DEVELOPMENT OF A SPACE HEATER AND A RESIDENTIAL WATER HEATER BASED ON THE PULSE COMBUSTION PRINCIPLE

William H. Thrasher, Robert J. Kolodgy and James J. Fuller
American Gas Association Laboratories

ABSTRACT

The Research Department of the American Gas Association Laboratories, under sponsorship of the Gas Research Institute, has developed a highly efficient space heater and a residential water heater based on the pulse combustion principle. The space heater, being developed in conjunction with Martin Industries, will provide a safe, low cost, compact heating appliance with efficiencies approaching those of unvented heaters without requiring venting the flue products directly into the heated area. Prototype models were developed that operated with steady state thermal efficiencies in excess of 92 percent at a fuel input rate of 18,000 Btu/hr. Twelve space heaters were successfully field tested during the 1983-1984 heating season at test sites throughout the country.

The attributes of pulse burners which make them particularly attractive for water heaters are excellent heat transfer capabilities leading to high recovery efficiency, low standby losses because of the absences of a conventional internal flueway and self-powered venting without the necessity of a chimney. The latter attribute is especially desirable for a water heater in view of the growing availability of home heating equipment which also can dispense with a chimney. General construction features of the 40 gallon water heater having a nominal fuel input rate of 42,000 Btu per hour are described. Recovery efficiencies in excess of 90 percent, when tested in accordance with the Department of Energy test procedures, have been demonstrated. These measurements of recovery and service efficiencies are presented and compared with those of conventional units. Operating noise, which appears to be well within acceptable limits, is also discussed.

DEVELOPMENT OF A SPACE HEATER AND A RESIDENTIAL WATER HEATER BASED ON THE PULSE COMBUSTION PRINCIPLE

William H. Thrasher, Robert J. Kolodgy and James J. Fuller
American Gas Association Laboratories

The American Gas Association Laboratories, under the sponsorship of two separate research programs from the Gas Research Institute, has developed highly efficient models of a space heater and a 40 gallon residential water heater, both based on the pulse combustion principle. A minimum efficiency goal of 90 percent was established for the space heater program. The recovery efficiency goal of the water heater program was set at a minimum of 92 percent when tested in accordance with U.S. Department of Energy procedures(1). An auxiliary water heater efficiency goal of 85 percent annual service efficiency(2) was also established.

There are basically three types of space heaters in the market today: 1) unvented, 2) vented and, 3) direct vent units. Each of these three types of appliances have their own advantages and disadvantages. Unvented methods of heating are efficient since all of the heat of combustion is useable. With very tight structures the supply of air for both combustion and dilution of combustion products may be marginal and create an unsafe condition. Vented heaters have a lower efficiency than unvented heaters since the flue products carrying energy are vented outside the heated area. The exhausting of heated warm air through the venting system further reduces the overall heating system efficiency. Direct vent heaters, which obtain combustion air from outside and discharge flue products outside, seal the combustion system from the conditioned area. American National Standards specify a minimum efficiency of 70 percent for gravity and auxiliary fan type direct vent heaters. These efficiency levels have room for improvement. The pulse combustion space heater will provide the consumer with a directly vented appliance that has efficiencies approaching those of unvented heaters without the disadvantage of discharging the combustion products into the heated area.

Three market areas are targeted for the high efficiency space heater being developed. First, the home improvement market where existing heating systems cannot reasonably supply additional heated air. The heater could be utilized in any area where vented or unvented space heaters are presently supplied. Second, areas in the sunbelt that have only marginal heating requirements or do not normally have central heating systems installed. One or more pulse space heaters could be utilized to heat the total dwelling and keep both installation and operating costs to a minimum. Third, American consumers who find it difficult to keep up with the increasing cost of energy, burn fuel inefficiently or heat their home with equipment not intended for that purpose. The pulse space heater will also be ideal for leasing programs by gas utilities.

The actual service efficiency of any storage water heater depends strongly on the specific circumstances of water usage versus storage volume, thermostat setting and installation. Thus it is impossible to state across-the-board figures of the efficiency improvement and resulting gas savings that a given home owner will realize with an advanced appliance. Currently gas units average 70 percent DOE recovery efficiency and 44 percent annual seasonal service efficiency.

