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DIRECT EFFICIENCY MEASUREMENT AND ANALYSIS OF RESIDENTIAL OIL-FIRED BOILER SYSTEMS

ANNUAL REPORT FY 1978

BURNER-BOILER/FURNACE EFFICIENCY TEST PROJECT

R.J. McDONALD, J.E. BATEY, T.W. ALLEN, AND R.J. HOPPE

November 1979

MASTER

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY
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Abstract

A laboratory study is made to measure the efficiencies of residential heating equipment. A direct measurement technique provides an accurate evaluation of the efficiency of residential heating units during full-load and part-load operation. The laboratory data is then used to determine annual fuel consumption and fuel-weighted seasonal efficiency for each heating unit based on typical operating parameters (size of residence, geographic location, and usage). The results of the study include both the evaluation of a wide range of hydronic (hot water) burner-boiler package units and the evaluation of retrofit items which are added to an existing heating system to enhance efficiency and performance. The combination of direct, accurate efficiency measurement and calculation of annual fuel use provide a standard method for comparison of individual heating units and retrofit modifications on a common and realistic basis. This allows a cost effectiveness analysis to be performed so that direct quantitative comparisons can be made.

I. INTRODUCTION

The Burner-Boiler/Furnace Efficiency Test Project at Brookhaven National Laboratory is a continuing program described in "Energy Mangement in Residential and Small Commercial Buildings, Fiscal Year 1976."¹ The project is funded through the Department of Energy and is designed to provide the technical basis for reduced consumption of oil and gas for space heating of residential and small commercial buildings by identification of high efficiency heating equipment. Manufacturers and developers of heating equipment were encouraged to voluntarily submit heating units and refit devices to BNL for efficiency testing and evaluation. Public dissemination of test reports is used to promote the use of high efficiency equipment, and in addition, BNL provides technical presentations to industrial and educational groups to encourage utilization of energy conservation technology. The system of voluntary participation in the program by equipment manufacturers did result in some characterization of general design features that produce high efficiency performance. A plan for detailed characterization of design features has been formulated and will be conducted on a non-voluntary basis.

The efficiency measurement technique utilized by BNL provides accurate experimental determination of the overall efficiency of heating equipment by considering heat losses incurred during operation. In considering operational losses, BNL has chosen to categorize losses in three areas. The energy lost up the chimney during burner operation is referred to as operating stack loss. The heat energy lost through the boiler casing to the surroundings where it is located is referred to as jacket loss, and the energy lost when the burner is not operating is referred to as off-cycle loss. Off-cycle losses through the chimney occur when conditioned air within the general vicinity of the boiler is drawn through the burner air inlets, passes through the boiler, and exits via the chimney. This air removes heat contained within the boiler and boiler water. Boilers are usually maintained near a specific temperature (between 140 and 200°F) during the burner off-period to provide heat and/or domestic hot water on demand.

The magnitudes of various heat losses in oil-fired hydronic boilers are shown in Figure 1 along with that portion of the heat which is actually delivered to heat the living space. The ratio of useful heat delivery to the total heat content of the fuel is defined to be the overall system efficiency. At BNL operating stack losses were observed for oil-fired boilers and ranged between 15% and 35%, while operating jacket losses ranged up to 10%, and off-cycle losses varied between 5% and 15%.

When all loss rates are measured, a calculation is performed to determine the efficiency performance of a boiler in a home, including the effect of burner on-off cycling in response to varying heat loads in the residence. This is directly related to outdoor temperature variations which vary with geographic locales. The laboratory measurements include burner operation over a wide range of load conditions. Efficiency measurement results from the laboratory are then combined with hour-by-hour annual weather data for a given location to determine seasonal efficiency of the particular boiler,

Figure 1. Energy Flow for Oil-fired Hydronic Boiler

based on residence heat load (design load) and operational factors. The seasonal efficiency is defined to be the total useful heat energy delivered to the home divided by the heat energy contained in the fuel consumed, over a one-year period. The seasonal efficiencies that have been observed at BNL range between 55% for low efficiency systems to 75% for high efficiency oil-fired boilers.

The basis for efficiency testing is direct heat flow measurement where the useful heat delivered by the boiler is compared to the total heat content of the fuel. Details of these techniques are found in Section II of this report. Steady-state tests are performed by allowing the burner to operate constantly while maintaining boiler water outlet temperature at a constant value, and the steady-state efficiency is defined as the ratio of useful heat produced by the boiler divided by the total content of the fuel. Cyclic testing is performed by programming the burner to cycle on and off at a constant rate and measuring heat input and heat output for each cycle. The overall efficiency is defined as the ratio of useful heat delivered by the boiler divided by the heat content of the fuel consumed during cyclic operation. As such, the overall efficiency is a function of the ratio of on-period to off-period, and is plotted as a function of burner fractional on-time as shown in Figure 2 for a typical boiler.

In addition to the accurate tests already mentioned, flue gas tests are performed during each heat flow measurement during steady state operation. Although flue gas efficiency tests are less accurate than the direct heat flow measurement technique, these tests are useful in monitoring air fuel mixture and variations in operational conditions on a day-to-day basis. Also, flue gas analysis tests can be used in combination with direct heat flow measurement to evaluate heat loss that occurs through the boiler jacket during steady state operation.

The BNL test project is now operating two hydronic test stands with electronic data acquisition/control units that allow approximately 48 tests to be performed per year, and a forced air heating equipment test stand is now ready for start-up procedures. A testing schedule has been established through the beginning of Fiscal Year 1980. To meet the demand for testing in the early stages of the project, the second hydronic test stand was proposed and was brought on line at mid-year of Fiscal Year 1978. Approval was also acquired for the performance of characterization testing in accordance with a proposed schedule and for the expansion of the testing program scope to include gas-fired residential heating equipment.

Reports were issued on tests performed on voluntarily submitted equipment, and these reports are sent to the manufacturer with copies added to the existing files at BNL and at the DOE Branch Office in Washington. These files will be used by both offices to disseminate test reports, and serve to maintain a record of both equipment efficiency results and retrofit topical reports. Many oral presentations of the project work were provided by the program staff to add to the effort in disseminating results.

Figure 2. Dry Base Single Pass Steel Boiler Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

The equipment tested from the beginning of the project to date include various commercial and prototype units. Equipment that was tested is summarized in Table 1.

Table 1

Types of Equipment Tested	Total Number of Units Tested to Date
Hot Water Boilers (Hydronic Units)	20
Flame Retention Head Burners	7
Conventional Head Burners	5
Vent Dampers	2
Stack (Flue) Economizers (Hydronic)	3
Combustion Air Humidification/Vapor Assisted Devices	5

Note: Individual tests represent various combinations of items from this table.

II. EFFICIENCY TESTING BY DIRECT HEAT FLOW MEASUREMENT

A. Hydronic System Testing

1. Efficiency Measurement Technique. A heat flow measurement technique provides a direct, fundamental physical measurement of heating equipment during steady-state (continuous) and cyclic (intermittent) burner operation. The quantity of heat transferred to the boiler water is measured directly and compared to the corresponding heat content of the fuel consumed. The efficiency of operation is defined to be the ratio of heat transferred to the water to the total heat available from the fuel consumed. The enthalpy flow measurement technique does not depend on any simplifying assumptions but results from basic physical laws including the definition of enthalpy. Consequently, the accuracy of the test results is limited only by the measurement accuracy of the physical quantities of interest including mass flow rates and temperature.

The quantities that are measured include: (see Figure 3)

(a) $\dot{m}_w$ - water flow rate through boiler (pounds per minute)

(b) ΔT - temperature rise across the boiler

$$\Delta T = T_{\text{outlet}} - T_{\text{inlet}} \text{ (degrees F)}$$

(c) $\dot{m}_{\text{oil}}$ - fuel flow rate to burner (pounds per minute)

(d) h_{oil} - heating value of fuel (Btu per pound)

From these values the efficiency of operation can be determined:

$$\eta = \frac{\text{Heat transferred to boiler water}}{\text{Total heat available from combustion of fuel oil}}$$

The heat transfer rate to the water is simply the product of the water mass flow rate and temperature rise.

$$\dot{H} = \dot{m}_w \times C_p \times \Delta T.$$

Similarly, the heat available from the combustion of fuel is the product of the fuel mass flow rate and the heating value of the fuel.

$$\dot{H}_{\text{total}} = \dot{m}_{\text{oil}} \times h_{\text{oil}}.$$

The efficiency is the ratio of these two quantities

$$\eta = \frac{\dot{m}_w \times \Delta T}{\dot{m}_{\text{oil}} \times h_{\text{oil}}}$$

The enthalpy flow measurement technique is a fundamental method for direct determination of the efficiency of heating equipment, and can be considered a "standard" method (traceable to basic laws) whose accuracy depends solely on the accurate measurement of the above mentioned quantities.

2. Efficiency Definitions

a. Steady-State Efficiency. During continuous burner operation, a fraction of the heat released by combustion of the fuel is lost as combustion products vented through the stack and as radiative and convective boiler jacket losses. The steady state efficiency represents the fraction of total heat that is transferred to the boiler water for continuous burner operation.

b. Cycle Efficiency. During burner on-off cycling, additional heat is lost and the cycle efficiency indicates the fraction of the useful steady-state heat that is available during intermittent burner operation. As the burner "on" time decreases, the "off" time increases, resulting in larger off-cycle heat losses. Therefore, the cycle efficiency decreases as the fractional burner "on" time is reduced.

