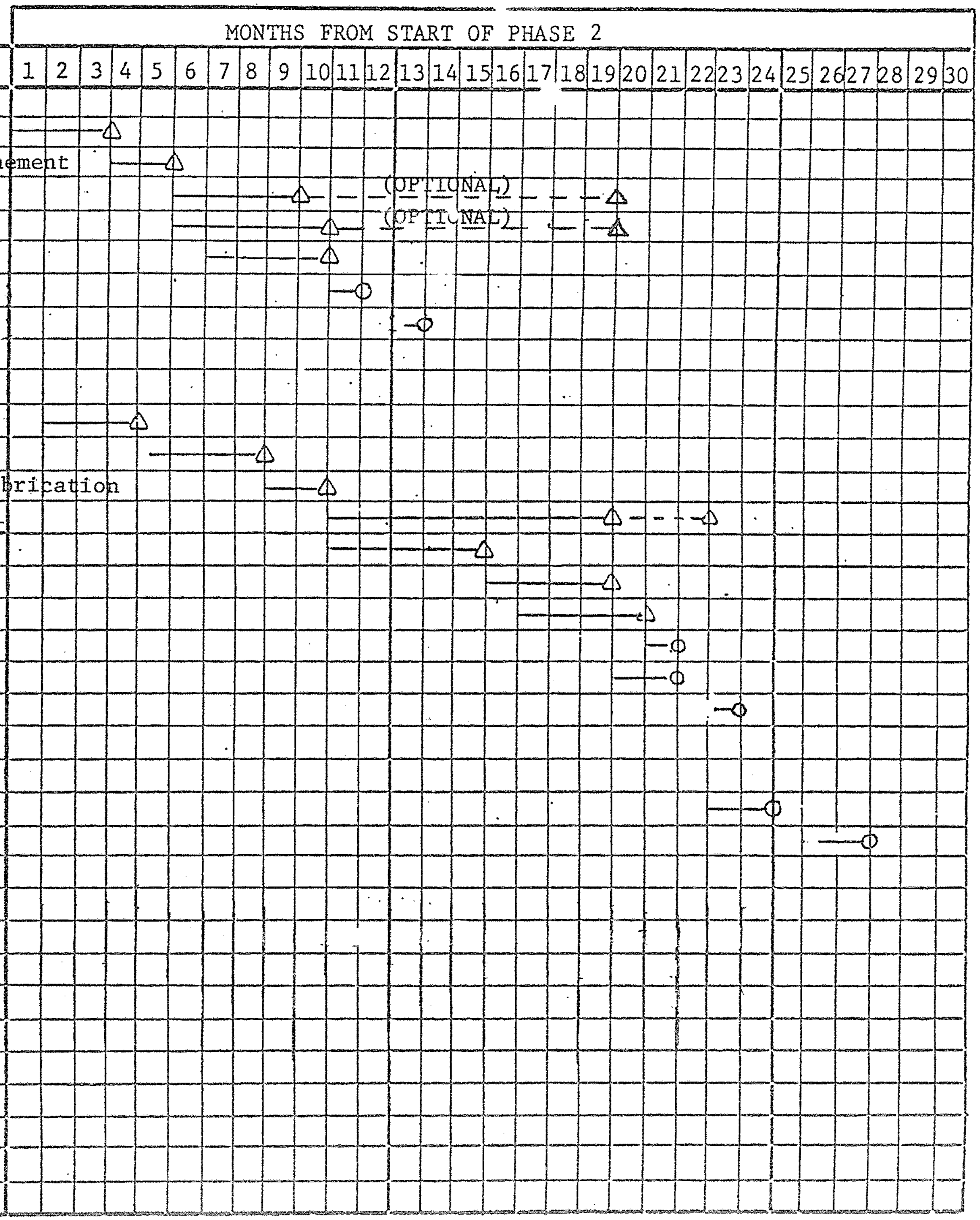


Figure 1. Phase 2 PROGRAM SCHEDULE

2.0 Prototype Manufacture and Test

Prior to the design, manufacture and field testing of the production version of the water heater, ten water heaters will be built to the engineering prototype design developed in Phase 1 of the current contract. These units will be used to evaluate the design from a manufacturing standpoint during the construction phase. Some of the units will remain at Amtrol and be used by them for independent evaluation of the unit. Others will be used by AMTI to perform endurance tests which will yield information that can be used in the design of the field test units to insure trouble free operation. If the prototype design is sufficiently close to the production design, a unit will be taken to AGA for evaluation.

2.1 Prototype Construction

In order to evaluate the design of the water heater from a manufacturing viewpoint, Amtrol will build ten prototypes. AMTI will supply the working drawings for the combustion system, heat exchanger module, and stack configuration.

The current plan is to use modified "off-the-shelf" components for some parts and small lot fabrication techniques for others. The internally insulated tanks will be produced on a full-scale production line. Table 1 shows a list of the major components and the intended fabrication techniques.

2.2 Design Evaluation and Refinement

The objective of this task is to evaluate the prototype units both as to average unit performance and reproducability of performance. The evaluation will include differences in energy recovery, standby losses, control action and firing rate. All ten units will be checked out by AMTI. Any required modifications will be made at this time. Seven units will then be sent to Amtrol for a separate evaluation. The remaining three units will

TABLE 1

Ten Prototype Manufacturing Plan

	Component	Fabrication Technique
1.	Tank and Stand	Amtrol Manufactured Component
2.	Heat Exchanger	
	Tubing	Amtrol Manufactured Component
	Headers	Modified Plumbing Fittings
	Shroud	Hand Fabricated From Sheet Metal Stock
3.	Burner/Aspirator	
	Burner	Hand Fabricated From Perforated Sheet Stock
	Aspirator	Modified Plumbing Fittings, Spinnings
	Pilot	Purchased and Modified
	Igniter	Purchased and Modified
4.	Control	Purchased
5.	Piping and Valving	Purchased

be used by AMTI for the endurance testing and advanced development.

2.3 Manufacturer's Evaluation

Up to this point, Amtrol has not had a prototype unit. This was due to the existence of only one prototype at AMTI and even this unit was constantly being changed during Phase 1. It is planned that Amtrol will run prototype units in their plant so that their engineering, manufacturing, and design personnel can evaluate the unit. Evaluation will involve both testing the units at the plant, and after sufficient confidence is gained in the reliability of the units, Amtrol will place some in residences to evaluate performance in a field setting.

2.4 Endurance Testing

Prior to committing to a production design and field testing units, a unit will be set up in the laboratory to evaluate its performance both for satisfying residential household demands and for unattended long term usage.