More than half the residences in the United Stated have gas water heaters. After space heating, water heating is the next largest residential use of gas. However, in the National Association of Home Builders (NAHB) Research Foundation Energy Efficient Research 2 Home, the cost of heating water for domestic use exceeded the cost for heating the home (report presented at the NAHB 39th Annual Convention and Exposition, January 22-25, 1983).

With the cost of natural gas, it is important to develop fuel efficient residential appliances which will be economically attractive to the consumer. The pulse combustion principle has been proven to reduce fuel consumption significantly in residential furnaces and shows similar promise when applied to domestic water heaters and space heaters.

Direct venting, which is possible with pulse combustion systems, provides an additional economic benefit. The consumer who elects to install pulse combustion appliances in a new building, or one who elects to convert from other energy sources, will not require a chimney.

Test results indicate the feasibility of applying the pulse combustion principle to residential water heaters.

SPACE HEATER

Design and Technical Approach

The space heater, being developed with Martin Industries as the participating manufacturer, is the first pulse combustion appliance that is specifically designed to be installed in the living area of a dwelling. Other pulse combustion appliances marketed today are designed for basement or closet installations which are somewhat removed from the living area. Because of this close proximity to the occupants the operating noise generated by the appliance is most critical and the final design must be quiet enough for a bedroom installation. The operating efficiency of the design is to be as high as possible, however, no less than 90 percent. The design should fit within a compact cabinet, no larger and preferably smaller than and styled similar to contemporary space heating equipment.

A fuel input rate of 18,000 Btu/hr was selected as being appropriate to cover the widest range of the market. The various individual components were developed with the consideration that they may be used in other models with a different fuel input rate. A fixed gas line is used and the heater is designed for attachment to the inside of an outside wall in a manner similar to contemporary direct vent units. The pulse space heater also utilizes outdoor air for combustion and vents the flue products directly outside thereby sealing off the combustion system from the conditioned area.

The basic concept of the combustor system is presented in Figure 1 with the various major components noted. An inner housing encloses the combustor and serves to distribute the circulating air flow, supplied by a centrifugal blower, over its components. An ignition control, inlet air decoupler box, air inlet/exhaust outlet system, fan/limit control and other components required to complete the space heater are attached and assembled as appropriate. A decorative outer cabinet encloses all components. The combustion system basically consists of a cast iron combustion chamber with an integrated mixer head, a cast iron exhaust pipe and a secondary heat exchanger fabricated from aluminum finned stainless steel tube. Circulating air flows over the combustor from bottom to top first passing over the secondary heat exchanger, then the exhaust pipe and finally over the combustion chamber prior to discharge into the heated area.

An oval shaped combustion chamber was selected as the most appropriate shape to maintain a minimum depth cabinet. All combustor system components were designed to fit within a 6 inch depth. The combustion chamber is internally enhanced and has external fins to facilitate heat transfer. Cast iron is the material of choice because Martin Ind. has an extensive casting facility and is most compatible with their existing production capabilities. The externally finned cast iron exhaust pipe has a length and inside diameter appropriate for good operation and heat transfer. The exhaust pipe is folded directly underneath the combustion chamber. The secondary heat exchanger is attached to the outlet of the exhaust pipe and is positioned directly underneath the exhaust pipe. The entire combustor system fits within a space 23-1/2 inches wide by 11 inches high by 5-1/2 inches deep. The exhaust outlet of the secondary heat exchanger is positioned close to the air inlet facilitating a concentric air inlet/vent outlet arrangement.

This pulse space heater design operates without an exhaust decoupler, a component normally utilized on pulse combustion equipment to acoustically break the system and permit various vent lengths after it. The exhaust decoupler can be eliminated because the heater is designed to be mounted on the inside of an outside wall. Normal variations in dwelling wall thickness, and the resulting vent system length, result in only minor variations in unit operation. Eliminating the exhaust decoupler also significantly reduces the size of the unit.

Several other components are added to the combustor to complete the space heater system. The air flapper valve, which controls the flow of combustion air, is enclosed within the air decoupler chamber, which also encloses a starting air (purge) blower. This blower operates only in a starting capacity prior to the pulse combustion process becoming self-sustaining and again for a short period of time after the thermostat is satisfied. A gas flapper valve and two gas orifices control the flow of gas to the combustor. Conversion from natural gas to propane is easily accomplished by changing one of the two orifices.