MEASURED QUANTITIES

$\dot{m}_w$ = WATER FLOW RATE
 ΔT = TEMPERATURE RISE
 ACROSS BOILER
 $\dot{m}_{oil}$ = FUEL FLOW RATE
 h = HEATING VALUE OF
 FUEL

EFFICIENCY DETERMINATION

HEAT INTO WATER = $\dot{m}_w \Delta T$
 TOTAL HEAT FROM FUEL = $\dot{m}_{oil} h$
 EFFICIENCY = $\frac{\dot{m}_w \Delta T}{\dot{m}_{oil} h}$

Figure 3. Brookhaven National Laboratory Boiler Efficiency Measurement Schematic

Overall Efficiency: The total fraction of useful heat available at the boiler outlet is the product of the steady state and cycle efficiencies.

$$\eta_{\text{overall}} = \eta_{\text{steady state}} \times \eta_{\text{cycle}}$$

For example, if $\eta_{\text{ss}} = .70$ and $\eta_{\text{cycle}} = .70$ for a particular burner load, then the overall efficiency is equal to $(.70) \times (.70) = .49$ or 49% of the heat released by the combustion process is available as useful heat in the boiler water. For continuous burner operation the cycle efficiency equals unity ($\eta_{\text{c}} = 1.0$) and the overall efficiency equals the steady state efficiency.

3. Test Results

From the steady-state and cycle data, annual efficiency and fuel use are calculated. The seasonal efficiency is a measure of the overall efficiency of a particular heating unit averaged over the heating season for a particular design heating load and weather pattern for a variety of operating conditions. For each seasonal efficiency a corresponding value for annual fuel use (in gallons of oil) is determined.

A detailed description of the actual test procedures and the hydronic test facilities can be found in BNL 50753, Direct Measurement of the Overall Efficiency and Annual Fuel Consumption of Residential Oil-Fired Boilers, reference 9 of this report. Included are details of transducer design, instrumentation and testing procedures.

B. Warm Air Furnace Test Facility

As in the boiler test facility the enthalpy flow technique provides direct measurement of heating equipment efficiency. The warm air furnace test facility is being automated at this time. This automation involves the design, fabrication, and installation of a data acquisition and control unit. This unit is being designed and built at Brookhaven National Laboratory based on the technology and techniques acquired by operation of the hydronic test facilities. The major difference in the two heating systems is that the working fluid for the warm air system is room air, while water is used in boiler systems. The control systems of warm air furnaces are different than those of hydronic (hot water) boilers, and the test procedures used at BNL reflect these differences. A detailed discussion of the warm air furnace test procedures and test facility instrumentation is found in Appendix B of this report.

Again, the enthalpy flow measurement technique does not depend on any simplifying assumptions but results from basic physical laws, including the definition of enthalpy. Consequently, the accuracy of the test results is limited only by the accuracy of the measurement of the physical quantities of interest (mass flow and temperatures).

The quantities that are measured include:

- (a) $\dot{m}_a$ - mass flow rate of dry air through furnace (pounds per minute)
- (b) $\dot{m}_v$ - mass flow rate of water vapor through furnace (pounds per minute)
- (c) ΔT - temperature rise of air and vapor across the furnace

$$\Delta T = T_{\text{outlet}} - T_{\text{inlet}} \text{ (Degrees F)}$$
- (d) $\dot{m}_{\text{oil}}$ - mass flow rate of fuel to burner (pounds per minute)
- (e) h_{oil} - heating value of fuel (Btu per pound)

From these values the efficiency of operation can be determined:

$$\eta = \frac{\text{Heat transferred to furnace air}}{\text{Total heat available from combustion of fuel oil}}$$

The heat transfer rate to the furnace air is simply:

$$\dot{H} = (\dot{m}_a \times C_{pa} \times \Delta T) + (\dot{m}_v \times C_{pv} \times \Delta T)$$

where: C_p = specific heat at constant pressure of air or vapor

Similarly, the heat available from the combustion of the fuel is:

$$\dot{H}_{\text{total}} = \dot{m}_{\text{oil}} \times h_{\text{oil}}$$

The efficiency is the ratio of these two quantities

$$\eta = \frac{(\dot{m}_a \times C_{pa} \times \Delta T) + (\dot{m}_v \times C_{pv} \times \Delta T)}{\dot{m}_{\text{oil}} \times h_{\text{oil}}}$$

And, again, the enthalpy flow technique is a fundamental method for direct determination of the efficiency of heating equipment. It can be considered a "standard" method (traceable to basic laws) whose accuracy depends solely on the accurate measurement of the above mentioned quantities.

C. Annual Fuel Use and Efficiency (AFUE)

As mentioned, the objective of the BNL test methodology is to evaluate seasonal efficiency and fuel consumption for a particular heating unit operated under standardized conditions. Laboratory measurements provide specific heat loss data that enable computation of annual fuel consumption for heating equipment. This calculation relies on precise measurement of the "intrinsic merits" of a particular heating unit expressed in terms of steady-state efficiency and cycle efficiencies over the entire range of

heating loads. The annual fuel consumption for the heating unit under investigation varies as a function of several key parameters including: geographic location, building design heat load, outside design temperature, room temperature, domestic hot water use (in the case of hydronic boilers), and design fuel firing rate. Each of these parameters can be varied over a range of practical values in order to determine the resulting change in overall seasonal efficiency and fuel consumption for a particular heating unit. The output of these calculations is expressed as a matrix of overall seasonal efficiency and fuel consumption values (gallons of fuel oil per year) as a function of the important variables.

The BNL Annual Fuel Use and Efficiency calculation in conjunction with precise laboratory measurements, provide the basis by which the intrinsic merits of individual heating units can be compared under a full range of "standard" conditions. "Standard" conditions include any given design heat load, any given hour-by-hour weather pattern for the heating season, any given range of domestic hot water requirements (in the case of hydronic boilers), and any given cycle characteristics which may be employed in a home heating strategy. AFUE analysis cannot be used to evaluate the annual fuel consumption of a particular building/heating unit system, unless all specific building heat sources and losses can be incorporated into the total heat load. Instead, the strength of the procedure is that various designs can be compared on a realistic and common basis.

A detailed discussion of the AFUE analysis is available in the Annual Fuel Use Efficiency Reference Manual prepared by BNL staff, reference 10 of this report.

III. EFFICIENCY TEST RESULTS

The test facilities at BNL are designed for maximum flexibility in application and for testing the wide range of equipment utilized in the residential heating industry. The hydronic testing facilities were used in testing several different types of oil-fired residential heating devices. These can be divided into two major divisions, boiler-burner package units and refit actions. Boiler-burner package units are designed for new installations or replacement of existing heating plants in homes, while refit actions involve devices and control modes designed for upgrading the efficiency of existing heating units. Refit actions include boiler cleaning and adjustment, automatic vent damper installation, replacement of conventional burners with flame retention head burners, etc..

A. Boiler-Burner Package Units

Boiler-burner package units of various designs have been tested at BNL, and four basic categories will be used to classify them according to basic design features such as steel construction, cast iron construction, wet-base, and dry-base designs. In some cases, certain common design features occur between boilers of similar efficiency and performance and these will be mentioned. This does not imply that all units of similar design will perform

with the same efficiency. In fact, it has been found that every trend has exceptions based on the numerous tests performed. Instead, this classification is intended to illustrate that there can be considerable variation in performance related to particular design features. As more tests are completed in the characterization phase of the project, we intend to identify those design characteristics that most often produce high levels of efficiency. In the final analysis, every design and every manufacturer's equipment line would have to be tested to identify all efficiencies exactly. Unfortunately, this is not within the scope of the program, and it would be some time before consumers could benefit from this approach. Rather, the characterization of "generic types" may provide the consumer with some general considerations to keep in mind when selecting equipment.

1. Dry-Base, Steel. The dry-base feature refers to the fact that the combustion chamber is not surrounded by water, and is separate from the heat transfer section. Generally, this design characteristic leads to increased heat loss and lower efficiency. The single pass, vertical fire-tube design normally employed in these boilers allows for only one pass of the hot combustion gases through the heat transfer section as opposed to a multiple-pass system. The combination of dry-base and single-pass design is generally less costly to produce and, therefore, commonly encountered in the field. The boiler type is very common in Long Island homes. One purpose of the current project is to provide sufficient quantitative information to justify investment in highly efficient equipment and retrofit options in order to reduce operating costs through reduced fuel consumption. From the data to be presented, it is obvious that in many cases installation of high efficiency equipment is cost effective for the homeowner, with some pay-back periods on the order of two years.

The test results for the two dry-base, single-pass steel boilers tested to date can be found in Appendix C, Figures 1 and 2. The performance curve which plots overall efficiency versus burner fractional "on" time indicates the efficiency variation in response to various loads from idle condition to steady-state operation. The steady-state efficiency of the two units were 69.2 and 64.9 percent when operated with an average outlet temperature of 180°F. Jacket losses during the burner-on periods were 5.1% and 6.1%, respectively. The effect of off-cycle heat losses can be seen in the curves showing the overall efficiency as a function of burner fractional "on" time (heat load). Note that as burner fractional "on" time is reduced (burner "off" time is increased), the overall efficiency decreases corresponding to increases in off-cycle heat losses. The overall efficiency reaches zero at a burner fractional "on" time of a few percent, corresponding to boiler standby losses. The standby or idle condition occurs when no load is applied to the boiler (no domestic hot water use or space heating) and the burner operates to replace heat lost from the boiler during the off-period to maintain set point temperature.