In order to run the unit over extended periods of time and for various duty cycles, a series of timers and solenoids will be set up as pictured in Figure 2. Thermocouples will be placed in the tank, on heat exchanger surfaces, and burner surfaces as shown in the figure. An elapsed timer will be used to keep track of burner operating times. The timers will be programmable to allow varying cycles and draw rates to be simulated. For example, it is planned to set up the heater to operate at an accelerated pace to simulate one-year's burner operation. Daily burner operation for a 64.3 GPD(1) draw and a burner input of 40,000 BTU/Hr is about 1.7 hrs. or 622 hours per year. With a 10 minute tank drain time and a 1 hour

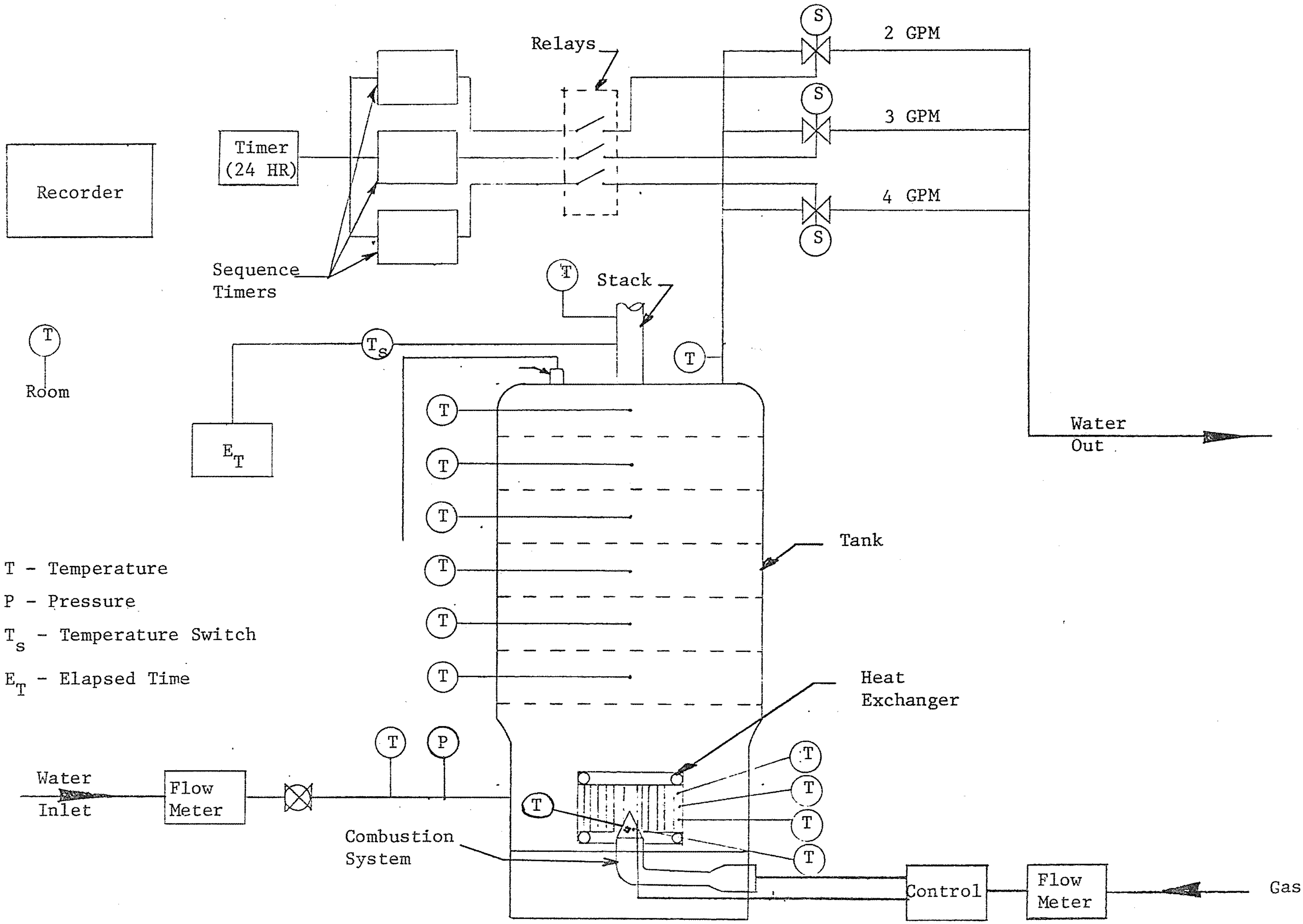


FIGURE 2. ENDURANCE TESTING FACILITY

burner on-time to heat up the tank, about 20 cycles per day could be programmed. This would result in 18 hours of burner operation per day or 622 hours in 35 days. By monitoring temperatures and gas and water consumption, the performance of the unit as a function of time can be evaluated. Temperature of the heat exchanger surfaces and of the water temperature drop across the heat exchanger will give an early indication of fouling or scale.

At the end of this time the unit will be examined for potential problems. Burner components will be examined for overheating. Surfaces exposed to the combustion gases will be examined for corrosion. The heat exchanger will be cut apart to examine it for evidence of scale and fouling.

Other testing which will be done on this rig will be to simulate various usage patterns and the unit's response to these patterns. Combinations of various draws for plumbing fixtures can be run to evaluate the ability of the heater to meet household demands. A series of short draws of sufficient length to initiate burner operation, but not long enough to change all the water in the tank will be used to evaluate the "stacking" tendency of the water heater. Energy consumption tests can be made using a draw pattern such as that in Table 2.[2]

While many performance tests will be planned for this unit, the primary purpose will be to insure the success of the field testing by identifying and eliminating problems with the design.

2.5 AGA Design Review

While it will be premature to seek AGA certification[3], an early indication of certification deficiencies would be valuable in designing the production unit. Some potential problems have already been identified by a consultant familiar with the ANSI design standards. These center mainly on pilot/burner accessability and servicing. Also pilot lighting was identified as a potential problem area.

After an evaluation of the prototypes by both Amtrol and AMTI a

TABLE 2

DRAW SCHEDULE[2]

Time (Min)	Flow (GPM)
0	0
420	5
423	0
435	5
437	0
1140	4
1141	0
1146	4
1147	0
1152	4
1153	0
1158	4
1159	0
1260	3
1265	0
1320	3
1325	0
1440	0

Total Gallons	71
Ambient Air Temperature (°F)	70
Water Temperature (°F)	60

decision will be made whether it will be worthwhile submitting the unit to AGA. If so, a unit will be submitted to AGA's research labs for evaluation instead of being entered in their certification facilities. This unit will be run through the ANSI tests, and deficiencies, if any, will be reported. This is an informal procedure offerred by AGA to provide an early indication of certifiability.

If Amtrol and AMTI feel there will be sufficient differences between the prototype and production unit to render the AGA tests meaningless, a unit will not be sent.

3.0 PRODUCTION VERSION MANUFACTURE AND FIELD TEST

This section forms the main part of the Phase 2 Project Plan. This is to perform a field demonstration test of the high-efficiency water heater. The first task of the plan improves the unit from a manufacturing and operational viewpoint. A production design will then be performed and production prototypes will be manufactured. Laboratory efficiency tests will establish unit performance. These units will then be field tested for one year. At the end of these field tests, results will be disseminated.

3.1 Advanced Development

This development task is required prior to the production design and will include the following subtasks:

- Evaluate sealed combustion.
- Improve servicing of the Unit.
- Improve reliability of the Unit.
- Lower manufacturing costs.
- Perform critical AGA tests.
- Improve service efficiency.