A concentric air inlet/vent arrangement is utilized to minimize the size of the hole required in the exterior wall of the structure. A 2-1/2 inch by 3-1/2 inch rectangularly shaped cutout is required in the structure. A vent cap, designed and fabricated by Martin Industries, provides a termination for air inlet and exhaust outlet.

Operation

Most of the heat transfer occurs from the combustion chamber where about 68 percent of the heat is transferred to the circulating air, the exhaust pipe transfers another 14 percent and the secondary heat exchanger which cools the flue gases to a temperature below condensing, typically below 120°F, transfers another 10 percent of the heat. Overall about 92 percent of the heat is transferred to the circulating air.

Combustion quality is good and the nitrogen oxide emissions are very low when compared to data obtained from conventional direct vent space heaters, see Table I (Conventional data reported by Thrasher and DeWerth, "Evaluation of the Pollutant Emissions From Gas-Fired Room Heaters", A.G.A. Laboratories Research Report No. 1515, Cleveland, Ohio, March 1979). Table I indicates that the average NO_x emission in ng/J of useful heat output for four field test pulse space heater units is about 22 percent of that reported for the conventional units. Those four units emitted an average of 21.1 ng/J of NO_x ($NO + NO_2$).

Table I. Space heater NO_x emissions.

	Average Of Four Field Test Units	Conventional Direct Vent Space Heaters*
NO, ppm Air-Free	29.0	97.6
NO_2, ppm Air-Free	12.7	7.6
NO_x, ppm Air-Free	41.7	105.3
NO_x, ng/J	21.1**	94.3***

NOTES: * A.G.A.L. Research Report No. 1515.
** Based on 90 percent seasonal efficiency.
*** Based on 50 percent seasonal efficiency.

One of the major problem areas inherent in any pulse combustion design is the sound level generated by the combustion process itself. The two major sound sources from the combustor are the exhaust outlet and the air flapper valve. The air flapper valve is enclosed in a heavy wall insulated air decoupler box which also contains the starting air blower. The air box acoustically breaks the system and also absorbs much of the air valve sound. The short transition piece between the air box and the concentric air inlet/vent arrangement also can transmit some sound to the interior of the dwelling. Earlier models, including the field test models, which had sheet metal and PVC air inlet/vent systems produced about 56 dBA measured 3 feet from the center front of the unit. The most current design has a PVC only air inlet/vent system and produces sound pressure levels inside the room of only 42.5 dBA, which is significantly lower. Exterior sound pressure levels of 63 dBA were obtained with the unit. This is only 2 dBA more than that obtained from a 5200 Btu/hr wall mounted window air conditioner.

The loudest sound source is now the circulating air blower. An air flow through the system of about 250 CFM is required to obtain the desired efficiency level. Reducing the circulating air flow will result in a corresponding decrease in system efficiency. The current design heater, with the PVC vent/inlet system described in the previous paragraph, operates with an interior sound pressure level of 59 dBA. Additional testing has indicated that essentially all of that noise is generated by the blower and is not from the air passing over the various heat exchanger components. We are now in the process obtaining a blower that moves the required air with a lower noise level. We are also considering other design changes that may reduce the air flow requirements while maintaining the desired efficiency level.

Field Testing

Planning commenced early in the program so that a field test could be accomplished during the 1983-1984 heating season. The objective of the field test was to evaluate the operational characteristics and user acceptance of the design and to demonstrate the safety and reliability of the heater and its individual components. Eight units were installed at gas utility test sites throughout the country, see Figure 2, and two each were installed at A.G.A.L. and Martin Industries. These twelve test units resulted in a wide variety of test installations and climatic conditions.

Each of the eight units assigned to utilities were installed for an average of 2.8 months. They operated for an average of 266 hours with an average cycle time of 14.4 minutes. No major operating problems were reported, however, there were some minor component failures. Several control boards, transformers and one data acquisition box required replacement. Safety was maintained throughout the test. The comfort level and warm air distribution of the heater were considered by the occupants to be good. The major problem during the field test was the noise level generated by the circulating air blower as it was considered excessively loud by almost all occupants. The occupants reaction verified the laboratory sound work previously discussed and is the primary reason additional fan work is being accomplished. The occupants did not consider the combustor noise by itself or the slight hum produced by the starting air blower to be objectionable.