The Annual Fuel Use and Efficiency (AFUE) calculation procedure was performed for both boilers tested. The results can be found in Appendix III. The annual fuel consumption in gallons of oil per year and seasonal efficiency

(SE) vary with many operational parameters including the overfiring ratio, and domestic hot water use in gallons per day. As the firing rate is increased (with all other factors held constant), annual fuel use increases corresponding to smaller burner fractional "on" times, and increased heat loss during the off-cycle. For a design heat load of 50,000 Btu per hour in New York City, with an inside set point of 68°F, 40 gallons per day of domestic hot water, and an overfiring ratio of 2 (100% overfired), the annual fuel consumptions were 1455 and 1550 gallons for the two boilers tested with overall seasonal efficiencies of 56.2% and 52.8%. This means only 56.2% (or 52.8%) of the heat available from the fuel is delivered to the heating loads, while the remaining 43.8% (or 47.2%) is lost by heat loss mechanisms discussed earlier (on-cycle stack, on-cycle jacket, and off-cycle losses). In contrast, seasonal efficiencies as high as 75% have been measured for commercially available equipment of more efficient design under identical operating conditions. This indicates a 30% differential in annual fuel use for the oil-fired boilers tested to date.

The homeowner with an inefficient heating unit can choose one of three actions. The homeowner may choose to leave the system alone and operate at relatively low efficiency and high fuel costs. The second option is to modify the existing boiler by means of one or more refit options available on the market. These refit options are devices or control system that are added to the existing system or replace existing components to increase efficiency and decrease fuel consumption. Several of these refit options have been tested and evaluated at BNL and the results appear in Section III-B of this report. The third option left to the homeowner is to replace the existing unit with a new high efficiency boiler-burner heating unit, which may or may not be justified by individual economic constraints and current operating costs.

2. Wet-Base, Steel Boilers. Four different wet-base, multi-pass horizontal fire-tube steel boilers have been tested at BNL. In each of these boilers the combustion gases pass through the combustion chamber and turn back through horizontal steel fire tubes. Two units were fired with forced draft flame-retention-head burners and the other two units were fired with induced draft design burner systems with an exhaust blower located at the boiler flue outlet to induce combustion air flow through the burner. No advantage or disadvantage was observed with the induced draft designs, and these units contain combustion heads similar to flame-retention-head designs.

The overall efficiency curves and annual fuel use calculation for the four units are presented in Appendix C, Figures 3-6.

A summary of test results for the four units of this design type is shown in Table 2. Annual fuel use and seasonal efficiency (SE) were calculated for a load of 50,000 Btu per hour in New York City, with an inside room temperature of 68°F, 40 gallons per day of domestic hot water, and an overfiring ratio of 2 (100% oversized). These results indicate a 20% to 30% reduction in fuel consumption when compared with the two dry-base

steel boilers fired with conventional burners discussed earlier. It is important to remember that this comparison involves different boiler and burner designs. In the future characterization program, we intend to investigate in more detail the specific boiler and burner design features that contribute to improved operating efficiency.

Table 2

Wet Base Multi-Pass Horizontal Fire-Tube Boiler Performance

Boiler	Steady State Efficiency (%) (180°F outlet)	Seasonal Efficiency (%)	Annual Fuel Use (Gallons)
i	81.2%	74.6%	1100
ii	82.1%	71.0%	1150
iii	84.4%	72.3%	1130
iv	82.1%	74.1%	1100

3. Dry Base, Cast Iron Boilers. Two dry-base cast iron boilers equipped with flame-retention-head burners have been tested to date. The dry-base design refers to a combustion chamber which is thermally separated from the heat exchanger section of the boiler. The combustion chamber is usually insulated in an attempt to reduce boiler jacket losses.

The test results and performance curves can be found in Appendix C, Figures 7 and 8. The first dry-base cast iron boiler had a steady-state efficiency of 74.8% compared to 83.9% measured for the second boiler both at outlet boiler water temperatures of 180°F. The respective seasonal efficiencies were 64.2% and 70.5% corresponding to 1275 gallons and 1160 of fuel consumed per year as calculated by the AFUE analysis. These annual fuel consumption rates are based on the identical condition mentioned in previous sections of this report, and if we compare these values with those for the dry-base steel boilers, we observe a 12% to 25% variation in annual fuel consumption.

It is of interest to mention that these dry-base cast iron boilers were both manufactured by the same company. The difference between the two boilers is that the more efficient unit contained a new design flame-retention-head and a large boiler volume for the same fuel fire rate. The more efficient unit was also heavily insulated around the combustion chamber section which reduced jacket losses from 12.5 to 4.4 percent.

4. Wet-Base, Cast Iron Boilers. To date only one wet-base cast iron boiler has been tested, although more will be tested in the future. The overall efficiency curve and AFUE calculation results appear in Appendix C, Figure 9. The steady-state efficiency at a 180°F outlet temperature was measured to be 81.0% including a jacket heat loss of 1%. The seasonal

efficiency was 75.3% with an annual fuel consumption of 1090 gallons per year. These numbers again are related to the operating conditions mentioned earlier in this report. This particular boiler is a new design and therefore, we do not mean to indicate that all wet-base cast iron boilers will perform as well. It is important to remember, as mentioned earlier, that each general design group has exceptions and we do not propose that these results can represent every boiler of any given type. It is hoped that these results will only be used as a guideline in grouping general performance trends.

In the preceeding discussions, we have dealt with boilers fired by flame-retention type burners, and these units were submitted to BNL manufacturers for testing. In most cases a flame-retention head burner was matched to the boilers as part of the package design, but the boilers of Section III-A-1 are fired with conventional burners, and are commonly observed in the Long Island area.

B. Refit Modifications

When the total replacement of an existing heating unit is not economically possible, the homeowner still has many options available which can increase the efficiency of a low performance oil-fired hydronic system. As mentioned, the low efficiency boiler typically found in this area is the dry-base steel boiler of single-pass vertical tube design fired with a conventional burner. In most cases, refit options evaluated at BNL have been tested on low efficiency units of this design to determine the maximum benefit that might be realized in the field. However, in order to establish relative savings for a range of heating units we have also tested the effects of refit devices on boiler systems of high efficiency.

1. Flame-Retention-Head Burners. Laboratory measurements were performed to determine the efficiency improvement of typical residential hot water boilers when oil burners of conventional design are replaced with burners of flame-retention head design. A comparison of burner head designs is shown in Figure 4. It was found that refit flame-retention head burners reduced annual fuel consumption for the four different boilers tested. These included two boilers of dry-base steel single-pass design and two wet-base cast iron boilers. In all, seven flame-retention head burners and three conventional burners were used in combination with the different boilers for a total of fifteen different tests.

Overall efficiency versus burner fractional "on" time is plotted in Figures 10-25 in Appendix C. These curves illustrate the increase in overall efficiency due to the installation of flame-retention head burners compared to the performance with conventional burner(s). Burners (A), (B), (C), (D), (E), (F), and (G) are flame-retention head burners, while burners (1), (2), and (3) are conventional burners.

Fuel consumption over an entire year is determined from the test data

Figure 4a. Non-Retention Head Burner

Figure 4b. Retention Head Burner

for each burner using the AFUE (Annual Fuel Use and Efficiency) computation. Temperature data for New York City was used with a design heat load of 50,000 Btu per hour, and 40 gallons of domestic hot water use per day. Based on field surveys, an overfire ratio ($\alpha=2$) of 100% is assumed in all cases for comparison. The results of the AFUE analysis appear in Appendix III, Figures 10 to 25 for the various tests performed. A summary of flame-retention-head burner installation results is shown in Table 3. The results for four different boilers indicate the percentage change in annual fuel use for replacement of a properly adjusted conventional head burner with various retention-head burners (A to G). It is seen that the effect of burner replacement on fuel use and efficiency can range from 5% to 18½% depending on particular burner-boiler interactions.

The average savings observed for the dry-base steel boilers was 14.7% (or 215 gallons) with a range between 11.7% and 18.1%. The average savings for the two wet-base cast iron boilers was 9.1% (or 130 gallons) with a range of 5.1% to 15.5% savings when compared with conventional burner performance. It seems that boiler (D) derived less benefit from retention-head burner refit than the other boilers. The reason may be in the design of boiler which includes a loosely fitting view door of sizeable dimensions. This design allows significant amounts of ambient air to enter the boiler through the view door mounting and results in dilution of the combustion process. Air leakage into a boiler can reduce thermal efficiency during burner operation and, also, during the off-cycle.

The increase in overall efficiency (η_0) can be separated into two parts, improvement in steady-state performance and reduction of off-cycle heat losses. The improvement in steady-state efficiency results from the ability of retention-head burners to burn the fuel in a more controlled way, allowing excess combustion air to be minimized. The flame-retention head design can enhance air fuel mixing, decrease excess air, and reduce on-cycle stack heat loss. The increase in cyclic performance can be attributed to the added restriction to air flow through the burner during the off-cycle, reducing the total convective heat loss from the boiler. The ratio of off-cycle to on-cycle benefits resulting from flame-retention head burner installation varies with burner and boiler design. The major savings usually 2/3 of the total savings, result while the burner is operating. The remaining savings is attributed to decreased off-cycle heat losses.

