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DIRECT EFFICIENCY MEASUREMENT AND CHARACTERIZATION OF RESIDENTIAL HEATING EQUIPMENT

ANNUAL REPORT
FISCAL YEAR 1979

R.F. KRAJEWSKI, R.J. MCDONALD, AND J.S. MILAU

May 1980

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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ABSTRACT

A laboratory project, now in its fourth year of formal operation, is currently engaged in a new phase designed to provide a data base for the identification of residential heating equipment efficiencies as a function of observable design characteristics. Preliminary characterization results for hydronic (hot water) oil-fired systems are presented along with the results of other work conducted to fulfill commitments made under an earlier phase of the project. The first results from the fully operational warm air furnace test facility are included with a brief description of the equipment and the technique used in measuring furnace efficiencies.

The laboratory procedures are designed to measure the efficiencies of different types of residential heating equipment. A direct measurement technique permits an accurate evaluation of the efficiency of residential heating units during full-load and part-load operation. The laboratory data are 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 the evaluation of a wide range of hydronic burner-boiler systems. The combination of direct, accurate efficiency measurement and calculation of annual fuel use provides a standard method for comparison of individual heating units and retrofit modifications on a common and realistic basis.

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I. INTRODUCTION

Approximately 20% of the energy consumed in the United States is used in residential buildings. The most likely candidate for savings in the residential sector is space heating which accounts for more than half the residential energy demand (∿11% of the total national use).

The goals of the present program are to promote the efficient use of all energy sources in space heating of residential and small commercial buildings. These include improvements in specific devices, methods of interfacing devices with the building structure, and formulation of optimum control strategies to manage the thermal systems involved.

The primary objective of the space heating equipment testing program is to provide the technical basis for reduced consumption of oil and gas by identification of high-efficiency heating equipment. Public dissemination of test reports and results 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. Testing results are used to compare individual heating units and identify design characteristics that produce high operating efficiency. The economic advantages of high-efficiency heating units can then be established to provide an incentive for utilization of these types of equipment.

The project is funded through the Office of Buildings and Community Systems within the Department of Energy, Washington, D.C. The program has had wide success to date and it will be continued through the interaction of the BNL project staff with industry representatives, state level energy offices, oil companies, and the general public. Earlier in the project, manufacturers and developers of heating equipment were encouraged to voluntarily submit heating units and refit devices to BNL for efficiency testing and evaluation. During Fiscal Year 1979, the last of those commitments were resolved and attention was directed to several new phases of work. The system of voluntary participation in the program by equipment manufacturers resulted in some characterization of general design features that can commonly be associated with high efficiency. A plan for detailed characterization of such features was implemented during Fiscal Year 1979 and will continue as a major work phase of the project. Details of the characterization testing phase are contained in this report. In addition, the project continues to lend technical support and evaluation to both the DOE/BNL Space Conditioning Equipment RD&D Program and the DOE/BNL Fuel Oil Conservation Marketing Demonstration Program. Even though the original voluntary submission of equipment phase has been concluded, the project will continue to investigate new equipment from any source. If, on the basis of a technical review, a device or concept is found to be unique with some demonstrated potential for energy conservation a test can be provided, but only if no previous test has been performed and if approval is granted by those who control test scheduling and planning.

The efficiency measurement technique developed by BNL can be used to accurately determine the overall efficiency of heating equipment by taking into account all heat losses incurred during operation. In considering operational losses, BNL has chosen to categorize losses in three areas. The first, energy lost up the chimney during burner operation, is referred to as operating stack loss. The second, the heat energy lost through the boiler casing to the surroundings during burner operation, is referred to as operating jacket loss. Thirdly, the energy lost from the boiler when the burner is not operating is referred to as off-cycle loss. Off-cycle losses occur in two ways. 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. In addition, heat is lost through the boiler jacket when the burner is off. 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. These boiler standby temperatures provide the driving force for off-cycle losses.

The magnitude 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 were found to range 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, 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 contained in the fuel consumed, over a one-year period. The seasonal efficiencies that have been observed at BNL range from 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. 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 heat 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 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 Fig. 2 for a typical boiler.

In addition to the direct measurement tests already mentioned, flue gas tests are performed during each heat flow measurement in steady-state operation.

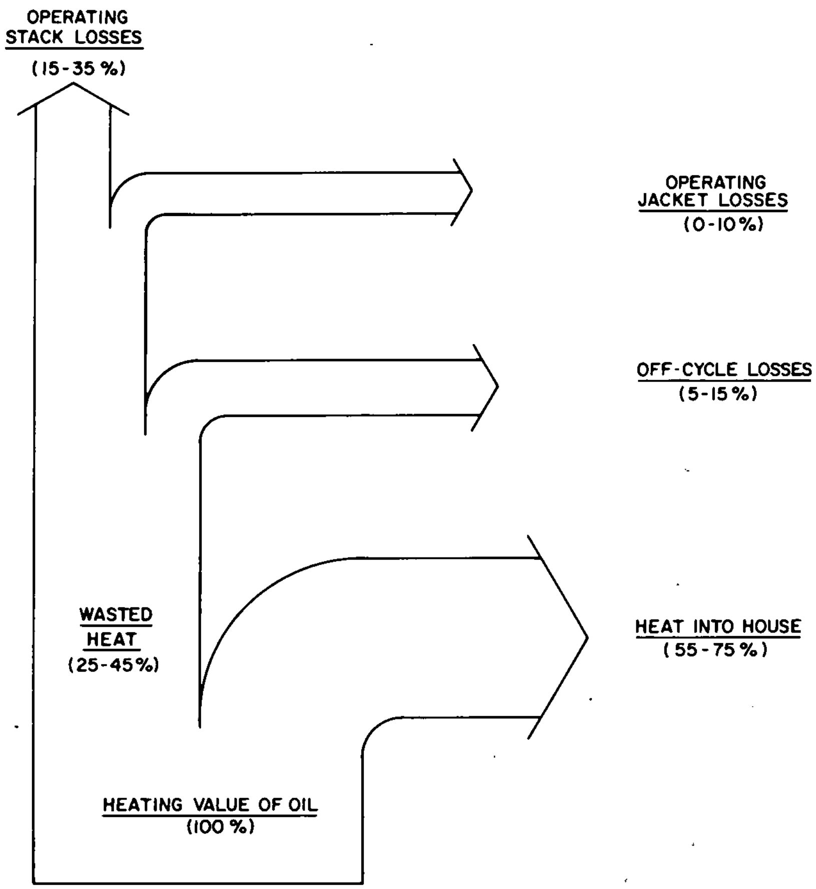

Figure 1. Energy flow for oil-fired hydronic boiler.