Service Efficiency Goal

The service efficiency goal for this project is 70% including the effect of exfiltration. This has been evaluated for a draw of 75 gallons per day at a water inlet temperature of 60°F, an ambient temperature of 70°F, and 90°F water temperature rise. Figure 3 is a plot of service efficiency versus energy recovery for these conditions excluding exfiltration. In order to account for exfiltration losses, the project goal is increased to 78%(4) when results are presented excluding exfiltration. Shown on this plot are the revised project goal of 78% and the measured prototype results of 66.4%. For reference, a conventional water heater with a service efficiency of 51.3% and a current "high efficiency" unit with a service efficiency of 61%. As can be seen, the project water heater falls short of the project goal by 11.6 percentage points. The elimination of sealed combustion as a design feature accounts for 8 of the 11.6 percentage points

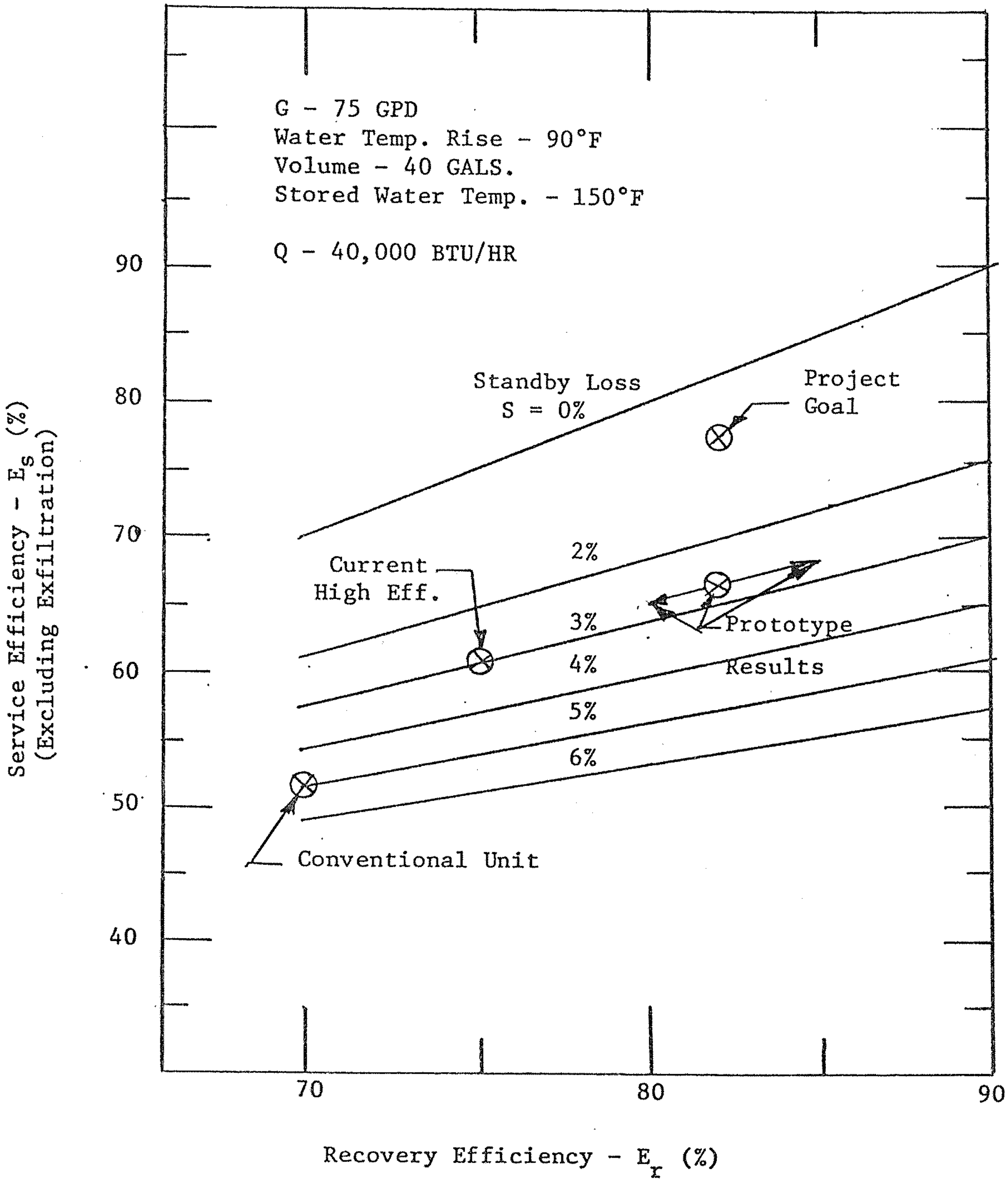


Figure 3: Service Efficiency Versus Recovery Efficiency at Various Standby Losses

while the remaining 3.6 points are due to higher than expected standby losses.

Figure 4 shows the standby loss as a function of tank and fitting losses and pilot energy recovery. As can be seen in the figure the tank and fitting losses were 450 BTU/HR versus a goal of 300 BTU/HR and the pilot recovery was 30% versus a goal of 80%. The tank and fitting losses should not be considered final values because the tank is still undergoing development at Amtrol. The new tank will have a different insulation composition and the thickness at the top will be increased. This should decrease the tank and fitting losses. Also, during this task, an evaluation will be made of heat traps for use on the water heater to evaluate their impact on the standby losses.

Because of developmental problems with the combustion system, extensive development of pilot energy recovery was not performed. The pilot system was debugged to the point that it was operational and the pilot efficiency was measured. There was no attempt to add transfer surface to the heat exchanger to improve this efficiency nor was the placement of the pilot varied nor was the air-fuel ratio in the pilot optimized. In the advanced development task this will be done.

Evaluate Sealed Combustion

During Phase 1, with sealed combustion, firing rates above 30,000 BTU/HR were difficult to achieve. Consideration of the relative importance of sealed combustion led to its temporary shelving until satisfactory performance could be demonstrated. However, the use of a concentric section to act as a thermal check valve was kept in the design. While this does not stop the loss of conditioned air and the heat loss from the heat exchanger during the standby cycle.