In discussing the relative change in fuel use observed in flame-retention-head burner installation, we have only dealt with changes compared to performance of a single conventional burner [burner (1)], which was in new condition and properly adjusted. Conventional burners in field installations may not be in comparable condition, but may be less efficient providing higher savings when replaced by a flame-retention-head burner. Two additional tests were performed in boiler (C) to investigate this possibility using burners removed from private homes after years of operation. No attempts were made to improve the condition of these burners, but rather they were installed with minor adjustments (air-fuel ratio and mounting) required for installation in the test boiler. The results of these tests appear in Table 4, and

TABLE 3

FLAME-RETENTION HEAD BURNER REFIT
FUEL SAVINGS % COMPARED TO CONVENTIONAL BURNER*

Burners		A	B	C	D	E	F	G
Boiler								
A								
	Dry-Base Steel	18.1	12.8	15.1	13.1	16.5	15.6	--
B								
	Dry-Base Steel	--	--	--	11.7	--	--	--
C								
	Wet-Base Cast Iron							
	Modern High Efficiency Design	15.5	--	10.4	--	--	--	--
D								
	Wet-Base Cast Iron							
	Older Design	--	--	--	5.3	--	--	5.1
Range 5.1 - 18.1		Overall Average 12.7%						

*Note: The original tests included a new conventional head burner which was properly installed and maintained. Burners A to G are flame-retention head burners.

TABLE 4

FLAME-RETENTION HEAD BURNER REFIT
IN HIGH EFFICIENCY CAST IRON WET-BASE BOILER

Conventional Burner	Fuel Savings %	
	For Flame-Retention Head Burners Burner (A)	Burner (C)
#1 New Burner	15.5	10.5
#2 Field Burner - Good Condition	16.8	11.9
#3 Field Burner - Poor Condition	<u>22.0</u>	<u>17.4</u>
Average	18.1	13.4
Overall Average	<u>15.8</u>	

the performance curves and AFUE results can be found in Appendix III-B-1. Note that burner (2) was found to be in good condition and well maintained while burner (3) was in poor condition. For the particular boiler tested, the relative saving by burner replacement is indeed greater for burners (2) and (3). This indicates that the BNL test results may be conservative in nature, and that refitting existing boilers with modern flame-retention burners may increase efficiency even more than previously discussed. Also, it should be remembered that in one case, boiler D, the relative savings was only 5% per year. Boiler design is an important factor with regard to optimized efficiency performance, and overall fuel savings is directly related to the combination of burner and boiler designs. In the field, it is recommended that steady-state efficiency (flue gas) analysis be performed before and after burner replacement to ensure favorable results. All burners are tuned in the laboratory to provide the maximum CO₂ percentage (a measurement used to indicate excess air during combustion) using a Bacharach smoke spot of one as a criterion for the air-fuel setting. These same measurements can be performed by oil service personnel in the field and should be made available to the homeowner to insure proper burner installation and adjustment.

In support of the New York State Energy Office (NYSEO) Oil Refit Program, which is operating with the technical assistance of Brookhaven National Laboratory, a series of field investigations of refit actions was undertaken. Although the eventual scope of this program will include many different refit actions, to date a single refit action has been investigated; namely, the installation of flame-retention head burners. Installation and fuel delivery records for 250 installations were made available and 94 were found suitable for analysis. Considerations for selecting suitable cases included: fuel use records before modification, change in the equipment other than the refit under investigation, frequency of oil deliveries and several other factors. Details of the data analysis technique involved will be available in a report soon to be released by BNL. The results are presented in summary in Table 5 with an average savings of 13.5% per year for the 94 installations considered. This is based on two different retention-head burners replacing a wide variety of conventional burners in various conditions in many different boiler designs. If we compare this to the average of all tests performed at Brookhaven, we find an excellent correlation. Laboratory tests averaged 13.7% savings compared to 13.5% found in the field.

It would seem, based on both laboratory tests and actual field installation data, that the flame-retention-head burner can significantly reduce the demand for home heating oil when used to replace conventional equipment. It is recommended that qualified personnel install and adjust these burners although a competent do-it-yourself homeowner may be capable of this task. Depending on the service contract between the homeowner and his or her local oil dealer, the cost for installing these units can range between \$150 to \$350. In addition to the burner costs, the possibility exists that the combustion chamber may require replacement at a slight additional cost. This can be determined by examination of the heating unit by a trained service representative. It is also advisable to get more than one price for any refit action, as is the case for any major capital investment by the consumer. The pay-back period for this flame-retention-head refit action will be approximately one to three years, depending on individual conditions found in each case. A pay-back period of less than two years is a reasonable estimate in most cases, but a one-year payback is more common as fuel costs escalate. Rising fuel costs are expected to continue to improve the cost-effectiveness of all equipment refits.

Retention-head burners can operate at higher efficiency than conventional head designs by reducing the amount of excess combustion air required to achieve an acceptable smoke level. This provides higher percentages of CO₂ in the flue gas, and generally lowers flue temperatures. The overall effect is to reduce the stack heat loss rate, and thereby improve thermal efficiency. However, reduction of excess combustion air will produce higher flame temperatures which may result in combustion chamber problems in the case of boilers which are not designed to accommodate higher temperatures. Therefore, attention must be directed toward inspection of combustion chamber condition when conventional burners are replaced with those of flame-retention design.

TABLE 5

ANALYSIS OF FLAME-RETENTION HEAD BURNERS PERFORMANCE IN THE FIELD

PERFORMANCE SUMMARY

<u>Equipment</u>	<u>Quantity</u>	<u>Average Annual Fuel Usage Savings (%)</u>	<u>Attributable to Steady State Efficiency Improvement (%)</u>	<u>Attributable to Cyclic Efficiency Improvement (%)</u>
Burner (D)	46	16.9	8.6	8.3
Burner (G)	48	10.2	6.4	3.8
All	94	13.5	7.5	6.0

The actual temperature reached within a specific combustion chamber varies with many factors including: excess combustion air, boiler design (e.g., wet or dry-base), combustion chamber material and configuration, location of heat exchange surfaces within the boiler, and flame size, shape, and radiation properties. Comparison of adiabatic flame temperatures for various concentrations of CO₂ can provide an estimate of the temperature changes which may be expected in actual installations. The adiabatic value is the maximum temperature that can be achieved by the combustion products before heat is removed. Various mechanisms including radiative heat loss tend to reduce the actual temperature that is reached, and the adiabatic value represents an upper limit for a specified burner adjustment.

The flame temperature is a strong function of the excess combustion air as shown in Figure 5, which provides the relationship between adiabatic temperature and CO₂ percent for distillate fuel oil. The temperature rises from about 2200°F at 7.4 percent CO₂ to a value in excess of 3400°F at 15 percent CO₂ (near zero excess combustion air). The total quantity of heat contained in the combustion products can be the same for these two operating temperatures because the total mass of combustion products is larger at 2200°F than at 3400°F. However, higher temperature flames (with less excess air) are generally more efficient as indicated by flue gas efficiency tests.

The change in temperature resulting from burner replacement will depend on the initial and final values of CO₂ in the flue gas. A typical example may be considered by selecting average values of excess air for conventional and retention-head burners. Field tests indicate that the average oil-fired system in 1971 operated with 8 percent CO₂, and retention-head burners are capable of achieving 12 percent. For this case the adiabatic temperature increases from about 2500°F to 3100°F. This is a substantial increase in temperature, and could result in combustion chamber failure in certain types of residential heating units.

It must be noted that the flame temperatures indicated above are maximum values that may not be observed in actual installations. The maximum temperature reached in specific boilers varies with many design and operating conditions as noted earlier. However, it is clear that a substantial increase in peak flame temperatures can be expected for any modification which reduces excess combustion air, including installation of flame-retention head burners. The problems created by higher flame temperatures may be more severe for certain boilers such as those of dry-base design. It is recommended that combustion chamber inspection become a standard part of the burner replacement procedure. Replacement of combustion chambers or installation of higher temperature linings is recommended whenever the original chamber is found to be inadequate. Further field investigation of the effects of higher flame temperatures is required to establish a better understanding of problem areas and possible solutions.

2. Vent Dampers. Residential oil-fired heaters generally operate at a fixed firing rate which is designed to satisfy maximum building heating requirements during the winter months. The heating requirements lessen for

References

- 1., 3. Smith and Stinson, Fuels and Combustion, McGraw Hill Book Company, New York, 1952, p. 107, 105.
2. North American Combustion Handbook, The North American Manufacturing Co., Cleveland, Ohio 1965.
4. Calculated Values Based on the Heat Content of Combustion Gases.

Figure 5. Adiabatic Flame Temperature for Various Percentages of CO₂ in Dry Flue Gases (for Distillate Fuel Oil)

warmer outside temperatures, and burner operating time is reduced to accommodate smaller heating loads. Consequently, the burner-off period increases, and off-cycle heat losses increase in magnitude affecting both overall seasonal efficiency and annual fuel use. Convective heat flow from the boiler is a major source of burner-off period heat loss, and it occurs as a direct result of cool room air flowing through the boiler, removing heat from hot internal surfaces, and exiting through the flue. This process removes heat that has been stored in the boiler and reduces overall system efficiency.

Installation of a vent damper in the boiler exhaust pipe is a direct approach for reducing heat loss by minimizing the flow of air through the heating unit during the burner-off periods. Several types of vent dampers are available and have been tested under laboratory and field conditions. It has been observed that the fuel savings that result will vary with many factors including overall efficiency and off-cycle stack heat loss of the equipment before vent damper installation. The cost effectiveness of vent damper utilization is dependent on both the original and final heating system efficiencies. A range of fuel savings has been observed for vent dampers, and both laboratory and field measurements indicate similar results for oil-fired heating units. A schematic of vent damper operation is provided in Figure 6. The damper is in the "open" position (Figure 6a) during burner operation and closes after termination of burner firing (Figure 6b).