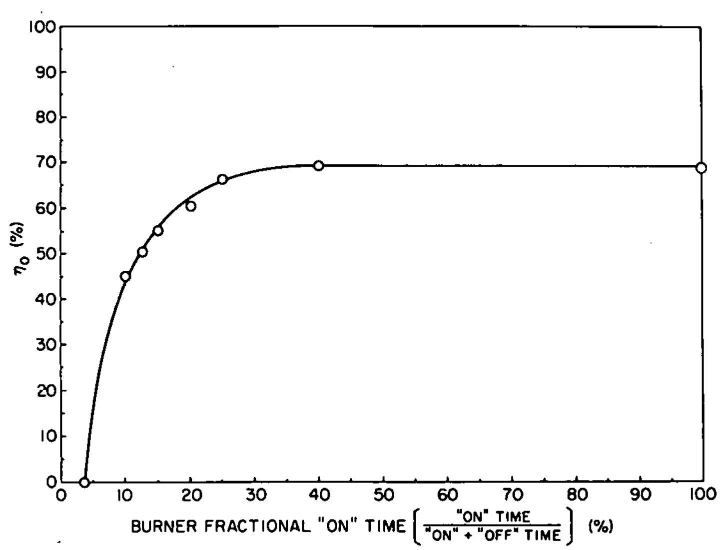

Figure 2. Dry-base single-pass steel boiler overall efficiency (η_o) vs. burner fractional "on" time (%).

Although flue gas efficiency tests are less accurate than the direct heat flow measurement technique, these tests are useful in monitoring air/fuel mixture ratios 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.

At present the BNL space heating equipment test project is operating two hydronic test stands with electronic data acquisition/control units on a full-time duty cycle, 24 hours per day, 6 days per week, utilizing a third stand as turnaround and backup to the primary units. One of the hydronic test stands has been retrofitted with equipment to enable a dual fuel testing capability. The unit will be optionally available for use as an oil-fired hydronic or a natural gas-fired hydronic test stand. In addition, the facility includes a warm air test stand with its own data acquisition/control system. A testing schedule has been established through the beginning of Fiscal Year 1981 to maximize utility of the current facilities.

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 office in Washington, D. C.[2] In addition, several public information sheets have been written along with a booklet for general release entitled, "Upgrading Oil Home-Heating Systems", which is available through BNL.

To date, most of the work has been associated with oil-fired hydronic heating systems. At this time, a large effort is underway to provide test data for oil-fired warm air furnaces and gas-fired heating equipment, while continuing characterization testing.

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

II. CHARACTERIZATION TEST PROGRAM

Up to about January 1979 the BNL efficiency test program treated residential heating equipment essentially as black boxes, that is, as equipment which had only inputs (fuel) and outputs (useful heat and losses). The test program has been expanded to incorporate a more detailed view of the equipment tested in an attempt to identify those readily observable characteristics which are indicators of performance potential.

The physical characteristics of home-heating equipment which affects thermal performance can be expanded upon at great length. Unfortunately, as one continues to describe the individual test articles in greater and greater detail the number of characteristic categories can approach the number of test items. For example, some of the features that could affect performance in a single generic group of equipment, let us say oil-fired hydronic equipment,

Table 1
Cumulative Test Summary

Types of Equipment Tested	Total Number of Units Tested to the End of FY79
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.

are:

1. Burner type.
2. Fuel flow rate/excess air requirements.
3. Combustion chamber size or shape.
4. Combustion chamber refractory and insulator.
5. Wet-base or dry-base design.
6. Heat exchanger area exposed to radiation.
7. Heat exchanger area exposed to hot gas.
8. Flue gas velocity through heat exchanger.
9. Jacket insulation over combustion chamber and wetted surfaces.
10. Boiler construction material.
11. Heat exchanger area exposed to water.
12. Water velocity through heat exchanger.
13. Design stack temperature.

It is quite apparent that equipment differences examined at this level of detail would be interesting from a design optimization point of view but not useful in developing an overall feel for performance effects of certain characteristic design features. This issue combined with the time constraints of the program required some paring of the above list and the development of a logical format of presentation for performance parameters which are influenced by these design features. The characteristic design features that were selected were limited to those obtainable by visual observation of the equipment or from manufacturers' literature, or to those that can be inferred from test measurements of inputs, outputs, and losses. These characteristic features are described as follows:

A. Boiler Type

1. Dry Base. The boiler combustion chamber is lined with a high temperature refractory material in the form of a pot which is open at the top and exposed to the heat exchanger tubes and the lower tube sheet. This pot is surrounded by structural metal forming the base of the boiler and is generally covered with jacket insulation.

2. Wet-Base. The boiler combustion chamber is exposed to some water-cooled surfaces at the rear sides or bottom of the combustion chamber. Part or all of the combustion chamber may be covered with high temperature refractory. The outer perimeter of the base is generally enclosed in an insulated jacket as well.

B. Boiler Construction Material

The boiler is fabricated of either sheet or plate steel, or is made of cast-iron sections. The type of construction generally prescribes shaping of the heat exchanger surface with cast iron lending itself to torturous arrangements of flue gas passages and surfaces while the use of steel generally limits the gas flows to that through straight tubes and across relatively smooth surfaces.

C. Type of Heat Exchanger

1. Steel Boilers. The heat exchanger construction of these boilers is largely limited to the use of fire tubes (to carry hot combustion gases through the heat exchanger water) mounted in tube sheets and enclosed in sheet steel to form a box or can-like heat exchanger.

These fire tubes are oriented in either the vertical or horizontal direction (see Figs. 3 and 4). In a horizontal fire tube type the hot combustion gases may travel through the heat exchanger more than once in opposite directions. Each flow direction is called a pass and heat exchangers can have multi-pass configurations. In residential units the number of passes is generally limited to two with a single-pass being the most common.

As noted previously, the wet-base design in boilers provides additional heat exchange surface around the combustion chamber, but this exchange surface is considered separately as a characteristic feature and not as an additional pass in the heat exchanger.