Using a simple model, the savings due to sealed combustion were estimated in Phase I to be about 9-10%. While nothing has been found to change this result, it is felt that this option should be re-examined during this phase of the project. A cost/benefit analysis for this option will thus be performed to update that performed during Phase 1.[5]

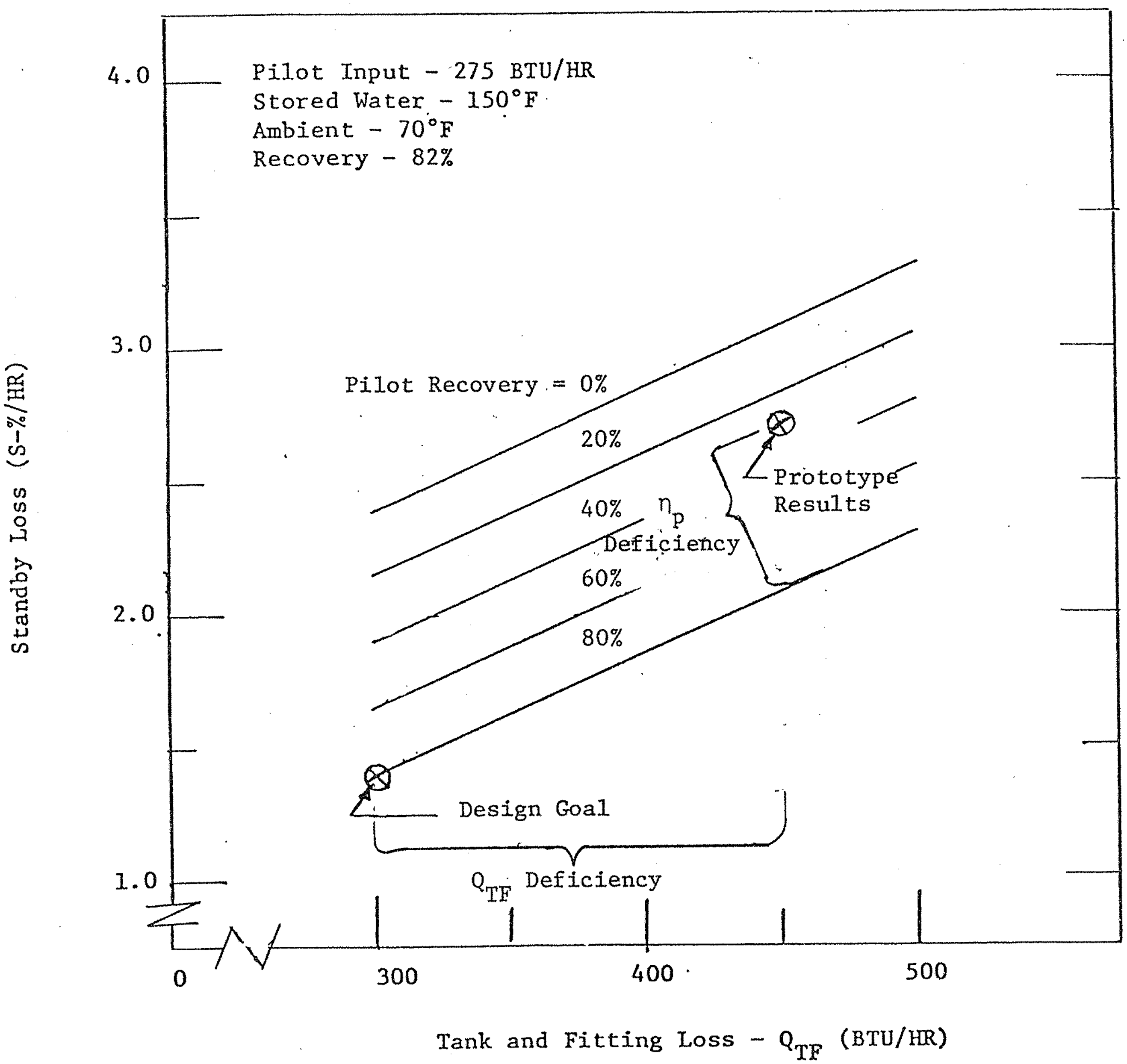


Figure 4 : Standby Loss as a Function of Tank and Fitting Losses and Pilot Recovery

Improving Servicing of The Unit

Improving servicing of the unit centers primarily around the burner/aspirator/pilot assembly. The pilot and pilot thermocouple are installed in the burner by feeding the units through a tube on which the burner is mounted and up into the burner. They are mounted integral with the surface of the flameholder screen as can be seen in Figure 5. This was done to place the pilot high in the burner/heat exchanger assembly to promote stratification of the pilot exhaust products and thus promote high pilot recovery. This configuration will be re-examined to try and divorce the pilot from the burner assembly with the objective of improving servicing of the unit. With the current design the entire burner/pilot assembly including the aspirator has to be removed from the unit in order to service the pilot. An approach will be evaluated in which the pilot, the thermocouple and the igniter are mounted in a ceramic base which is installed from the bottom of the unit.

The large size of the aspirator causes some difficulty during installation. In order to achieve a high efficiency in the aspirator, a very long mixer/diffuser was used. An attempt will be made to shorten this length by either using multiple gas orifices or by using an aspirator with dual mixer and diffuser assemblies.

Another area which requires improvement is pilot lighting. The AGA code requires igniting the pilot with a paper match. With the current unit this is difficult to achieve.

An area requiring improvement in reliability is the burner/pilot system. The main problems with burner reliability are coupling the heat exchanger and exhaust ducting. Because of the character of natural draft, it is difficult to treat these components as separate elements. Commonly, a large pressure drop (or "controlling orifice") would be used to minimize or "uncouple" the burner from the other components. Because the burner is natural draft, decoupling in this fashion is impractical due to the low

ADVANCED MECHANICAL TECHNOLOGY.