RESIDENTIAL WATER HEATER

Technical Approach

Flue loss tests were first made with different combustion system geometries in a cascading water trough. To obtain the goal of a 92 percent DOE recovery efficiency, a flue loss of 5 percent or less is required. Water trough tests were therefore used to obtain a combustion system that met the 5 percent flue loss requirement.

Testing was then performed with the combustors in model water heaters. These units were designed to be disassembled to allow modification of the internal combustion-exhaust system. Initial testing was to develop stable burner operation.

Energy balances for the recovery efficiency test periods were made to evaluate the engineering models. Energy lost in exhaust products and energy absorbed by the system's metal components must be less than 5 and 3 percent respectively, in order to achieve the project goal of 92 percent DOE recovery efficiency.

Bench Scale Testing

Bench scale testing involved evaluating the performance of several combustion system combinations to select the optimum design for engineering models. To test various combustion/exhaust pipe configurations a water "trough" was used. The "trough" was built with four equal compartments. Water entered the highest compartment and then cascaded to each successively lower compartment. The water is drained from the lowest compartment which houses the combustion chamber. This method of testing was used to predict recovery efficiency. In order to obtain a recovery efficiency of 92 percent DOE in an actual water heater, a flue loss of less than 5 percent in the trough is required.

Several combustion chamber geometries and exhaust pipe combinations were tested in the water trough. The combustion system components that were tested are shown in Figure 3. Initial flue loss tests indicated the combustion system components with the lowest flue loss was an internally enhanced oval combustion chamber with dual 85-inch long, 1-1/2-inch diameter exhaust pipes. This system exhibited a flue loss of 2.6 percent.

The decision was made, based on the bench scale testing, to fabricate the first engineering model water heater using the internally enhanced oval combustion chamber with the dual exhaust pipes.

Engineering Models

The engineering models were fabricated such that the system could be easily altered. The alterations were to either optimize heat transfer characteristics, clean combustion or increase the operational stability.

The engineering model water heater employing the internally enhanced oval combustion chamber with dual exhaust pipes fabricated had a baseline recovery efficiency of 85 percent (uninsulated). This unit exhibited a flue loss of 8 percent. This loss had to be reduced to 5 percent or less to achieve the project goal of 92 percent DOE.

The flue loss was reduced by three different approaches:

- internally enhanced exhaust pipes,
- cold zone baffle, and
- exhaust deflectors.

Exhaust pipes were fabricated with internal enhancement. The surface area was increased to increase heat transfer from the exhaust pipes to the water. The flue loss was decreased 1 percent by utilizing the internal enhancement.

Cold zone baffles were used to separate the water in the storage vessel into a hot zone and a cold zone. The baffle produces a desired water temperature stratification around the exhaust pipes. This cooler zone enhances heat transfer from the hot exhaust pipes to the cooler water. Several cold zone baffle geometries were tested. The design shown in Figure 4 produced the lowest average water temperature within the cold zone.

Hot exhaust gases are directed upward towards the tank bottom with U-exhaust deflectors shown in Figure 4. The velocity of the exhaust products decrease the boundary layer thickness. With a decrease in boundary layer thickness, there is a decrease in heat transfer resistance. The exhaust deflectors provide a final "wringing out" of the exhaust products before exiting the system.

The resulting unit:

- internally enhanced combustion chamber,
- internally enhanced exhaust pipes,
- cold zone baffle, and
- U-exhaust deflectors

has exhibited a DOE recovery efficiency of 90.3 percent when fully insulated. The flue loss was decreased from the 8 percent (baseline) to 5.1 percent which approaches the project goal of 5.0 percent or less.

Before entering the market, a water heater must pass several stringent tests. One such test is the hydrostatic test. The test procedure calls for 300 psi water pressure within the storage vessel. The vessel and all other water backed portions of the unit cannot deform more than a certain percentage of the vessel diameter. During one such test, the oval combustion chamber deformed excessively. Strengthening the chamber with pins and other support mechanisms proved impractical. A major design change was needed which led to an internally enhanced cylindrical combustion chamber. The cylindrical chamber satisfied all hydrostatic test requirements.