2. Cast-Iron Boilers. The heat exchanger construction of these boilers generally consists of interlocking castings that form water passages around which hot combustion gases are permitted to flow. The casting designs include end sections which permit the assembly of boilers of various sizes through the stacking of multiple sections. For example, a typical residential boiler might be defined as a three-section cast-iron unit. In this case,

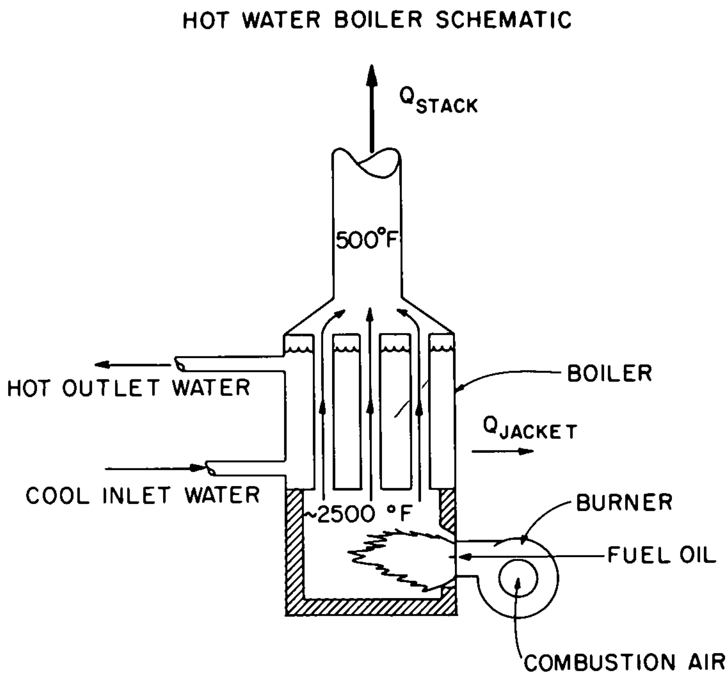

Figure 3. Dry-Base Vertical Fire Tube Steel Boiler with Conventional Burner

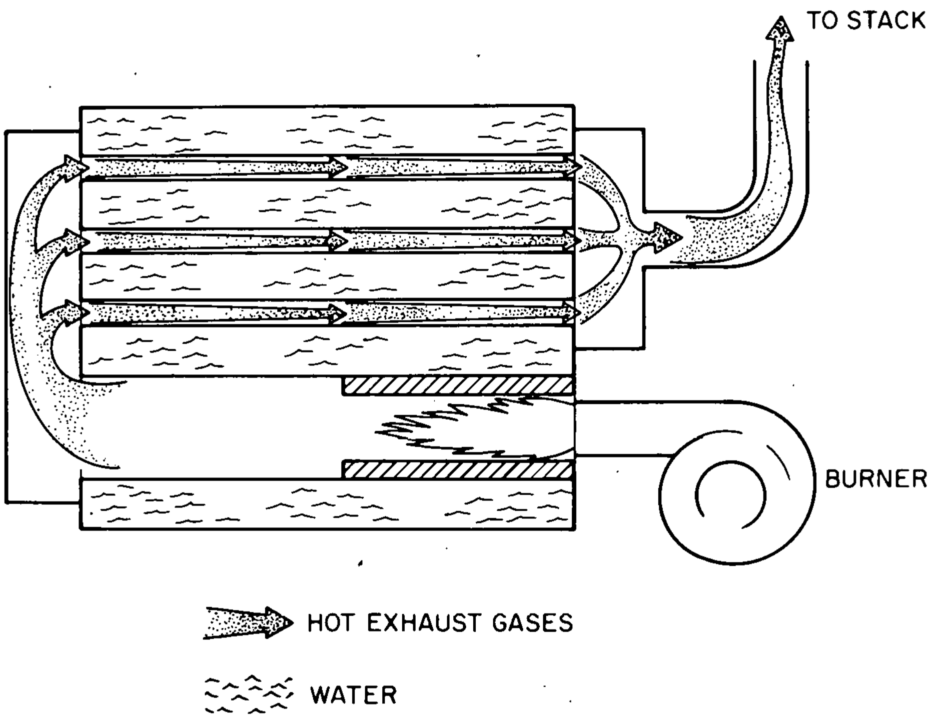

Figure 4. Wet-Base Horizontal Fire Tube Steel Boiler with Burner

the unit would consist of a front section, a single center section, and a rear section. A four-section unit would be assembled using two center sections and the same front and end sections.

In these boilers the dry-base design would feature castings that contained water flow passages above the combustion chamber. In wet-base design the wetted passage might extend down the sides of the combustion chamber and in some cases across the bottom.

D. Burner Type

1. Low-Speed Non-Retention-Head Burner (LSNRH). This burner is the type most commonly found in existing residential installations. It utilizes a low-speed (1725 rpm) motor-driven fan which supplies combustion air through the burner blast tube. Some air flow turbulence is achieved by vanes in the blast tube to promote mixing of the combustion air with the spray pattern of atomized fuel droplets. This type of burner generally requires a considerable amount of excess air to operate without sooting and consequently contributes to operating stack losses. In the off-cycle the burner does little to restrict convective heat loss through the boiler because of its relatively open air shutter setting and open blast tube and contributes to off cycle losses.

2. Retention-Head Burners (HSRH, LSRH). The use of this type of burner can increase a boiler's overall efficiency (η_o). The burner may use either a high-speed (3450 rpm) or a low-speed (1725 rpm) motor-driven fan. In addition to vanes in the blast tube, an end turbulator is used to disturb and rotate combustion air as it leaves the burner tip and enters the fuel spray pattern.

The increase in overall efficiency (η_o) 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 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 operating 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 two-thirds of the total, result while the burner is operating. The remaining savings is attributed to decreased off-cycle heat losses.

3. Blue-Flame Burners. This class of burner generally utilizes hot combustion gas recirculation to promote prevaporization of fuel droplets before reaching the combustion zone. These burners are discussed in detail in Section III Hydronic Boiler Results, Part C.

E. Performance Parameters

1. Operating Stack Losses. The amount of heat that leaves the boiler during combustion and is then lost through the flue is an indicator of heat

exchanger effectiveness. This effectiveness is in turn a function of how well the heat exchange surface of the boiler is matched to the available radiant and convective heat flow and flue gas velocities produced by a particular burner/combustion chamber combination. Thus a particular boiler may exhibit quite different performance characteristics with different burners. These differences in performance are indicative of the sensitivity exhibited by a given boiler heat exchanger configurations to burners of different design and performance capabilities.