The vent dampers evaluated at BNL were tested on commercially available oil-fired boilers designed for residential space heating. Both high and low efficiency boilers with conventional head and flame-retention-head burners were selected for the vent damper tests. Also, vent damper operating characteristics were investigated to evaluate the effects of time delay before damper closure and damper blade bypasses, which are two methods by which off-cycle odor problems can be reduced by purging combustion products from the heating unit during the off-period. Vent damper testing continues as part of the on-going efficiency characterization activity at Brookhaven. The test results to be discussed summarize the information which is currently available.

An 11.0 percent reduction of annual fuel usage is the largest value measured for oil-fired boilers using a commercially available vent damper featuring a three-minute time delay before closure. The boiler-burner combination with which this fuel saving was obtained is an inefficient boiler of dry-base steel design with a conventional head oil burner. In contrast, the same vent damper reduced annual fuel use by only 2.6 percent when installed on an efficient wet-base cast iron boiler with a flame-retention-head burner. The results of four vent damper tests are shown in Table 6. While conclusions based on four tests may be subject to modification with further testing, there are several performance characteristics that should be considered:

- 1) The largest savings of 11.0 percent occurred on the least efficient heating unit with an off-cycle stack heat loss of 13 percent.
- 2) Relatively small savings of 2.6 percent were observed for a high efficiency boiler-burner combination.
- 3) Based on these four tests it may be concluded that flame-retention-head burners affect the total fuel savings possible from vent damper installation. This substantiates previous test results which indicate that flame-retention head burners may reduce burner off-cycle heat losses.

Figure 6. Vent-Damper Schematic

Table 6
Vent Damper Fuel Savings

Burner Design	Boiler Design	Annual Savings in Gallons	Annual Savings in Percent*
Conventional Head	Dry-Base Steel	160	11.0
	Wet-Base Cast Iron	100	7.0
Flame-Retention- Head	Dry-Base Cast Iron	30	2.3
	Wet-Base Cast Iron	30	2.6

*Note: Savings for New York City
Three-minute time delay damper
50,000 Btuh Design Load
40 Gal/day domestic hot water
100% Overfired

The effect of damper blade bypass was investigated on the low efficiency steel boiler with a conventional head burner. These data are presented in Table 7 in which the baseline case without a vent damper is shown at the bottom of the list. The annual fuel uses for various vent damper time delays and various percentages of bypass area are compared to the "no damper" case for calculation of annual fuel savings.

The best performance of 11.6 percent savings occurred for a damper without time delay and without bypass. A slight decrease in performance was observed for a three-minute time delay to an annual fuel savings of 11.0 percent. For the two cases in which damper bypass was tested, the annual fuel savings dropped significantly to 5.5 to 4.1 percent for 8 and 13 percent damper blade bypass. It can be concluded that a three-minute time delay is better than adding bypass to the damper blade for maximum efficiency and minimum annual fuel use. The bypass corresponding to 8 percent of the total damper blade area resulted in a 50 percent reduction of annual fuel savings compared to a vent damper without bypass.

Table 7
Effect of Bypass and Time Delay on Vent Damper Fuel Savings

Boiler: Dry-Base Steel Burner: Conventional Head			
Type	Off-Cycle Heat Loss (%)	Annual Fuel Use (gal)	Annual Fuel Savings (%)
No Delay No Bypass	5.9	1290	11.6
3-Min. Delay No Bypass	6.3	1300	11.0
No Delay 8% Bypass	9.8	1380	5.5
No Delay 13% Bypass	10.9	1400	4.1
No Damper	13.0	1460	----

Laboratory efficiency tests evaluate the fuel savings that result from reduced off-cycle heat losses from the boiler. Additional fuel savings are possible for boilers in residences, because the vent damper can reduce the flow of cold outside air entering the structure to replace the warm room air that is vented through the heating unit during the burner-off cycle. This part of the heating requirement of the building can be reduced by installing a vent damper. However, this component of savings is small in magnitude, and is highly variable depending on the location of the boiler within the building.

The magnitude of the resulting boiler-burner induced infiltration has been estimated to be less than 2 percent for oil-fired heating units. Also, this additional savings can be much less than 2 percent for heating units located within the building such that the off-cycle air flow through the boiler does not affect building air infiltration (e.g., boiler located in garages and drafty basements). The savings resulting from boiler-induced infiltration is highly variable depending on the boiler-building interaction, and the maximum estimated value is generally small compared to the component of fuel savings resulting from reduced heat loss from the boiler.

It is possible that annual fuel savings from vent dampers can exceed the 11.0 percent value for heating units in which off-cycle losses are unusually large. For example, systems with large heat storage capacity and large off-cycle air flow rates may provide the potential for more than an 11 percent savings. Massive boilers designed for coal burning and converted to fuel oil may represent such a system, but further testing and field evaluations are required to investigate this possibility. In addition, a detailed evaluation of the existing national inventory of residential boilers and furnaces is required to properly assess the possible impact of vent dampers on fuel use in residences.

The Federal Energy Administration funded a field study by Walden Division of Abcor, Inc. to investigate the effect of vent dampers on oil-fired boilers and furnaces in residences. Performance data were collected from field-installed heating units from which changes in annual fuel use were calculated. An average fuel savings of 6.5 percent was measured for 21 vent damper installations with a predicted annual fuel savings for the average climate in the U. S. of 8.2 percent. The field evaluations include six steam boilers, nine hot water boilers, and six warm air furnaces. The average savings observed for hot water boilers was 5.9 percent with a range from 2.2 to 9.5 percent. The range of values observed by Walden for oil-fired hot water boilers is similar to the laboratory test results obtained at Brookhaven.

One limitation of the Walden investigation is the relatively small sample size obtained. While the total sample size of 21 units can be expected to provide a reliable value for average fuel savings, extraction of more detailed fuel savings data by burner, and boiler or furnace design is not possible. A larger test sample could provide the necessary information for a more detailed field evaluation. Future field studies should be large in size to accommodate data scattering introduced by many uncontrolled parameters experienced by field investigations.

Laboratory efficiency measurements indicate that vent dampers may reduce fuel oil consumption in residences within a range of values between 2 and 11 percent. Field tests have substantiated the range of savings for oil-fired boilers, giving an average value of 6.5 percent for steam, hot water and warm air systems. Savings in excess of 11 percent are possible for heating systems with unusually large off-cycle heat loss rates, and further testing and field evaluation is required to identify the conditions under which vent damper impact may be maximized.

3. Boiler Stack Economizers (Heat Reclaimers). The stack economizer is designed to reclaim heat from the boiler exhaust gases and return it to the boiler where it can be utilized. To date, two stack economizers have been evaluated in the test facility. The concept used in both designs is identical and a schematic of the economizer is shown in Figure 7. Water is pumped from the boiler across heat exchanger surfaces located in the stack economizer, and the heated water is returned to the boiler for distribution to the heating load. The economizer reduces stack heat loss during burner operation by decreasing the temperature of exhaust gases vented through the chimney, and energy savings are directly related to the stack temperature reduction that occurs between the inlet and outlet of the economizer. Obviously, high stack temperatures indicate high stack heat losses which could be reduced by economizer installation. Actual fuel savings in field installations will vary over a wide range, depending on the stack temperatures of individual heating units.

Figure 7. Economizer Schematic

In testing both units, the economizer was installed on a dry-base steel boiler known to have relatively high stack temperatures and low efficiency, representing the most probable market for such economizers. If the units were tested on boilers with lower stack temperatures, the results would indicate less benefit for the same investment. The results and operational curves determined from laboratory tests appear in Figures 26 and 27 of Appendix C for the models tested. The first unit was of prototype design and provided good performance indicated by a drop in stack temperature of 330°F from 590°F to 260°F. The corresponding decrease in annual fuel consumption for a home located in New York City (under conditions described earlier) was 20% or 290 gallons per year. The second unit tested was a commercially available unit with a design based on a scaled-down industrial economizer used in larger commercial boiler systems. This unit was tested on the same burner-boiler system used in testing the first economizer. However, the savings realized under the identical operating constraints mentioned above were only 9% or 130 gallons of fuel per year. Although 9% savings is significant, it appears that specific design features limit the unit's performance. One possibility is that the comparatively large surface area of the second unit's sheetmetal housing was acting to increase jacket losses through the economizer. Re-design to minimize such exposed surfaces might improve performance.

One possible problem area observed with both units during operation is the tendency for soot to collect on heat exchanger surfaces. The smoke number was maintained at a low level (#1 Bacharach) and soot accumulation was observed after two weeks of testing. The average smoke number observed in a field study⁶ was #3, which could contribute to substantially increased fouling of stack economizer surfaces. Eventually soot deposition will degrade economizer performance, and could result in reduced draft at the fire-box as the flue passage becomes restricted. Another area that requires investigation is the possibility of equipment damage from flue gas condensation after economizer installation, if stack temperatures drop too low and condensation cannot be avoided.

4. Vapor Systems/Combustion Air Humidification. Several vapor systems were accepted for testing and two different units were evaluated by the end of fiscal year 1978. These systems were alleged to increase combustion efficiency by introducing water vapor into the combustion air. Several designs exist on the market and two representatives were tested.