An engineering model water heater was fabricated employing:

- an internally enhanced cylindrical combustion chamber,
- internally enhanced dual exhaust pipes,
- cold zone baffle, and
- U-exhaust deflectors (see Figure 5).

This fully insulated engineering model has exhibited a DOE recovery efficiency of 90.3 percent. The flue loss was reduced to 5.0 percent.

Operating Cost

A recovery efficiency of 90.3 percent DOE has been obtained. With a standby loss(3) of 0.7 percent /hour, a corresponding service efficiency of 83 percent is calculated. This pulse water heater now exceeds its closest competition by 18 percent in service efficiency. This higher efficiency is better illustrated by annual operating costs(4). Annual operating cost of several water heaters are compared in Table II. The operating cost of a conventional water heater is $248.32/year. The pulse unit would operate at $131.64/year, which is a savings of $116.68/year. With the pulse unit exhibiting high efficiencies and low operating costs, manufacturers are considering manufacturing techniques for producing field test units.

Noise

An underlying objective of the program is to provide a relatively quiet pulse water heater. It was difficult to determine that the water heater was operating while standing next to it at the ambient noise level 70-75 dBA on the laboratory test floor. No effort had been made to attenuate the sound produced by this unit. The program proposal specified that the noise level around the water heater should not exceed that of currently marketed water heaters.

Conclusions

Tests performed on the engineering model resulted in a DOE recovery efficiency of 90.3 percent. The operating cost of the pulse water heater is $131.64/year which corresponds to a savings of $116.68/year over the conventional water heater. The pulse unit far exceeds competition in efficiency and high paybacks will prove it a desirable appliance in tomorrow's market.

DEFINITIONS OF EFFICIENCIES AND TERMS

United States Department of Energy (DOE) Recovery Efficiency Test

Expressed in Percent (Ref. 1)

$$E_{rd} = \frac{k \times V \times \Delta T}{Q_c \times H} \times 100$$

United States Department of Energy (DOE) Standby Loss Test

Expressed in Hour^{-1} (Ref. 3)

$$S = \frac{Q_c \times H}{k \times V \times \Delta T_2 \times t} - \frac{\Delta T_1}{\Delta T_2 \times t \times E_{rd}}$$

Annual Service Efficiency Equation

Expressed in Percent (Ref. 2)

$$E_s = \frac{75{,}000\ G}{\frac{75{,}000\ G}{E_{rd}} + 24 - \frac{75{,}000\ G}{P\ E_{rd}}\ 7.5VS}$$

Estimated Cost of Operation

Expressed in Dollars, $ (Ref. 4)

$$C = \frac{H_G}{E_F} (U)\ 365$$

The following symbols apply:

E_F Energy Factor

E_{rd} Recovery Efficiency (DOE Method), Percent

G Daily Quota (Gallon)

H Heating Value of Gas, (BTU/ft.^{3})

H_G Heat into Daily Quota (47743 BTU)

k Nominal Specific Heat of Water (8.25 BTU/U.S. Gal - °F)

P Power Input (BTU/hr.)

Q_c Fuel Consumed Corrected To 60° F and 30" Hg, sat (Ft.^{3})

S Standby Loss

T Water Temperature at Top of Tank, (°F)

T_o Maximum Outlet Water Temperature, (°F)

T_1 Difference Between Initial and Final Mean Tank Temperatures, (°F)

T_2 Difference Between Average Mean Tank Temperature and Average Ambient Air Temperature, (°F)

t Duration of Standby Loss Test, Hr.

U Unit Cost of Fuel ($)

V Tank Capacity, U.S. Gal.

W Weight of Water, LB.