2. Operating Jacket Losses. Heat that leaves the boiler through the jacket during operation and in the off cycle is considered as lost heat in the BNL test procedure. The degree of recovery of these losses as contributions to the space heating needs of the residential building is highly variable and a function of the location of the boiler in the building and the thermal integrity of the local building envelope. It is a subject of continuing investigation by others. A measure of the percentage of heat lost and therefore the effectiveness of jacket insulation can be inferred from the boiler performance as the difference in measured steady-state efficiency (η_{SS}) using the stack gas analysis method and the direct heat flow method in steady-state. These losses are referred to as operating jacket losses.

3. Off-Cycle Losses. During the off cycle, the boiler also loses heat to the surroundings through the jacket (a function of jacket insulation) and to air which is drawn through the boiler and up the stack (a function of burner and heat exchanger design). These losses are combined as a single performance parameter called off-cycle losses.

A study by BNL of the effects of these losses using procedures other than the direct heat flow measurement technique is discussed in Appendix C of this report.

III. HYDRONIC BOILER RESULTS

The characterization during the latter part of Fiscal Year 1979 consisted of eight (8) packaged boiler tests. A packaged boiler is one that is commercially available from the manufacturer complete with burner. The burner is presumably matched to the boiler by the boiler manufacturer and the entire package is specified by the catalog number.

The packaged boilers tested were as follows:

Boiler Type	Quantity
Wet-Base Steel	1
Wet-Base Cast Iron	3
Dry-Base Steel	2
Dry-Base Cast Iron	2

The results of these tests are summarized in Table 2. All performance parameters shown herein are percentages of the calculated annual fuel use for a residential design heat load of 50,000 BTU per hour in New York City, with an inside design temperature of 68^o and 0^{o}F outside, 40 gallons per day of domestic hot water, and an overfiring ratio of 2 (100% oversized). The performance parameters delineated throughout this report are operating losses, off cycle losses, and seasonal efficiency (useful heat).

A. Characterization Results

1. Operating Stack Losses. Of the boilers tested, the steel units appeared to have an advantage over the cast-iron units in terms of operating stack losses. Despite the relative complexity of both the wet-base and dry-base cast-iron unit heat exchangers, the average operating stack loss in these units was about 19% whereas the dry-base vertical tube steel heat exchanger units average 16%. The single wet-base steel unit with horizontal fire tubes had a 14.5% operating stack loss. To be sure, operating stack losses are also a function of the specific burner operating characteristics and these effects will be reviewed in the boiler analysis section.

2. Operating Jacket Losses. In most of the boilers tested, these losses could be reduced through increased jacket insulation. All of the boilers tested were insulated with a nominal 1-inch-thick fiberglass blanket wrapped around the boiler structure. All but one had a relatively tight-fitting metal cabinet covering the insulation. The one exception had a cabinet which enclosed the burner as well as the boiler structure itself. All the boilers tested had no jacket insulation on their bottom faces.

Table 2 shows these operating jacket losses to range between 1 and 7.5%, representing 11 to 91 gallons of fuel wasted. These losses could be reduced by half with improved jacket insulation, and additional savings may be achieved through reduced off-cycle losses.

The dry-base steel boilers had the highest operating jacket losses, while the dry-base cast-iron boilers were just over the average. This may be related to the different mechanisms of heat conduction from the combustion chamber during operation and should be investigated further.

3. Off-Cycle Losses. The off-cycle heat losses of both the steel and cast-iron dry-base boilers tested were higher than those of the wet-base boilers. Burner effects aside, this may be again due to different mechanisms of heat conduction and consequential loss in the off-cycle.

Fundamentally, these are losses incurred when the burner has been shut down because there is no heating demand from the building; and the remaining heat is stored in the boiler. A reduction in mass of the boiler structural and water capacity would reduce the total amount of heat that could be lost in any off-cycle period. This design feature coupled with an operation strategy allowing a final purge of the boiler which sweeps the stored heat out of the boiler and into the insulated envelope or heated space of the building before it can be lost through the boiler jacket or by convection up the stack would dramatically improve the boiler's seasonal performance.[1] If such a boiler had low enough mass and the proper associated controls, it could fulfill on demand both the roles of space heating and instantaneous hot water heating with water storage. Off-cycle losses could be effectively reduced if not eliminated entirely.

Table 2 Boiler Characterization Summary							
Boiler Type	Boiler Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
			Stack	Jacket			
Wet-Base Steel	A	HSRH A	14.5	3.2	8.2	74.1	1105
Wet-Base Cast Iron	B	HSRH C	18.0	1.0	5.7	75.3	1087
	C	HSRH C	18.5	5.5	7.5	68.5	1195
	D	HSRH B	20.5	4.1	12.5	62.9	1301
Dry-Base Steel	E	HSRH C	16.2	7.5	8.7	67.6	1211
	F	HSRH A	15.7	7.0	13.9	63.4	1292
Dry-Base Cast Iron	G	LSNRH L	19.3	3.9	8.9	67.9	1205
	H	HSRH A	18.5	5.9	11.1	64.5	1269

Even without new boiler designs, the immediate impact of a modification of current practice and operation can be demonstrated by examining the performance parameters in Table 2. The seasonal efficiency of the units tested ranges from 62.9 to 75.3%. Assuming that with additional insulation around the boilers one could increase the useful heat delivered by an amount equal to half the original jacket loss and, further, that with suitable controls the boilers tested could be made to purge their stored heat to the house or to domestic hot water storage (either heating or preheating) the seasonal efficiency of the boilers tested could be increased to a range of 78.6 to 83.9%. This improvement could be translated into an annual fuel savings of 83 to 277 gallons with an initial investment of $500.00. At a fuel cost of $1.00 per gallon, this represents a worst case payback of less than 6 years; in most cases it would be less than 3 years.

The evaluation of innovative concepts of heating system design and operation will continue at BNL during Fiscal Year 1980.

B. Comparative Test Results

1. Wet-Base Steel Package Boiler. This boiler (Boiler A) used a single-pass horizontal fire tube heat exchanger. The unit was fired with a high-speed retention-head burner and achieved a steady-state efficiency of 82.3% and a seasonal efficiency of 74.1%. In comparison, the Baseline unit, a dry-base single-pass vertical fire tube boiler fired with a conventional low-speed burner, had a seasonal efficiency of 56.2%. The test boiler using the same type of conventional burner yielded a seasonal efficiency of 67.3%. The performance parameters of these tests are compared in Table 3.