The first system claimed that the water vapor in combination with a chemical mixture acted as a catalyst to the combustion process thus improving combustion and heat transfer and efficiency. Test results indicated a 1.3% annual savings with the addition of the device to a standard dry-base boiler fired with a retention-head burner. This is considered a negligible reduction in annual fuel use because the overall test facility has a system accuracy of 2%. If we consider a dollar estimate of savings, this 1.3% is equivalent to 16 gallons of fuel oil and, assuming a price of 80¢ per gallon, this results

\$12.80 per year. Typical costs for this system installed range above \$200 per unit. The manufacturer's representative was allowed to adjust the boiler-burner system to peak out the performance with the addition of his device before tests were recorded. This adjustment can account for a small improvement in performance, whether or not a refit modification is installed. In addition, this particular system consumed electrical power to supply a small pump and heater integral in the system design. This power consumption, though small, would be another economic consideration in evaluating the system's merits by a homeowner.

The second unit tested, also claimed to increase combustion efficiency by introducing water vapor to the combustion air. This unit was designed as a passive device which relied on the burner's combustion air fan for driving power. The unit was connected to the burner housing by two short lengths of tubing. One tube supplied air from the burner which then bubbled through the unit's water reservoir and then passed back via the second tube to mix with the combustion air supplied to the flame. The results of this test were very similar to those associated with the first unit, and a fuel savings of 1.4% was observed, which again is considered negligible.

Stack gas analysis was performed during the testing period and no change in flue gas analysis was observed. Steady-state tests indicated a slight increase in efficiency for both units (75.8 to 76.0 and 75.6 and 76.7, respectively). As mentioned, the final results which take into account this small change in steady-state efficiency, show no significant savings based on direct heat flow measurements.

5. Boiler Water Temperature Reduction. Several efficiency tests were performed to determine the potential savings associated with reduced boiler temperatures. The aquastat is the control device on a boiler which maintains the boiler water temperature within a preset range for space heat and domestic hot water supply. Tests were performed on a dry-base steel boiler fired with a conventional burner and it was found that lowering the boiler water temperature during burner off periods resulted in significant fuel savings through reduced off-cycle heat losses. Tests were performed with boiler water temperatures maintained at four different levels, 140°F, 150°F, 185°F, and 200°F. Complete efficiency tests including steady-state and a full range of cyclic tests were performed at 150°F and 185°F. Analysis of these tests was performed and annual fuel uses were projected to 140°F and 200°F.

The AFUE results and performance curves for these tests are found in Appendix C, Figure 28. A summary of overall efficiency versus burner fractional "on" time (BFOT) for the various curves is presented in Table 8.

The tests indicate a potential savings of 0-10% in annual fuel use associated with a 0-38% decrease in average off-cycle heat losses. The range indicates that the maximum savings is found when the average boiler water temperature is dropped from 200°F to 140°F. The actual savings in the field will be dependent on the present operating settings of the aquastat before and after modification. If the boiler tested is reduced from 185°F to 150°F, the

Table 8
Overall Efficiency vs. BFOT and Average
Boiler Water Temperature

Burner Fractional On Time-%	Average Boiler Water Temperature			
	140°F	150°F	185°F	200°F
5	32.1	27.7	12.5	6.0
10	54.3	52.2	45.0	41.9
15	61.7	60.3	55.7	53.7
20	65.4	64.4	61.0	59.6
25	67.6	66.8	64.2	63.1
30	69.1	68.4	66.3	65.4
40	69.1	68.9	68.0	67.7
60	69.2	69.1	68.6	68.4
100	69.2	69.2	69.2	69.2

savings will be approximately 6% of the annual fuel use. In dropping boiler water temperature, the homeowner must keep in mind that the system's response to heating demands and hot water usage will be somewhat slower. It is this factor that will determine how low the aquastat can be adjusted for individual cases. In the heating industry several automatic devices are available to adjust aquastat settings based on outside temperatures and domestic hot water use. Unfortunately, these devices cannot be evaluated in the laboratory and extensive field tests are required to prove the merits and claims of these devices.

Changes in annual fuel consumption were calculated using the AFUE analysis to evaluate the impact of lower boiler operating temperatures. The lower boiler water temperatures reduced fuel use up to 140 gallons of fuel per year in the best case (200°F reduced to 140°F) for a 10% fuel savings per year, and a reduction in average off-cycle losses of 38%.

The quantitative relationship between boiler temperature and off-cycle losses has been established by these tests which show that reducing boiler water outlet temperatures resulted in substantial reduction of burner off-cycle losses. While the evaluation was carried out for a fixed boiler temperature in actual applications the boiler water temperature could be varied (perhaps from 100° to 200°F) to accommodate varying heat loads.

This could be accomplished by an automatic boiler temperature controller sensing outside temperature and selecting the minimum boiler water temperature that is sufficient to meet the heating load of the house. Another approach would be for the homeowner to adjust the boiler water temperature manually, several times during the heating season (or more often), to minimum acceptable temperatures. By varying the boiler temperature automatically (or manually), the resulting fuel savings would be expected to be greater than the savings associated with a fixed temperature. A more detailed analysis is required to evaluate fuel savings resulting from variable aquastat operation.

This concept is directly applicable to all hydronic heating boilers that maintain a minimum temperature in order to supply space heat only. In the case of boilers used to supply domestic hot water and space heat, the boiler temperature must be maintained at a level sufficient to produce hot water at an acceptable temperature, and satisfy the space heat load. "Acceptable" temperature settings can vary, depending on individual preferences of residents and the condition of the boiler system.

C. Summary of Test Results

The results obtained for commercially available equipment must not be over-generalized because there are many variables that will affect the efficiency of a particular boiler, including burner type, quality of installation and control adjustment. In the laboratory, all burners were adjusted to peak efficiency with a zero-to-one smoke number on a Bacharach scale where in actual field installations there can be a wide range of burner adjustments from the optimum setting. It is not stated or implied that all boilers or retrofit options of any particular type are better or worse than another. However, we have presented all of the results found to date and have noted particular features that appear common to high efficiency burner-boiler heating units.

An updated retrofit option list appears in Figure 8. This list indicates retrofit options mentioned in this report along with other actions investigated earlier in the project's history. Details on particular items are available in the previous annual reports for the project, References 1 and 12 of this report. An important retrofit action not mentioned in this report is reduced fuel firing rate which is based on the observation that most field installations are approximately 100% overfired at design conditions. If these units were to be properly fired, the national fuel consumption by residential heating systems could be reduced significantly. In practice, this is also one of the least expensive options available and can be accomplished under existing service contracts during annual tuneups at no extra cost.

IV. INDIRECT EFFICIENCY TESTING METHODS COMPARED TO DIRECT HEAT FLOW MEASUREMENT

A. Introduction

Direct measurement of the useful heat output and fuel usage of heating units provides a fundamental method for evaluating thermal efficiency. The efficiency test procedure used at BNL is an example of a direct heat input-

Refit Action	Estimated Fuel Saving Range (%)	Approx. Cost (\$)	Payback Period (Years)
1. Reduced Burner Firing Rate (by 25%)	6 - 10 ^a	0 ^b - 25	0 - 0.3
2. Boiler Water Temperature Reduction (35°F)	3 - 7	0 ^c - 20	0 - 0.6
3. Thermostat Setback ^d - Manual Adjustment	6 - 10	0	0
4. Thermostat Setback ^d - Automatic	6 - 10	80	0.7 - 1.1
5. Burner Efficiency Adjustment	2 - 4	0 ^b - 30	0 - 1.3
6. Boiler Fire-Tube Turbulators	2 - 8 ^e	50	0.5 - 2.1
7. Retention Head Burner ^f	6 - 22 ^a	250	1.0 - 3.5
8. Vent Damper ^g	4 - 12 ^a	200	1.4 - 4.2
9. Stack Heat Reclaimer ^g (Economizer)	10 - 20 ^a	350	1.5 - 2.9
10. Low Input/Variable Firing Rate Burners ^h	15 - 25	~500	1.7 - 2.8
11. Ducting Combustion Air from Outdoors ⁱ	0 - 3 ^j	100	2.1 and up
12. Modern High Efficiency Burner-Boiler	23 - 25 ^a	1800	6 - 6.5
13. Blue Flame Boiler-Burner	21 - 28 ^a	1900	5.7 - 7.5
14. Outdoor Boiler Installation	0 - 10 ^k	-	-
15. Combustion Air Humidification	0 - 1	200	17.0 and up
16. Water Fuel Emulsion	0	-	-

Notes: Savings from Refit Actions are not additive. Payback period is based on 1500 gallons per year fuel use at \$.80 per gallon.

- a. Based on dry-based steel boiler with non-retention-head burner
- b. May be included as part of annual servicing
- c. Manual adjustment by homeowner
- d. Setback of 10°F for 8 hours per day
- e. Applicable only in boilers where turbulators are absent
- f. Firing rate reduction should accompany burner installation
- g. Possible safety hazard exists - long term testing required
- h. Commercial equipment not available at this time
- i. Including inlet air damper for burner off-cycle
- j. Will vary depending on boiler location in structure
- k. Will vary with boiler - testing required

Figure 8. Refit Modifications for Efficiency Improvement of Oil-fired Boilers

output testing technique. As discussed earlier, the accuracy of direct measurement does not rely on simplifying assumptions, but depends on the measurement accuracy of physical quantities including mass, time, and temperature. The accuracy of the efficiency test facility at BNL is maintained within 2% and equipment calibrations are performed each day. Direct heat flow measurement is an accurate, fundamental method that is free of simplifying assumptions, and provides a standard basis by which other test procedures may be compared quantitatively.