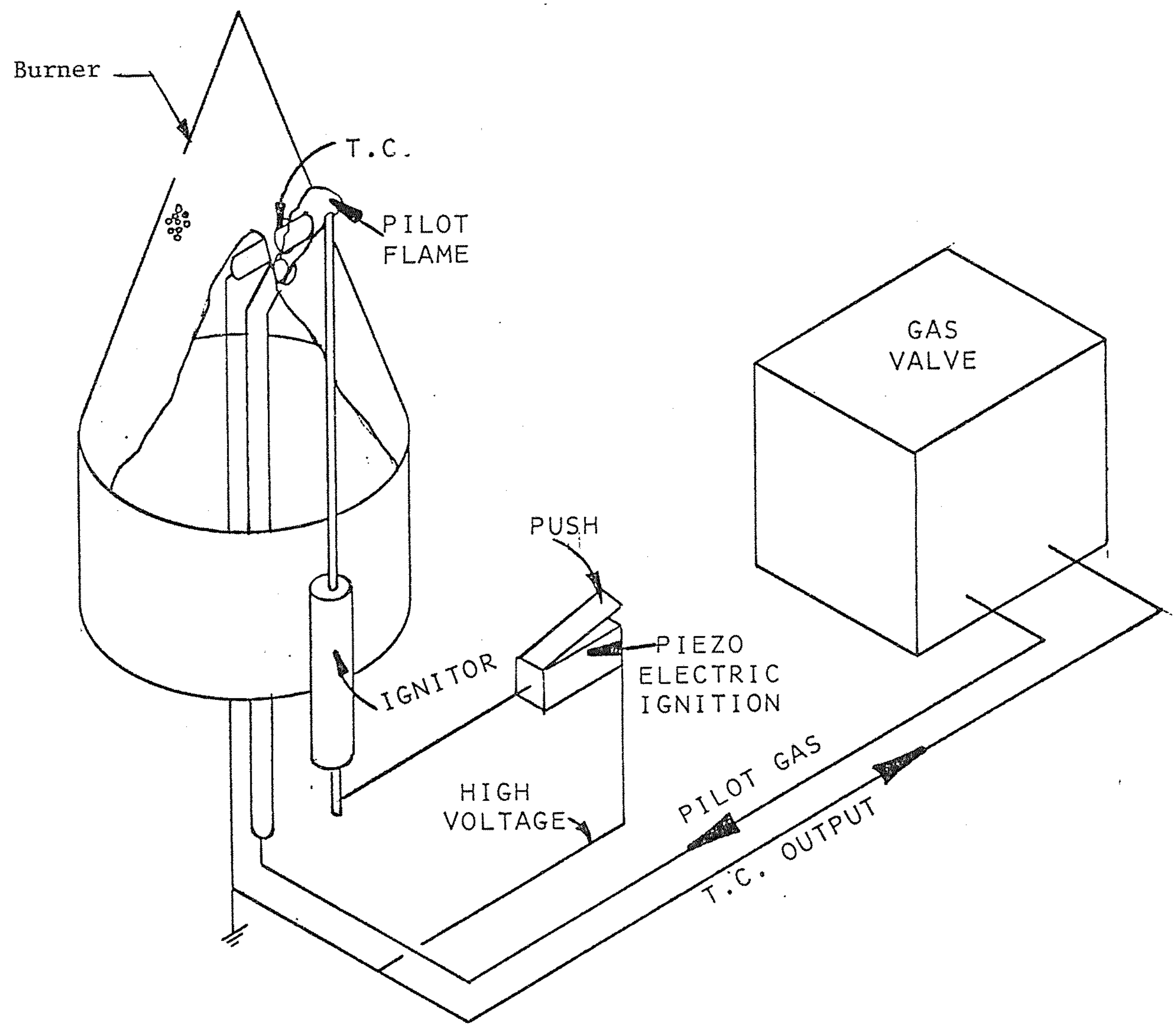


FIGURE 5. Pilot/Burner Configuration

available system head. Moreover, the flow resistance in all of the components is the same order of magnitude as that found in the burner. This may favor burner/system interactions. Further work is required to find methods other than large pressure drops to insure reliable burner operation.

Another potential reliability problem lies with the pilot. The "strength" of the pilot is low due to low BTU input. Thus, it is susceptible to draft, wind, and other environmental factors. Adddditionally, the pilot is ignited using a piezoelectric ignition system in combination with a high voltage electrode which uses the pilot thermocouple shield as the ground. Because the igniter is in the path of hot combustion gases there is a potential for corrosion or fouling of the high voltage electrode. This is also true of the pilot thermocouple shield. This would result in a weak spark decreasing the reliability of the ignition system. While this has not been a problem in Phase 1, it may be that with heavy usage this will become a problem.

Lowering Manufacturing Costs

The areas of manufacturing cost which have been pointed out by Amtrol as requiring attention are the heat exchanger assembly, the burner/aspirator assembly including the pilot, and the stack. With regard to the heat exchanger, the main areas of concern are the upper and lower headers and the extensive use of brazed joints. Amtrol has suggested that the headering arrangement be examined to see if it could be made in a different configuration. One suggestion would be to use square mitred tubing instead of the current "donut" configuration used. Another would be to use a rolled seam for the header halves instead of the present brazed seam.

There are two major criticisms of the burner/pilot design. The first is the shape of the burner. The conical shape being used would be expensive to manufacture and should be examined to see if another flameholder shape or type of burner can be used. The criticism concerning the pilot relates to the integration of the pilot with the burner. This has been cited in the previous section concerning servicing of the unit and will be examined to see if the pilot can be made separate from the burner.

These are some of the suggestions by Amtrol and are discussed here to illustrate the kind of activities intended for this task. Any major changes will be tested on the unit prior to inclusion into the production design.

Perform Critical AGA Tests

While it will not be worthwhile to run all of the AGA tests(3) on the unit, it felt advisable to perform some of the more critical tests early to uncover potential problem areas. These tests include: "Wind" tests to determine ability to withstand downdrafts and other external perturbation, combustion tests with alternate gases, and emissions tests.

3.2 Pre-Production Design

This task involves the first design of the water heater intended for production. While the prototype design was not intended to vary significantly from a production design, its development was more concerned with performance and operation than it was with production considerations. This design will differ from the engineering prototype in two areas. The first area involves the manufacturability of the unit. Prior to the production design, input from Amtrol will have been received from their evaluation of the prototypes. Any changes for production which are recommended will be incorporated into the production design. Any design change which might affect the performance will be tested on the advanced development unit prior to being included in the production design.

The second area which the production design will address will be the AGA(3) code. There are many details contained in the code which were beyond the scope of the engineering prototype design. These include such things as sheet metal thickness of the various components, the size and nature of access holes, and other such details. During this design phase, these code details will be incorporated into the design of the unit.

At the end of this design task, a full set of drawings consisting of assembly, subassembly, and detail drawings will be turned over to Amtrol. They will review the drawings and then build a "proof of design" unit as a final check on the drawings prior to building the field test units.

3.3 Pre-Production Prototype Fabrication

The construction of the production prototypes will take place at Amtrol using a combination of production techniques. Parts of the unit will use standard Amtrol manufactured components, and others will be made in the production configuration using small quantity fabrication techniques. Specifically, the tank assembly including the liner, insulation, stand, and fittings will be a standard manufactured sub-assembly. The heat exchanger tubing is a current Amtrol product. The remainder of the components will be specially fabricated. Figure 6 shows a schematic of the water heater showing the various component parts. Amtrol is now in the process of setting-up an automated production facility for the manufacture of internally insulated, plastic lined steel tanks which will be used for these units. A new plant has been built for the manufacture of these tanks as well as other product lines.

Table 3 shows the major components of the water heater, the techniques expected to be used for the production prototypes and one or more manufacturing options for the production version. A tank assembly will be made of deep-drawn steel halves, a one-piece molded liner, and molded insulation. The insulation will be reaction injection molded in two halves and inserted between tank and liner before the halves are welded. The heat exchanger headers including the riser and downcomer will be built from copper tubing and standard fittings in the production prototupes. The headers will probably be stamped in the final production version. The finned tubing is already an Amtrol product. The combustion chamber housing will be made by rolling and welding for the production prototypes, while they would be deep-drawn for large quantity production.