Table 3 Wet-Base STeel Package Boiler						
Test Article & Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
		Stack	Jacket			
Boiler A	HSRH A	14.5	3.2	8.2	74.1	1105
Boiler A	LSNRH J	17.9	4.1	10.7	67.3	1217
Baseline Boiler Z	LSNRH J	25.7	5.1	13.0	56.2	1455

The potential savings of Boiler A when compared to the Baseline is about 24%. The test unit was fired with a conventional burner (LSNRH). Comparison of the unit's performance when tested in this manner with the Baseline unit test results is used to evaluate how the total savings is proportioned between boiler and burner contributions. The savings attributable to the boiler is probably about 16.0% while the balance of 8% can be credited to the burner. Substantial reductions in operating and off-cycle losses are revealed by the comparison.

2. Wet-Base Cast-Iron Boilers. Three wet-base cast-iron boilers were tested as shown in Table 4. Each of the boilers had heat exchangers which were complex in that the vertical-pass surfaces were covered with fingers which extended the heat exchanger surface. Test Boiler B had a four-section heat exchanger about 8 inches high, whereas Boilers C and D each had three-section heat exchangers about 11 and 14 inches high respectively.

Boiler B is the best of three tested with the lowest jacket losses of any boiler tested to date. Fired with a high-speed retention-head burner, the unit achieved a steady-state efficiency of 81.0%. Under part-load operation, the unit yielded a seasonal efficiency of 75.3%. Compared with the Baseline, this unit has a savings potential of about 25% of which about 12% could be attributed to the boiler and 13% to the burner.

Boiler C, also fired with a high-speed retention-head burner, is able to operate in steady-state at 76.0% efficiency. It should be noted that even though the unit's stack losses were about the same as Boiler B, a marked increase in jacket losses plus a smaller increase in off-cycle losses resulted in a lower seasonal efficiency of 68.5%. Nevertheless, the unit displayed a potential savings of 18% when compared with the Baseline. These savings for boiler and burner were about 14% and 4% respectively.

Table 4 Wet-Base Cast-Iron Boiler Characterization						
Test Article & Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
		Stack	Jacket			
Boiler B	HSRH C	18.0	1.0	5.7	75.3	1087
	LSNRH J	22.5	1.2	12.7	63.6	1286
Boiler C	HSRH C	18.5	5.5	7.5	68.5	1195
	LSNRH J	20.0	4.2	10.4	65.4	1251
Boiler D	HSRH B	20.5	4.1	12.5	62.9	1301
	LSNRH N/A	-	-	-	-	-
Baseline/ Boiler Z	LSNRH J	25.7	5.1	13.0	56.2	1455

Boiler D, fired with a high-speed retention-head burner, achieved a steady-state efficiency of 75.4%. The total percent operating loss of this unit was not very different from Boiler C, but the significant increase in off-cycle losses resulted in a seasonal efficiency of 62.9%. Comparative tests of Boiler C fired with a conventional (LSNRH) burner were not made. Inspection of the results achieved revealed a savings of 11% of the Baseline unit.

3. <u>Dry-Base Steel Boilers</u>. Two dry-base single-pass vertical fire tube boilers were tested as shown in Table 5. Both boilers had tall heat exchangers, 24 and 23 inches respectively for Boilers E and F. Boiler E had 9 fire tubes while Boiler F had 8. In both boilers the fire tubes were nominally 3 inches in diameter.

Boiler E, fired with a high-speed retention-head burner, achieved a steady-state efficiency of 76.3%. The unit had relatively low operating stack losses considering the simplicity of the heat exchanger design. However, this was offset by high jacket losses. The unit was evaluated to have a seasonal efficiency of 67.6%. Comparison with the Baseline system indicated that the unit could produce a savings of about 17%. About 13% was probably due to the boiler while 4% can be credited to the burner.

Boiler F, also fired with a high-speed retention-head burner, had a steady-state efficiency of 77.3%. The unit had essentially the same operating losses as Boiler E, but substantially higher off-cycle losses reduced its seasonal efficiency to 63.4%. Boiler F was not tested with a conventional (LSNRH) burner. When Boiler F was compared to the baseline system a savings of about 11% was revealed. Comparative tests of this package boiler will be resumed in Fiscal Year 1980.

Table 5 Dry-Base Steel Boiler Characterization						
Test Article & Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
		Stack	Jacket			
Boiler E	HSRH C	16.2	7.5	8.7	67.6	1211
	LSNRH J	18.0	8.0	9.7	64.3	1272
Boiler F	HSRH A	15.7	7.0	13.9	63.4	1292
	LSNRH N/A	-	-	-	-	-
Baseline/ Boiler Z	LSNRH J	25.7	5.1	13.0	56.2	1455
	HSRH A	18.9	5.8	10.6	64.7	1265

4. Dry-Base Cast-Iron Boilers. Two dry-base cast-iron boilers were tested as shown in Table 6. Each boiler had a three-section heat exchanger with complex vertical pass surfaces similar in appearance to those of the wet-base cast-iron test boilers. The heat exchanger height for both units was about 15 inches.

Boiler G, tested as delivered with a low-speed non-retention-head burner, yielded a steady-state efficiency of 76.8%. The performance of the unit as tested was not very much different from its wet-base counterparts and, in fact, exceeded the seasonal efficiency of a wet-base unit of the same manufacture, Boiler D. Boiler G exhibited a seasonal efficiency of 67.9% which, when compared with the Baseline, could save about 17%, all due to the boiler. Boiler G was tested with a high-speed retention-head burner and produced a steady-state efficiency of 78.2% with a seasonal performance of 70.0%.

Boiler H with a high-speed retention-head burner produced a steady-state efficiency of 75.6%. It is interesting to note that although Boiler H had what is presumed to be a better burner its operating and off-cycle losses were greater than those exhibited by Boiler G. This resulted in Boiler H having seasonal efficiency of 64.5%. In terms of savings potential over the Baseline, the unit could reduce fuel consumption by about 13%, of which about 4% was due to the boiler and about 9% to the burner.

5. Baseline Savings Comparison. Although an insufficient number of units have been tested in the characterization test program to permit categorization of the performance of different boiler types, some interesting information has been yielded regarding the partition of energy between the various boiler losses and the useful heat delivered (summarized in Tables 3, 4, 5, and 6) and the savings potential of different package boilers. This latter information is summarized in Table 7.