Indirect efficiency measurement techniques do not evaluate heat input and useful heat output for the heating unit under investigation. Instead, the stack heat loss rate is determined, certain assumptions are employed regarding other heat loss rates, and the thermal efficiency of the heating unit is predicted. The accuracy and reliability of indirect methods depend on measurement accuracy of stack heat loss rates and the error introduced by various assumptions and assigned parameters that are used. The overall accuracy of indirect methods can be evaluated quantitatively by comparison of efficiency results to corresponding test results determined by direct heat flow measurement. Such evaluations have been performed at BNL where results from direct heat flow measurement have been compared to results from indirect techniques during continuous and intermittent burner operation. During steady-state burner operation, the indirect methods are useful for proper field adjustment of heating units, while indirect procedures have been found to be of limited value for assessment of part-load (seasonal) efficiency.

B. Steady State Efficiency by Indirect Methods

Indirect methods using flue gas analysis to measure stack heat loss can provide reasonable approximations of thermal efficiency during continuous burner operation. Generally, the dominant heat loss mechanism during steady-state operation is heat loss through the heating unit exhaust. Errors introduced by flue gas analyses during steady-state operation involve heat losses through the boiler jacket which cannot be evaluated by stack heat loss measurement alone. The magnitude of jacket heat loss has been measured at BNL to vary from 1 to 12% for oil-fired residential boilers. Uncertainty in efficiency results determined by stack heat loss methods, therefore, cannot be better than this range of values. Correction factors based on measured jacket losses for various boiler designs may partially eliminate this uncertainty and provide more accurate efficiency values based on stack heat loss calculations for continuous burner operation.

Indirect efficiency measurements using stack heat loss calculations have been used for many years to test and adjust combustion equipment. While uncertainty in jacket heat loss compromises the accuracy of efficiency measurement, flue heat loss methods are necessary to assure proper adjustment of combustion equipment in the field. All types of fuel-fired heating units are dependent on proper adjustment to assure maximum operating efficiency. Stack heat loss efficiency tests (flue gas analyses) provide a sound basis for maintenance of optimum efficiency. Furthermore, flue gas analysis can be used as a diagnostic tool by servicemen to justify replacement of burner components as required to maintain the highest possible efficiency for the unit being tested.

C. Efficiency Measurement During Part-Load Burner Operation by Indirect Methods

The operating efficiencies of residential heating units have been shown to vary with the burner load. Heat losses during the burner idle period have a significant impact on thermal efficiency and annual fuel consumption. A testing and labeling procedure has been developed by DOE using an indirect stack heat loss model to predict seasonal operating efficiency for residential heating units for use in the appliance labeling program.

In contrast to direct heat flow measurement procedures, the DOE test procedure is based on many simplifying assumptions and constant factors assigned for key parameters that, in reality, may vary from unit to unit. These assumptions and assigned parameter values include:

- the assumption of D_f , a constant burner off-cycle draft factor, that is the same value for all power burners (regardless of burner head design);
- the assumption that boiler jacket heat loss is small;
- the use of a fixed burner load factor (of 22.5%) for all boilers (instead of calculating fuel use based upon fixed heating requirements).

BNL has tested two commercially available boilers using the direct heat flow method and also the method proposed for labelling (see Figures 9, 10, 11, and 12). It was found that, due to the simplifying assumptions listed above, the DOE method in some cases shows a much smaller difference in annual efficiency between good and poor boilers than that determined by the BNL direct heat flow method (see Tables 9 & 10).

V. SUMMARY AND CONCLUSIONS

The efficiency test facility at Brookhaven provides direct quantitative evaluation of oil-fired heating equipment efficiency. A heat flow measurement technique provides direct and accurate evaluation of heating unit efficiency and the Annual Fuel Use and Efficiency calculation permits translation of test results to seasonal efficiency and annual fuel consumption values. Together, the direct measurement technique and AFUE computation provide a precise and common basis for comparing the performance of different heating units.

The test facilities have generated a wide range of performance characteristics based on equipment voluntarily submitted for testing. A continuing characterization test schedule will provide additional benefits and encourage the development and manufacture of high efficiency heating units. Many units have been tested that can substantially reduce fuel consumption and operating costs, while others have been identified that do not provide significant savings. It is important that the homeowner be properly informed of the potential savings of any device.

Figure 9. Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

*RESULTS OF WORK FUNDED BY NBS

Figure 10. Burner Draft Factors Measured in the Field*

Figure 11. Off-Cycle Stack Heat Loss vs. Burner Draft Factor.
(Predicted by DOE Labeling Procedures).

Figure 12. Cycle Efficiency (η_c) vs. Burner Fractional "On" Time (%).

Table 9
Annual Efficiency

Test Method	Boiler A	Boiler B
Direct Heat Flow Measurement	54.9	74.5
DOE Test Procedures ¹	70.7	78.1

Boiler A - Dry-base single pass steel boiler with non-retention head burner
 Boiler B - Wet-base cast iron boiler with retention head burner
 Both boilers tested had similar fuel input rates.

Table 10
Annual Fuel Savings

Test Method	Percent Change Annual Fuel Use (Boiler A to B)%	Fuel Savings Gals/Yr	Fuel Cost Savings(\$/Yr) (\$0.80/Gal)	Payback Period Years
Direct Heat Flow Measurement	26.3	350	280	1.3
DOE Test Procedures ¹	9.5	90	72	4.9

¹Department of Energy "Final Energy Conservation Test Procedures."
 Federal Register, Vol. 43, No. 91, May 10, 1978.

Fuel savings, efficiencies, and fuel usages noted in this report are based on specified operational conditions. The usefulness of the results is the relative comparison of different types of equipment, and an attempt was made to indicate performance ranges rather than average values. Actual fuel use by heating devices installed in the field varies depending on many installation and operation parameters. Field testing of equipment efficiency requires long term tests and large sample bases to average the many factors that occur in individual cases.

Proper installation of heating equipment in the field is necessary to assure peak efficiency, and there exists an endless list of improper installation practices that will degrade efficiency performance. Failure to insulate hot water piping for boiler systems and warm air ducting for furnace systems is an example of unwise installation practice. Long uninsulated runs of hot water piping from the boiler through unheated basements and crawl spaces can reduce the amount of useful boiler heat delivered to the heated space, and reduce operating efficiency. Similarly, uninsulated warm air ducting passing through cold attic areas can degrade the efficiency of furnace systems. Careful attention must be placed on these and all other equipment installation procedures in order to maximize the efficiency of the heating unit/house system.

The results of the testing program are made available to the public in several ways. Findings Reports are prepared for each unit tested at Brookhaven, providing detailed performance and annual fuel use information. Topical reports are prepared for general types of equipment and retrofit modifications that are tested, and an annual report is prepared summarizing the testing accomplishments for each fiscal year. Detailed verbal presentations of project work are provided on site at Brookhaven and other locations throughout the country by program staff members. A list of on-site presentations appears in Appendix A.

In the future, the BNL test project will serve in four different areas. The laboratory will be used to implement the characterization schedule during fiscal year 1979. In addition, the project will continue to provide evaluation of any new equipment that appears to have a significant potential for high levels of operating efficiency. Testing and technological evaluations will be performed as required in support of the DOE/BNL Space Conditioning Equipment RD&D program. In order to promote the use and installation of high efficiency units and retrofit options, a pilot promotional program is now in progress. This program, located in Nassau and Suffolk Counties in New York State, is being developed by the New York State Energy Office in cooperation with local oil dealers and BNL. The BNL test facility will be available to lend technological support when needed in this venture.

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APPENDIX A

PRESENTATIONS MADE AT BNL IN FY 1978

D. O'Neal, Oak Ridge National Laboratory

D. Ahrens, engineering firm

J. Dooher, Adelphi University

Suffolk County Energy Office

D. Saltzman, MIT

H. Straus, Meenan Oil Co.

Long Island Lighting Company

New York City Apt. House Supt. Organization

W. Weatherford, S.W. Res. Inst. California

New York Regional DOE group

C. Flink, Southern Maine Tech., Portland

Engineering students - University of Bridgeport, Connecticut

R. Polizzano, Oil King boiler manufacturer, Pennsylvania

G. McAlpine, University of Virginia

G. Eldring, P.E. Energy Audit Investigator

E. Nagle, HUD, New York

Suffolk Development Corp.