The aspirator will be spun or rolled and welded for the production prototypes, while a stamping or formed tube can be used in production. The burner flameholder will be rolled and welded both for the production prototype and for the final production unit. Purchased components such as the pilot, ignition, gas valve and thermostat, etc. will be purchased and modified for the production prototypes, while these items will be purchased in their final form on an OEM basis for a production run. The parts list

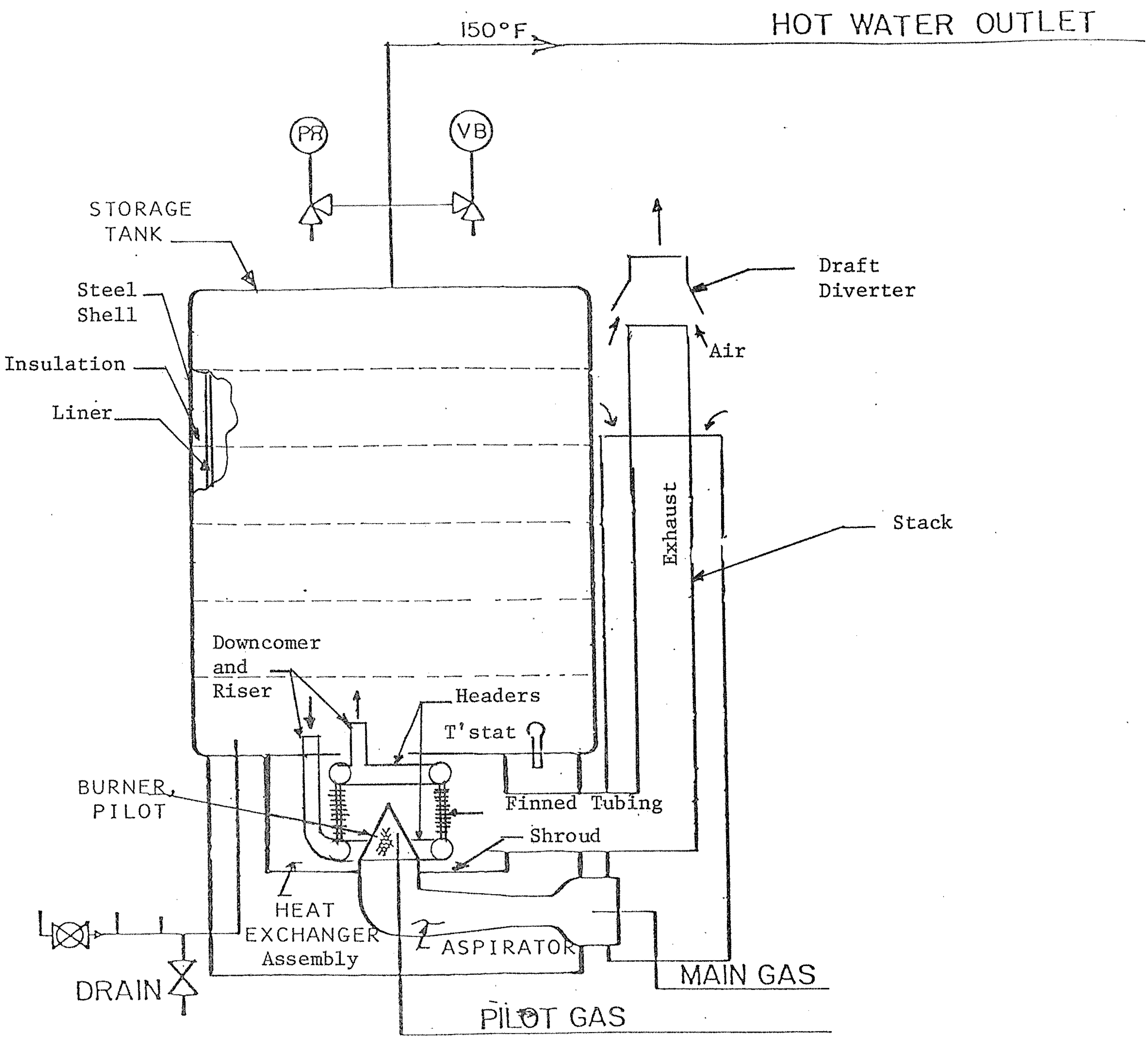


FIGURE 6. SCHEMATIC OF WATER HEATER AND COMPONENTS

TABLE 3. High Efficiency Water Heater - Production Plan

Component/Parts List	Prototype Production Technique	
	Production Prototype	Final Production
A. Tank		
1. Shell (Domes)	Deep-Drawn	Deep-Drawn
2. Liner	Molded	Molded
3. Insulation	Molded	Molded
4. Skirt	Rolled and Welded	Rolled and Welded
5. Flange	Cast	Cast
B. Heat Exchanger		
1. Headers	Fabricated	Stamped or Formed Tube
2. Riser and Downcomer	Purchased	Stamped or Purchased
3. Finned Tubing	Amtrol Product	Amtrol Product
4. Flange	Machined	Casting or Forging
5. Insulation	Purchased	Purchased
6. Exhaust Can (Shroud)	Fabricated	Drawn
C. Burner		
1. Aspirator	Spinning	Stamped, Pinched or Formed Tu
2. Flanges	Fabricated	Stamped or Drawn
3. Gas Orifice	Purchased	Purchased
4. Flameholder.	Rolled and Welded	Rolled and Welded
5. Pilot	Purchased and Modified	Purchased
6. Electrode	Purchased and Modified	Purchased
D. Controls		
1. Gas Valve	Purchased and Modified	Purchased
2. ECO Switch	Purchased and Modified	Purchased
3. Thermostat	Purchased and Modified	Purchased
4. Pilot Indicator	Purchased	Purchased
5. Piezoelectric Ignitor	Purchased	Purchased
E. Stack		
1. Intake/Exhaust Ducting	Purchased and Modified	Purchased
2. Draft Diverter	Purchased and Modified	Purchased
G. Piping, Fittings	Purchased and Modified	Purchased

in Table 3 is representative of the prototype unit and should be considered preliminary. It is included here to show the nature of the various components relative to their production version.

After the units have been assembled at Amtrol, they will be fired and checked out prior to shipping. Standard Amtrol quality control procedures will be followed during manufacture of the field test units.

3.4 Laboratory Efficiency and Field Testing

At the beginning of this task, the recovery efficiency and standby losses of the project water heater, conventional water heater, and current "high efficiency" water heater will be measured using the D.O.E. test procedure(1). It is planned to test two of each unit. This data will then be used to establish water heater performance over a range of operating conditions. These will include daily water usage, stored water temperature, and ambient temperature. This model will be verified using one or more of the tested units operated over a usage pattern such as that shown in Table 2 at different water delivery temperatures. This will be done on the endurance test facility shown in Figure 2. Once this model is developed it can be used together with the field test data to predict savings for the project water heater in comparison with other units.

It is expected to field test about twenty units at various test sites, some of these units with the support of gas utilities. This project has been discussed with both Boston Gas and Consolidated Natural Gas, and both have expressed an interest in participating in the project if the unit and field test procedures meet with their approval. Boston Gas currently has 22 specially metered test sites which are being used to evaluate a new integated hydronic boiler/water heater design in a side-by-side comparison with conventional hydronic boilers and separate gas-fired water heaters. Consolidated has one hundred test sites which are intended to be used to test and evaluate new energy efficienct gas appliances over the next few years. Thus, both utilities are active in the field testing of new gas appliances and should aide greatly in the field testing part of this project. Additionally, the participation of other utilities will be enlisted, especially if they serve an intended market area of the new water heater.

The objective of the field testing will be to operate the unit under realistic conditions and to compare its performance against both conventional units and current "high efficiency" models that comply with ASHRAE 90-75 standards. Of the twenty field test sites, five of these will be "side-by-side" comparisons with current "high efficiency" units. If these units are not found at the selected sites, they will be installed as part of the project. Particular attention will be paid the installation of these units. It will be important to insure that the units at each field test site are installed in a similar manner. Inlet and outlet connections should be similar in orientation and length to make a valid comparison. The possibility of using heat traps and insulation on piping connections at some of the test sites will be examined.