It would appear that the average operating loss for the boilers tested was about 22.4% with an average of 17.6% due to stack losses and about 4.8% due to jacket losses. The off-cycle losses for the group tested averaged about 9.6%.

Table 6 Dry-Base Cast-Iron Boiler Characterization						
Test Article & Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
		Stack	Jacket			
Boiler G	HSRH D	17	4.8	8.2	70.0	1169
	LSNRH L	19.3	3.9	8.9	67.9	1205
Boiler H	HSRH A	18.5	5.9	11.1	64.5	1269
	LSNRH J	23.3	6.1	12.2	58.4	1402
Baseline/ Boiler Z	LSNRH J	25.7	5.1	13.0	56.2	1455

All units fared well when compared to the Baseline unit which had operating stack, operating jacket, and off-cycle losses of 25.7, 5.1 and 13.0% respectively. The potential fuel savings over the Baseline unit ranged from 11 to 25%. Table 7 summarizes the individual percent savings over the Baseline unit as well as the division of that savings that can be credited to boiler performance and burner performance.

Table 7 Boiler Savings Comparison Relative to Baseline Unit					
Test Article & Code	Boiler Type	Burner Type & Code	Percent Savings		Percent Total
			Boiler	Burner	
A	WBST	HSRH A	16	8	24
B	WBCI	HSRH C	12	13	25
C	WBCI	HSRH C	14	4	18
D	WBCI	HSRH B	-	-	11
E	DBST	HSRH C	13	4	17
F	DBST	HSRH A	-	-	11
G	DBCI	LSNRH L	17	-	17
H	DBCI	LSRH	4	9	13

C. Additional Results

During Fiscal Year 1979, the major emphasis was shifted from the earlier voluntary program to the characterization phase of the project. Because several commitments made under the voluntary program were still incomplete, this transition was made over a period of several months. This section will deal with these and other results which do not correspond to the formal characterization program plan.

1. Oil-Fired Pulse Combustion Boiler (Test Article R). An early concept identified by this project was the use of a pulsating combustion system as the prime heat source for a residential boiler. This combustion technique can be traced back to the "buzz-bomb" rocket used by Germany in World War II. Until recently the concept had been utilized only in gas-fired boilers and was not applicable to oil because of the state of the art of oil atomization and vaporization. The pulse combustion device requires a very precise mix of fuel and air for extremely rapid combustion (small explosions similar to those in an internal combustion engine). The basic operating principle of a pulse-fired combustion device is illustrated in Fig. 5. A prototype system incorporating oil-fired pulse combustion was brought to our attention and arrangements were made to test the unit. The device has been developed by a private company located in Geneva, Switzerland.

The boiler submitted for testing incorporated several unique features. The system was designed to start up by use of a controlled spark ignition system which is needed only during the initial ignition period. After the first few cycles the pulsations of the exhaust gases draw in new fuel/air mixtures and re-ignite them continuously without requiring an external spark and power source. The entire combustion and exhaust system is immersed in the boiler water chamber allowing for almost direct heat transfer. The rate of pulsation is approximately 50 cycles/second creating exhaust gas velocities of approximately 70ft/second as determined by the manufacturer. The rapid series of pulsations creates very high levels of turbulence which can greatly enhance the heat transfer rate between the hot exhaust gases and the boiler water. The system submitted for testing was designed such that the exhaust was actually partially condensed in an economizer that is also in direct contact with the boiler water.

With the direct heat flow technique utilized at BNL, the steady-state efficiency of the prototype boiler was measured to be 88.1%. In comparison the best burner/boiler combination of conventional combustion equipment design had a steady-state efficiency of 84.4% based on the same test methods. The flue gas analysis gave an average steady-state efficiency of 91-1/3%, with a 13.8% carbon dioxide concentration and a net stack temperature of 108°F.

Some difficulty was experienced with setting up the unit for testing because of electrical supply in compatibility. This problem must be resolved if future testing of the unit is to occur. After several alterations to the controls and peripheral equipment, the unit was started, adjusted, and operated under steady-state conditions. Difficulties were encountered in restarting the unit after shutdown.

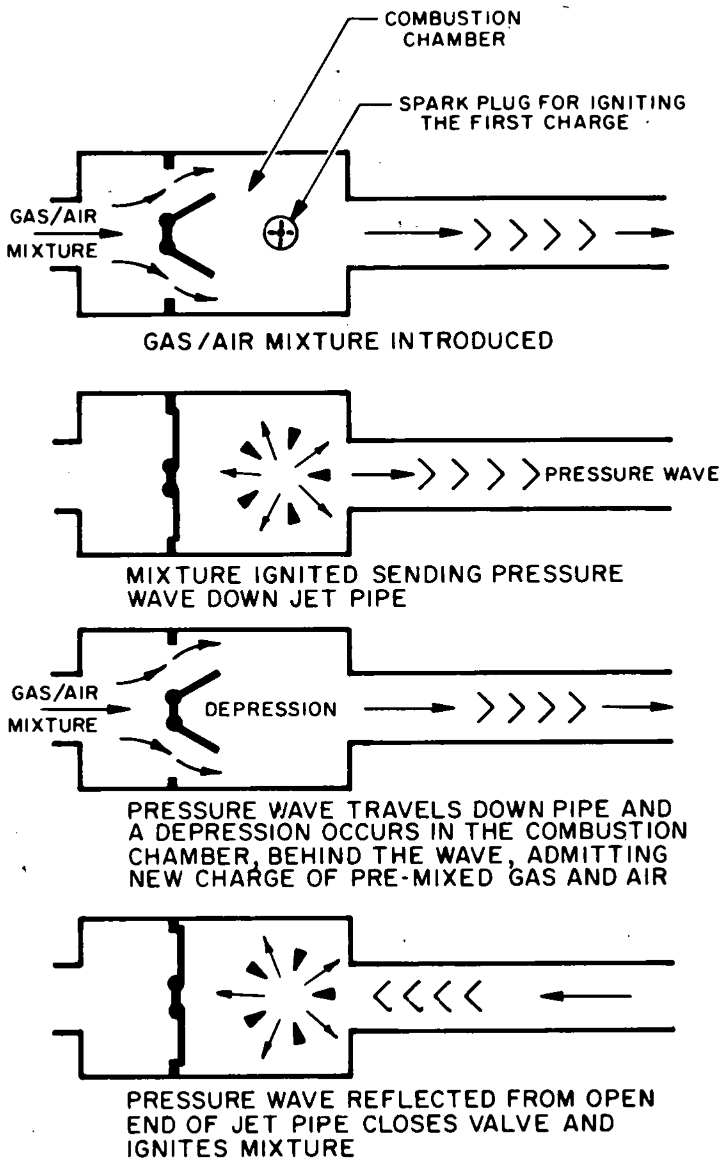

Figure 5. Principle of operation for a pulse combustion device.