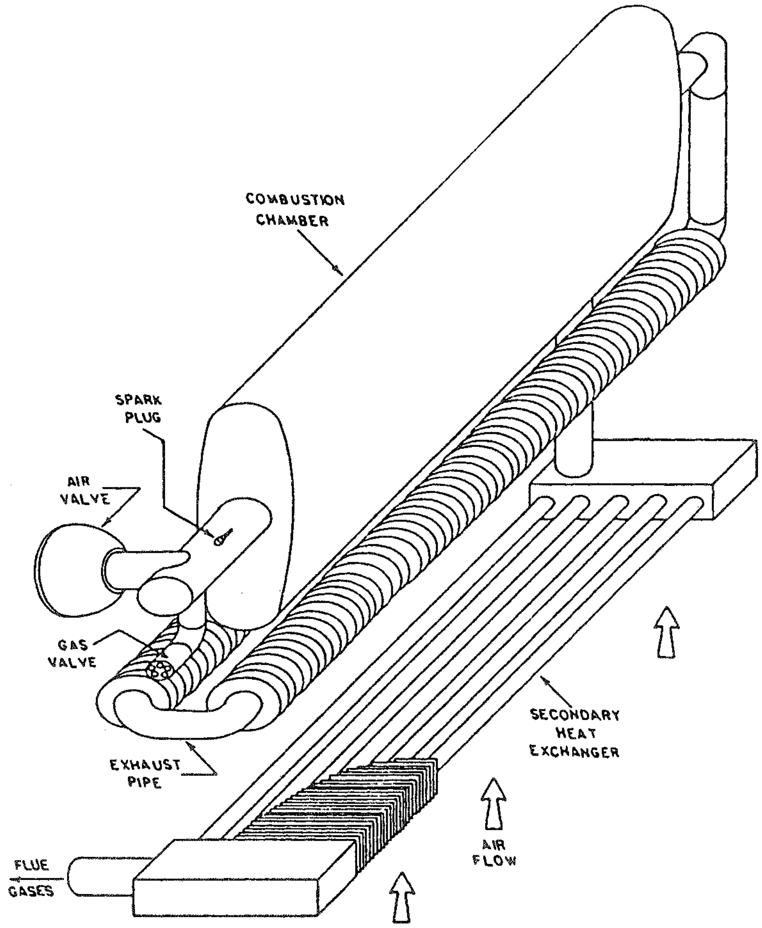

Figure 1. Concept of space heater combustor.

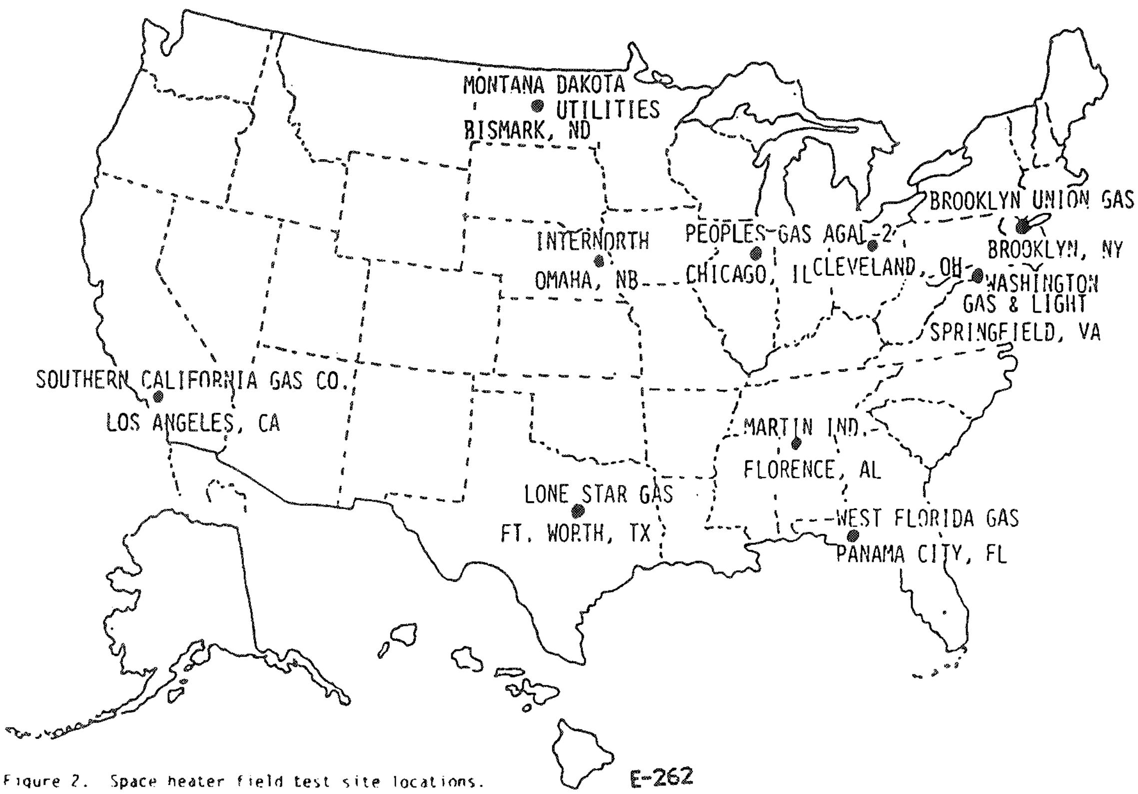

Figure 2. Space heater field test site locations.