E. Morgan, NOJC, Washington, D.C.

R. Dugan, Weil-McLain - boiler manufacturer

R. Beals, New Jersey State Conservation Office

G. Brandes, home builder - Connecticut

D. Emery, Vaporvak - New Hampshire

E. Cushman, Axeman Anderson - boiler manufacturer, Pennsylvania

L. Wichinsky - inventor, New York
Suffolk County - architects and builders
M. Aurbuch - economizer manufacturer, New York
J. Rizzuto - New York Public Service Commission
L. Donnenberg - Boiler designer, New York
W. Marran - Marran Oil, New York
G. Nehaus - Consumers Union
Dahlgren and Hirsch - Mobil Oil
Eric & Horton - Webster Oil Co., Connecticut
M. Hagin - New York State Energy Office
Nelson, London, Hartsell - DOE, Washington, D.C.
Halperin - Gordian Assoc., New York
ADL - Cambridge, Massachusetts

APPENDIX B

WARM AIR FURNACE TEST FACILITY DESCRIPTION

A. Instrumentation

The test facilities at BNL were designed and built to produce a maximum measurement accuracy and reliability. The following is a brief description of the instrumentation used:

- (1) $\dot{m}_a, \dot{m}_v$ - A vortex shedding flow meter is used to measure the air flow rate through the furnace. Pressure, temperature, and relative humidity are also measured to enable a conversion from volumetric to mass flow rates.
- (2) ΔT - A thermopile is used to measure the temperature rise across the furnace. This device consists of 20 thermocouples wired in such a way as to provide a differential temperature reading across the inlet and outlet ducts.
- (3) $\dot{m}_{oil}$ - A turbine flow meter is used to measure the fuel flow rate. A thermocouple is used to convert volume flow rates to mass flow rates.
- (4) h_{oil} - The fuel oil heating value is measured by use of an oxygen bomb calorimeter following the appropriate ASTM procedure.
- (5) Data Processing Equipment - An analog to digital "computer" has been built to provide for instantaneous automatic data reduction to facilitate more rapid operation and to eliminate human error as much as possible. The computer receives the analog signals from the various flow and temperature transducers and produces heat and efficiency values by the method outlined in Section II-B. The quantities of interest are converted to digital values and displayed on readouts and four 4-channel printers. The most powerful feature of the computer is the ability to perform integration over time for the heat input and heat output values. During cyclic operation, the mass flow rates and temperatures vary with time and the computer provides an instant-by-instant accumulation of the heat values. The only alternative method requires manual integration of areas under curves (e.g., the ΔT - time curve) which are time consuming and a large source of error.

B. Test Apparatus

A facility was built to measure thermal efficiencies of various air furnaces under identical conditions. Therefore, it was necessary to provide means to control air flow rates and inlet air temperatures to accommodate differently

designed furnaces. The following is a description of the test equipment used:

- (1) Blower - A blower was used capable of delivering large enough flows to provide sufficient air for any furnace expected. The internal blower of the furnace is not used in this facility.
- (2) Flow Control Valve - A valve is used to control the amount of air delivered to the furnace by "dumping" excess air to the outside. This valve is remotely controlled from the data processing equipment by the operator.
- (3) Temperature Regulators - Air used for furnace testing is brought in from the outside. This air must be maintained at constant temperature. To do this, cooling and/or heating is provided by an evaporator coil for cooling and an electric resistance heater.
- (4) Flow Meter - A vortex shedding flow meter is used to measure the air delivery rate to the furnace under test.
- (5) Cycling Valves - Two valves are used to allow air flow to the furnace or divert the air outside, isolating the furnace. This is done during part-load testing in order to keep the inlet air at constant conditions. This would not be possible if the blower(1) were shut down after every cycle.

C. Calibration

Calibration checks of all measured quantities are essential to maintain a high degree of accuracy. Checks are performed at least once daily and the techniques used for each quantity are explained below:

- (1) $\dot{m}_{oil}$ - The oil flow rate is calibrated gravimetrically using a balance and a timer. Oil is allowed to flow into a large flask atop a balance and the rate at which the oil mass increases is measured. This rate is compared to the rate displayed on the data acquisition and control unit. The maximum uncertainty in the calibration procedure is <0.1% while the uncertainty in $\dot{m}_{oil}$ is <0.5%.
- (2) h_{oil} - A calibrated oxygen bomb calorimeter is used to measure the oil heating value. Manufacturer states uncertainty at <0.1%.
- (3) $\dot{m}_{air}$ - The air flow rate is checked calorimetrically using electric resistance heaters. Air is passed through duct heaters and after thermal equilibrium is reached, the temperature rise of the air is measured (ΔT). The heat consumed ($\dot{Q}_{in}$) is measured (in the form of watts) with a digital wattmeter and integrated over time. The air flow rate is given by the expression:

$$\dot{m}_{air} = \frac{\dot{Q}_{in}}{C_p \Delta T}$$

- (4) ΔT_{air} - The temperature rise of the air is measured using a twenty (20) element differential temperature thermopile. This thermopile is checked by electronics and by comparison to a calibrated platinum resistance thermometer.

D. Test Procedure

Steady State Efficiency Tests. For steady state tests the burner firing rate and air flow rate through the furnace are maintained at constant values. The air flow rate is adjusted to give a 155°F ($\pm 5^{\circ}\text{F}$) outlet temperature while the inlet temperature is maintained at 70°F ($\pm 5^{\circ}\text{F}$). After the furnace has achieved thermal equilibrium, data is collected for one hour of steady operation and the thermal efficiency is calculated and recorded. Flue gas analysis is also performed for comparison to the enthalpy flow tests.

Cycle Efficiency Tests. A digital programmer is used to control the "on" and "off" times of the burner and the air flow through the furnace. The burner "on" time is varied from 5.0 to 15.0 minutes while the air flow time (fan "on" time) is varied accordingly to give furnace air outlet temperatures of 105°F to 145°F at the end of the fan "on" period. Burner and fan "off" times were adjusted to match the particular cycle length used. To begin a cycle, the burner and the air flow through the furnace start simultaneously. At the end of the burner firing period, the air flow is allowed to continue until the desired outlet air temperature is reached. At this time the air flow is stopped and the furnace sits idle for the remainder of the cycle. Once the cycle is programmed the system is allowed to operate for many cycles until "steady cycles" are achieved. At this point the heat input and output for each cycle becomes constant.

The amount of heat into and out of the furnace is measured and integrated over time. The ratio of the amount of heat extracted to the amount of heat generated in the furnace is the overall efficiency. This is true both in steady state and in cycle efficiency tests.

APPENDIX C

Efficiency Curves and Annual Fuel Use and Efficiency Data

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Boiler Tests	1 - 9
Flame-Retention-Head Burner Evaluation Tests	10 - 25
Hydronic Stack Economizer Tests	26 - 27
Reduced Boiler Water Temperature Tests	28

Location: NYC
 Seasonal Efficiency 52.8% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1550 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 2. Dry-Base Single Pass Steel Boiler With Conventional Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 56.2% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1455 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 1. Dry-Base Single Pass Steel Boiler With Conventional Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 71.0% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1153 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 4. Wet-Base Multi-Pass Horizontal Fire-Tube Boiler With Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 74.6% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1098 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 3. Wet-Base Multi-Pass Horizontal Fire-Tube Boiler With Induced Draft Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 74.1% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1104 Outside Design Temp 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 6. Wet-Base Multi-Pass Horizontal Fire-Tube Boiler With Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 72.3% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1132 Outside Design Temp 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 5. Wet-Base Multi-Pass Horizontal Fire-Tube Boiler With Induced Draft Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 70.5% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1161 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 8. Dry-Base Cast Iron Boiler With
 Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 64.2% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1275 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 7. Dry-Base Cast Iron Boiler With
 Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 68.7% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1191 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 10. Flame-Retention-Head Burner "A" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 75.3% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1087 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 9. Wet-Base Cast Iron Boiler With
 Flame-Retention-Head Burner
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 66.2% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1236 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 12. Flame-Retention-Head Burner "C" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 64.5% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1269 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 11. Flame-Retention-Head Burner "B" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 67.4% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1215 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 14. Flame-Retention-Head Burner "F" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 64.7% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1265 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 13. Flame-Retention-Head Burner "D" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 59.8% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1369 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 16. Flame-Retention-Head Burner "D" in Boiler "B"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 66.6% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1228 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 15. Flame-Retention-Head Burner "F" in Boiler "A"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 75.3% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1387 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 18. Flame-Retention-Head Burner "A" in Boiler "C"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 52.8% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1550 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 17. Conventional Burner "I" in Boiler "B"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 63.6% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1286 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 2C. Conventional Burner "I" in Boiler "C"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 71.0% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1152 Outside Design Temp: 0.0
 (Gal/Year)
 Domestic Hot Water 40.
 (Gal Per Day)

Figure 19. Flame-Retention-Head Burner "C" in Boiler "C"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Figure 22. Conventional Burner "3" in Boiler "C"
 Overall Efficiency η_0 vs. Burner Fractional "On" Time (%)

Figure 21. Conventional Burner "2" in Boiler "C"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Figure 24. Flame-Retention-Head Burner "G" in Boiler "D"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Figure 23. Flame-Retention-Head Burner "D" in Boiler "D"
 Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Figure 26. Prototype Hydronic Stack Economizer on Dry-Base Single Pass Boiler With Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Figure 25. Conventional Burner "I" in Boiler "D"

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Outside Design Temp: 0.0
 Domestic Hot Water 40.0
 (Gal Per Day)

Seasonal Efficiency	140°F	150°F	185°F	200°F
	60.8%	59.7%	56.2%	55.1%
Annual Fuel Usage	1346	1370	1455	1486
(Gal/Year)

Figure 28. Dry-Base Single Pass Steel Boiler with Conventional Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)

Location: NYC
 Seasonal Efficiency 61.8% Design Heat Load: 50,000 BTU
 Room Temp: 68.0
 Annual Fuel Usage 1324 Outside Design Temp: 0.0
 (Gal/Year) Domestic Hot Water 40.
 (Gal Per Day)

Figure 27. Commercial Hydronic Stack Economizer on Dry-Base Single Pass Boiler with Flame-Retention-Head Burner

Overall Efficiency (η_0) vs. Burner Fractional "On" Time (%)