Cycle efficiency tests were not completed because of several ignition failures related to internal condensation problems caused by the low temperature of the return-water. After three attempts at cycling, it was determined that as currently designed the unit could not function on the BNL test stand under the cycling procedure that is imposed on the test article.

The problems encountered with this unit are typical of those encountered with many early prototypes. It is important to note that the basis combustion equipment operated as required, clearly demonstrating that oil-fired pulse combustion can be achieved. The advantage of pulse combustion in terms of steady-state efficiency has been demonstrated and there is solid evidence for concluding that off-cycle losses will be small. In conventional equipment the major losses during the off-cycle can be attributed to the convective loss through the boiler and up the chimney. The pulse-fired boiler is a sealed system when not being fired, with no air flow through the unit. The only remaining off-cycle losses would be due to jacket losses.

The manufacturer of the pulse-fired boiler hopes to have an improved design available for testing within a few months which will be compatible with the testing requirement imposed by BNL and the local electric supply voltage and frequency.

2. Blue-Flame Combustion Systems. A significant consideration with oil combustion systems is the amount of excess air required to assure complete combustion without soot generation. From the standpoint of efficiency, the most desirable system would require no excess air at all. Excess air contributes nothing to the energy released during the burner process and acts as a sink for energy that passes up the stack, along with exhaust gases generated by the combustion process. If combustion is to occur under stoichiometric conditions, there must be a precise mixing of fuel and air such that the mixture ratio distribution is nearly constant across the flow in the reaction zone. If this can exist, it will produce the highest possible temperature difference maximizing heat transfer when compared to fuel-lean combustion. Unfortunately, there are several problems associated with near stoichiometric combustion of oil. First, the fuel/air mixture required cannot be generated by means of conventional pressure atomization techniques alone. The droplets are still too large to allow for the degree of uniform mixing required. The second problem is associated with what occurs when the mixture is just slightly fuel rich; generation of soot and carbon monoxide increases drastically (several orders of magnitude of concentration). The lack of complete mixing can cause these changes to occur even if the mixture is not fuel rich, as observed with conventional yellow-flame burners. Under these circumstances, soot generation increases rapidly before carbon monoxide becomes a factor. This soot fouls heat exchanger surfaces and greatly reduces system efficiency.

The blue-flame technology developed in recent years has solved most of these problems. The blue-flame combustion systems tested at BNL have included one burner/boiler unit developed under federal DOE funding, a burner/boiler unit developed in Italy, and a retrofitable burner unit developed in West

Germany which can be used in new burner/boiler units or retrofitted into existing boilers when appropriate. All three units are designed to operate near stoichiometric combustion with small amounts of excess air ranging from 10 to 20%. In different ways all three systems incorporate combustion/exhaust gas recirculation to the flame zone. This results in a momentum exchange between the primary fuel/air flow and the recirculating flow. The flow velocity is retarded so that the flame front can establish itself downward of the mixing tube region. Because of almost complete evaporation of the fuel ahead of the flame front, the mixing of fuel and air is very complete and a blue flame results.

The blue-flame burner/boiler (Test Article J) developed under DOE funding is now in the commercial market, and field evaluations are being conducted on a number of units by the manufacturer under contract agreements with BNL/DOE. The burner in this system is designed in conjunction with the boiler's combustion chamber and cannot be adapted as a retrofit burner at this stage. The burner is designed to maximize the mixing of externally recirculated combustion products with incoming combustion air prior to combustion. This is achieved by injecting the combustion air through a series of ¼-inch-diameter holes surrounding the oil nozzle on a circle diameter of 2 inches. The air jets issuing from these holes entrain combustion products from a re-entrant slot in the burner blast tube and create a recirculation eddy external to the flame within the combustion chamber. The baffle serves to ensure that the re-entrained combustion products do not short circuit the heat exchanger surfaces and re-enter the combustion process at excessively high temperatures (see Fig. 6). The ignition electrodes and burner nozzle extend beyond the re-entrant slot in the burner blast tube and are exposed to a mixture of combustion products and air. To avoid overheating of the oil supply line, the nozzle and nozzle adapter are sheathed such that air circulates continuously in the annulus between the sheath and the oil nozzle; the overall design of the burner head provides a measure of protection for both the electrodes and the sheath in the air curtain created by the array of jets. The system was designed in conjunction with a wet-base horizontal fire tube steel boiler matched to the 0.75 gph firing rate. The system's annual seasonal efficiency of 74.2% (at the design conditions mentioned earlier in this report) is among the highest measured in the test facility to date. This is comparable to those of several yellow-flame retention head burner/boiler units with similar seasonal efficiencies. The major advantage of the blue-flame technology systems is expected to be that the units will continue to operate at this level of efficiency while yellow-flame units will require periodic cleaning to remove soot accumulations. This will be investigated by evaluation of field installations because the test laboratory is not designed for long-termed operation tests. It should also be noted that there have been several problems in adjusting this equipment to assure minimal carbon monoxide generation. The manufacturer has since changed its installation manuals to recommend that excess air levels not be reduced below 15% and that a check of carbon monoxide concentration be performed to assure that no measurable level of carbon monoxide exists in the stack.