All but two of the test sites will be set up as shown in Figure 7. The new units will be installed with similar plumbing arrangements to the existing unit. Prior to starting the tests, the heaters will be tested to measure stack efficiency and the thermostats will be set to the same temperature. In addition, a tempering valve will be used to assure that both heater deliver water at the same temperature. Gas and water meters will be provided for each unit to measure consumption during active and standby periods. Weekly readings of gas and water consumption will be made. Thus, these tests will yield two sets of data each week: water heating consumption on one heater and standby losses on the other.

Two of the test sites will be instrumented to obtain more detailed data compared to the bulk of the sites. This will be done for one site with a conventional water heater and one with a "high efficiency" water heater. Figure 8 shows the test set-up which will be used at these two sites. This technique has been successfully applied by AMTI to measure relative and absolute performance in the field in an on-going program. In addition to gas and water consumption, BTU meters will be installed to obtain the useful heat content of the hot water delivered to the house. Thus, the service efficiency of both units can be determined accurately.

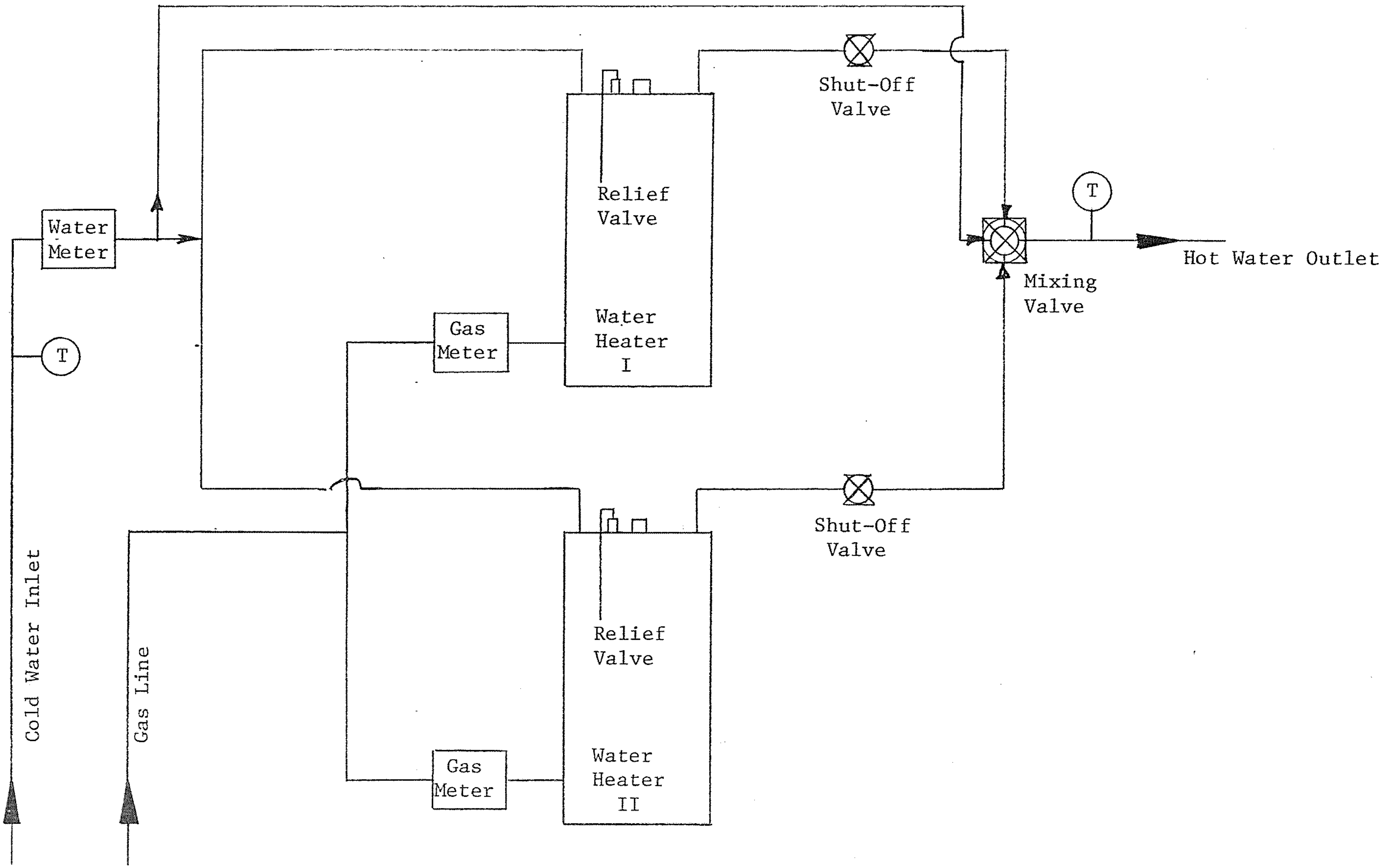


FIGURE 7. Simple Field Testing Schematic

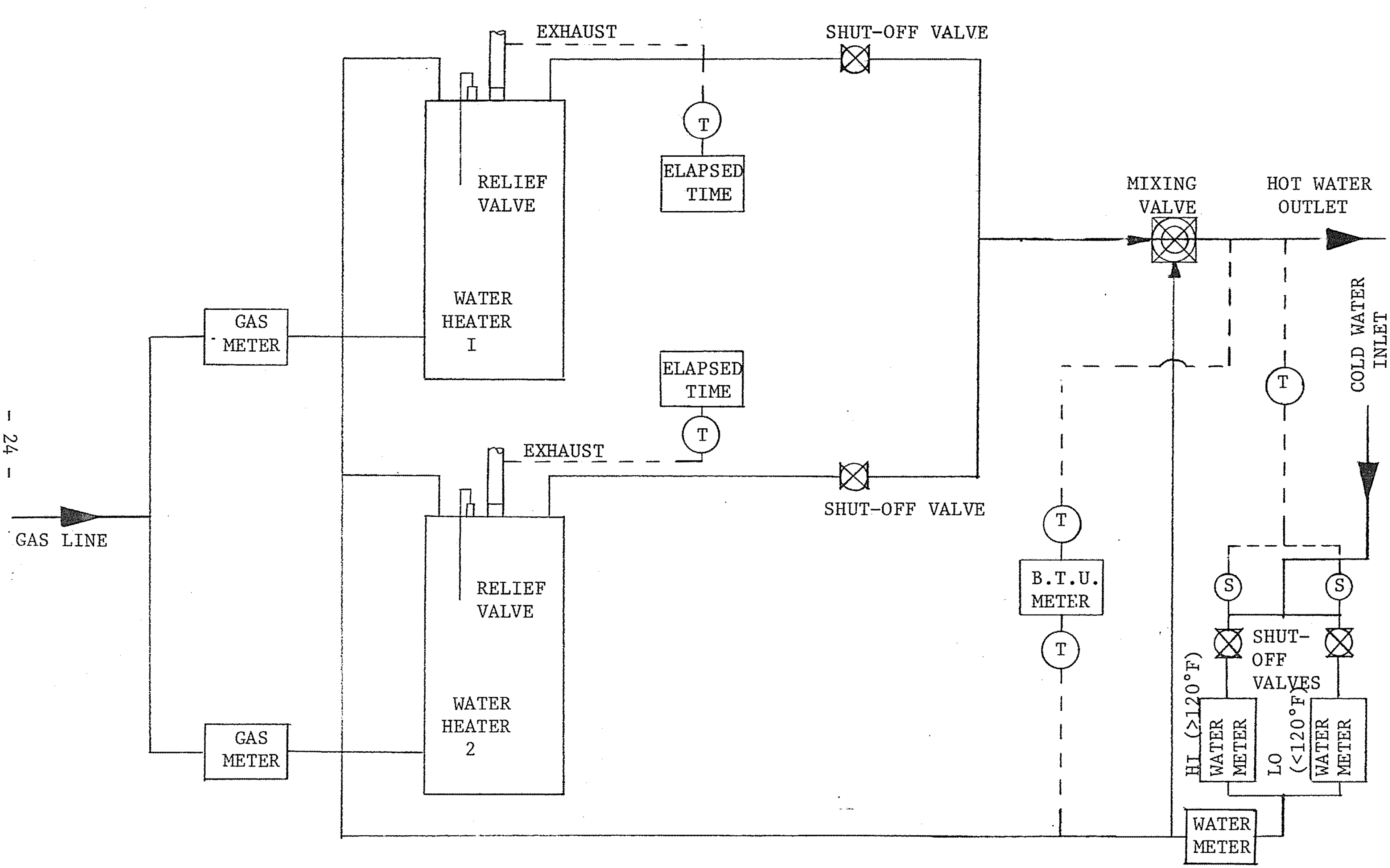


FIGURE 8. Detailed Field Testing Schematic

A recorder will be used to monitor hot and cold water temperatures, ambient temperatures, and exhaust temperatures. Elapsed time meters and counters will be used to monitor burner starts and on-time both during water heating and standby operation. These will be activated by sensing exhaust temperature.

Another parameter which will be tested at these two sites is the adequacy of the hot water. This will be accomplished by sensing the hot water outlet temperature and using solenoid valves to direct the water to be measured with one meter if it is below 120°F (inadequate) or with a different meter if it is above 120°F (adequate). Thus at the end of a test period, two meter readings will be obtained, water usage below 120°F and usage above 120°F. A schematic of this plumbing circuitry is shown in Figure 8.

While the field tests are expected to yield information regarding energy savings for water heating using the new unit being developed, of more importance will be the field information regarding operation and reliability, and consumer reaction. Based upon past experience, the field tests will point out technical, application, and consumer problems which would not have been uncovered in the laboratory. The field tests are expected to extend over a period of one year to observe operation of the unit under all seasonal conditions. The tests are expected, however, to yield valuable information from the beginning, including data on installation, servicing, and reliability. Test data will be reduced as it is acquired so that an early reading of energy savings is available. In order to expedite other tasks in the project, the data will be evaluated at the nine month point. Later this will be amended to include the last three months of testing.

3.5 AGA Certification

This part of the plan involves taking one of the units built to the production design and submitting it for AGA certification. The AGA certification procedure consists of two parts - the performance and the construction of the unit. The performance evaluation of the unit includes minimum energy recovery efficiency and maximum standby loss standards as well as proper combustion, controls, and safety features. The unit is subjected to tests which include abnormal gas line pressures, wind tests, and the use of hard-to-light gas/ air mixtures. This is all to assure that the unit can meet minimum standards for a safe design. The construction phase of the certification insures that the design of the unit meets standards for materials of construction, corrosion resistance of parts likely to be exposed to a corrosive environment, and protection of the unit from unauthorized access.