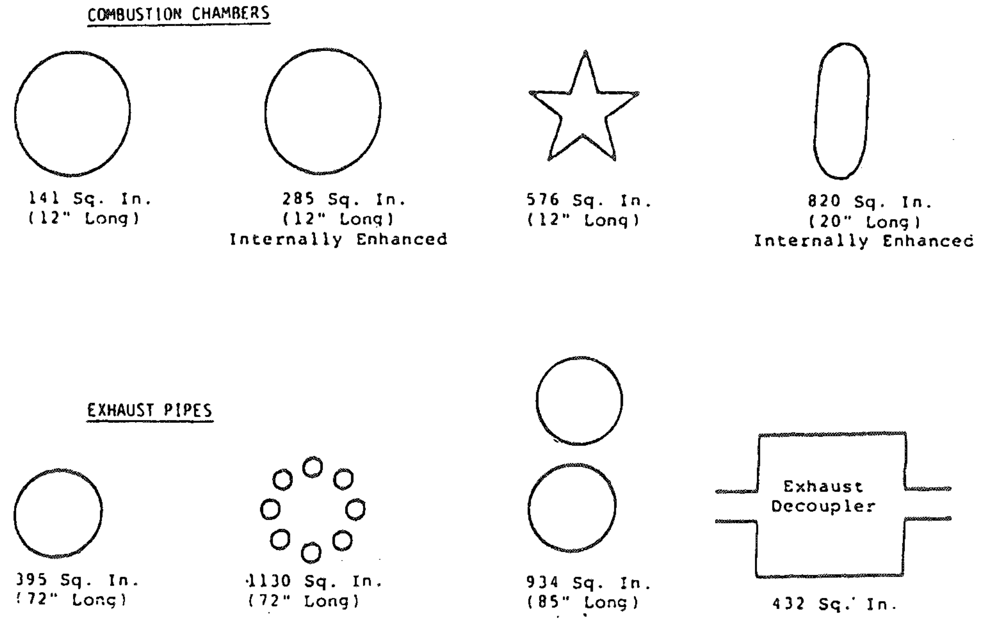

Figure 3. Combustion chamber and exhaust pipe configuration.

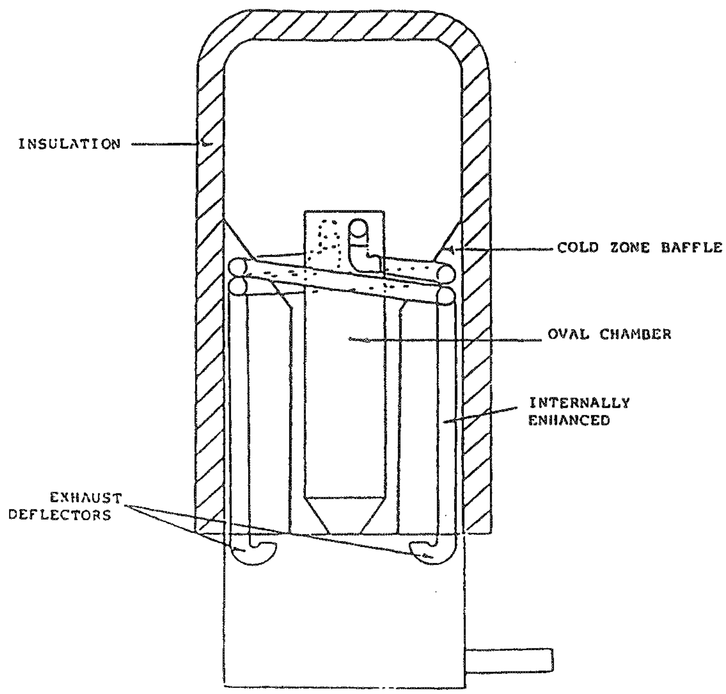

Figure 4. Optimum oval combustion chamber tested.