During the advanced development phase, some of the more critical tests will be performed in AMTI's laboratory. This will serve to indicate any potential problems and to deal with them in the production design. Prior to submitting the unit for certification, a heater will be pre-tested in a consultants laboratory near AGA. This laboratory is run by a consultant familiar with the code and who has the capability to run the unit through the AGA series of tests. This will provide an early reading on certification and an opportunity to correct deficiencies prior to submitting it to AGA. After the water heater has been satisfactorily pre-tested it will be submitted to the AGA certification labs. This is the same procedure AMTI has successfully used in the past for certification of a gas-fired boiler.

The last part of certification will be the approval of Amtrol's manufacturing facility. Amtrol is currently in the process of obtaining approval for the construction of gas-fired boilers on another project and will be familiar with the AGA requirements for the manufacturing of gas-fired appliances well before they require it for this project.

3.6 Water Heater Evaluation

The main objectives of this task will be to provide an analysis of the results of the field test for dissemination and to define any remaining problem areas which have arisen due to actual operating conditions found in the field.

While results from the field testing will be continuously monitored and recorded, at about the six-month point an evaluation of the water heater design will begin. This evaluation will consist of not only the energy savings of the water heater relative to the units it is being tested against, but also will include operational, servicing, reliability, and other factors. The overall life-cycle cost effectiveness of the water heater will be re-evaluated in light of the field test results. Any problems encountered during the test will be analyzed, and modifications, if any, to the design will be made. Any further work which might be required to accelerate the implementation of the improved units will be recommended.

3.7 Dissemination of Field Test Results*

The primary thrust of Amtrol's marketing campaign would be to installers, distributors, and builders. Promotional material will be prepared using the results of the field tests and laboratory test data to promote the product. To the extent possible, the help of utilities will be enlisted to advertise the energy saving features of the design. Public gas utilities will be approached to help with the introduction of the unit by promoting the unit by generic type. Advertising of units by brand names and selling of units can be done by uncontrolled utilities, and these will be approached to promote and/or sell the unit in their marketing areas.

AMTI will prepare promotional material to be used to describe the design and operation of the water heater for use in various publications. These will describe the principle of operation, how it differs from conventional units, and the results of the field tests. Promotional literature in the form of brochures currently being used to publicize D.O.E. projects will be prepared for this project.

Control of publicity regarding this water heater will be in the hands of

* Printed material related to the project will be submitted to ORNL-TM for approval prior to dissemination.

Amtrol's marketing staff. The timing of the various promotional activities and areas of the country which will be selected for the bulk of these activities will be chosen by Amtrol. The success of the project will depend on Amtrol timing the promotional and advertising with their production and sales plans. For this reason, they should control this part of the plan.

4.0 References

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

2. "Study of Energy-Saving Options for Refrigerators and Water Heaters", Vol. 2: Water Heaters; Arthur D. Little, Inc., May 1977.

3. "American National Standard for Gas Water Heaters", Vol. I, ANSI Z21.10.1-1975, American Gas Association.

4. "Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", Water Heater Development, Task 3.2 Report, AMTI January, 1980.

5. "Research, Development and Demonstration of a High Efficiency Gas-Fired Water Heater", Concept and Market Evaluation, Task 2 Report; AMTI, October 6, 1978