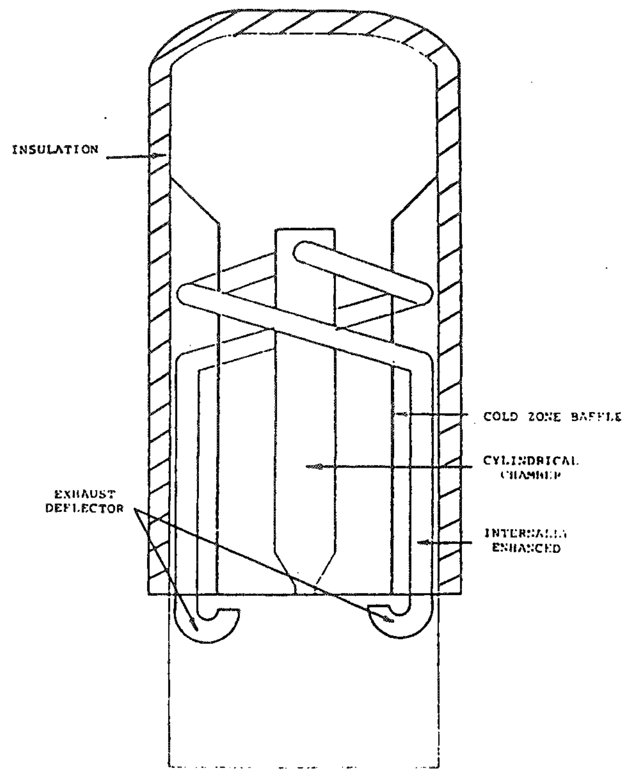

Figure 5. Optimum cylindrical combustion chamber tested.

Table II. Residential water heaters annual operating cost estimates based on DOE procedures and 1983 DOE natural gas cost of $6.27/10^6$ BTU.

40 Gallon Water Heater	Input Rate	Recovery Efficiency, %	Stand-By Loss, %	Calculated Service Efficiency, %	Annual Cost for Gas, $	Annual Savings Over Baseline
Baseline	40,000	70	6.0	44.23	248.32	-----
ASHRAE	40,000	76	3.8	54.17	202.34	45.98
NAUTILUS (414T)	48,000	81	4.0	55.52 57 (GAMA)	195.11 191.69	53.21 56.63
NAUTILUS (413T)	38,000	85	4.0	57.57 59 (GAMA)	188.38 185.19	59.94 63.13
AMTROL (Power Burner, Heat-Pipe)	38,000	82	2.2	65.16 64 (GAMA)	168.09 170.72	80.23 77.60
AMTROL	38,000	85	2.3	66.37	165.55	82.77
AMTI/DOE (w/Pilot)	40,600	81	2.15	64.72	168.09	80.23
AMTI/DOE (w/IID)	40,600	81	1.55	68.54	158.35	89.97
A.G.A.L./State/ GRI	42,500	88 89	0.70 0.70	80.95 81.79	134.89 133.25	113.43 115.07
		90	0.70	82.63	131.64	116.68
		91	0.70	83.47	131.64	116.68
		92	0.70	84.31	130.07	118.25

NOTES FOR TABLES

Table I.

1. Electricity usage converted to primary energy at 11,600 Btu/kwhr.
2. Domestic hot water supplied by electric tank.
3. Does not include portion of building where electricity is billed to a second agency.

Table II.

1. Space heating converted from oil to natural gas. Oil costs decrease from $6,400 to $0. Natural gas costs will increase $2,300. Net savings of $4,100. Projected decrease in space heating consumption of 46%.
2. Space heating converted from oil to natural gas. Oil costs decrease from $4,600 to $0. Natural gas costs will increase $1,700. Net savings of $2,900. Projected decrease in space heating consumption of 47%.

Table III.

1. Post retrofit bills not available for non-space heating period. Pre-retrofit base rate assumed.
2. Net change in space heating costs, primarily due to oil to gas conversion.
3. Measures of cost-effectiveness calculated with natural gas savings only.
4. Does not include base usage increase due to new company renting space in building.
5. Fees include retrofit of second building owned by same agency.
6. Net change in space heating costs.