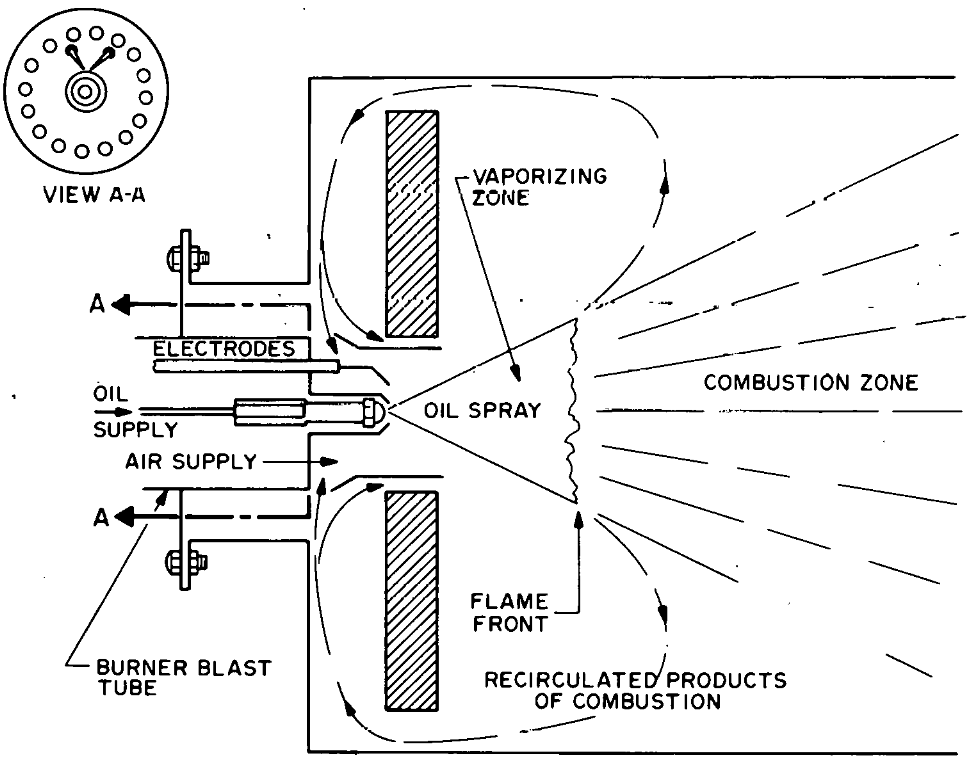

Figure 6. Combustion system used in blue-flame burner/boiler. Developed under DOE funding.

The second blue-flame system tested in the laboratory (Test Article K) was developed in Italy through private and government funding. This system was designed as a burner/boiler unit with an external recirculation loop cast into the boiler. The burner can be used only in conjunction with its matched boiler. The boiler used in this system was a unique design made of cast iron. Because of the very low soot levels produced with the blue-flame burner, the design of the boiler could be very complex without concern for fouling due to soot buildup. The unit utilizes relatively narrow heat transfer channels which are spirally wound around the combustion chamber, thus rendering a very compact design per unit of heat exchanger surface area. The back of the boiler, which closes off the combustion chamber, provides access to six distribution channels having the shape of annular segments, which are concentric with the longitudinal axis of the combustion chamber. Each annular intermediate element is a hollow cast-iron body. The circumferential space of this hollow element communicates with the two openings which are diametrically opposite each other and pass through each element parallel to the axis of the boiler. One opening is connected to the cold water return circuit, while the other is connected to the hot water distribution circuit. This system utilizes a flue gas recirculation such that the oxygen content of the gas mixture fed into the burner is typically around 16% according to the manufacturer. The dilution of the oxygen is claimed to reduce the flame temperatures according to the quantity of flue gas recycled. In turn, the lower temperatures correspond to lower levels of pollutants, namely nitrogen oxides, while low carbon monoxide and unburnt hydro-carbons are minimized by proper aerodynamic design of the system.

As yet the test facility lacks emissions monitoring equipment for stack analysis so only carbon-monoxide and carbon-dioxide measurements were made. The unit brought to this country was fitted with a prototype recirculation control device which gave us some problems in evaluating the unit. On several tests the device slipped out of adjustment which resulted in high carbon-monoxide levels and ignition problems. Eventually a full series of efficiency tests were completed. The seasonal efficiency for the unit was found to be 78.5% under the conditions mentioned earlier in this report. The steady-state efficiency was 83.7% at an average outlet temperature of 180^{o}F. The unit tested did not incorporate the domestic hot water coil typical of units of American manufacture; the seasonal efficiency calculated under the design condition of 40 gallons of domestic hot water used per day is assumed to be satisfied with an aqua booster storage tank. The losses incurred in using such a device are not represented in the seasonal efficiency noted above.

The last blue-flame system evaluated in the test facility was a retrofitable blue-flame burner (Test Article M) constructed such that recirculation occurred internally within the flame tube. The design includes a mixing tube inside the flame tube oriented on the same axis. The mixing tube is fabricated from nonscaling steel with the recirculation flow entering the mixing tube by windows at its head. The energy needed for evaporation is supplied by the hot gas recirculation flow and to a minor degree by heat radiation from the hot mixing tube walls. In that the recirculation occurs internally in the blast tube, this system does not rely on a matched boiler for its use. The unit was tested in a wet-leg horizontal fire tube boiler (Test Article A) and the seasonal efficiency at the stated conditions was found to be 68.1% with a steady-state efficiency of 87.3%. It was felt that the relatively high off-cycle losses were due to unrestricted air flow through the burner in the off-period, thus accounting for the lower seasonal efficiency noted. The unit will be retested in another boiler to see if this is true or if some other factor is responsible.

The test results for these units are presented in tabular form in Appendix A, Tables 17, 18, and 19. A summary of the blue-flame burner system is given in Table 8. It is important to restate that the main advantages of blue-flame technology systems are the lower levels of excess air required for combustion and the nearly soot-free operation which can be attained. This is reflected in very good steady-state and seasonal efficiencies developed by laboratory measurements. The long-term benefits of nearly soot-free operation must still be demonstrated through long-term field tests. Only by evaluation of life-cycle costs based on field demonstrations can a true comparison be made between the blue-flame systems and high-efficiency boilers incorporating yellow-flame retention head burners which also were designed to operate with relatively low levels of excess air (20 to 45%).

Table 8

Summary of Efficiency Results for Blue-Flame Combustion Systems

Test Articles	Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gals.)
			Stack	Jacket			
Blue-Flame Burner/Boiler Developed Under DOE/BNL Contract	J	Recirculating Gas, Integral with Boiler	14.0	3.6	8.2	74.2	1104
Blue-Flame Burner/Boiler Developed in Italy	K	Recirculating Gas, Integral with Boiler	11.8	4.5	5.2	78.5	1042
West German Blue-Flame Burner in WBST Boiler	A	Replacement-type burner. (M)	9.5	3.2	19.2	68.1	1201

3. <u>Special Wet-Base Cast-Iron Boiler (Test Article P)</u>. A wet-base cast-iron boiler, submitted under the voluntary test program, was given a full series of efficiency tests. Because of the unusual nature of the heat exchanger

design, it was not included in the characterization program but was described in a findings report. The results of the tests will be reviewed here.

Unlike conventional cast-iron boilers which typically have upright heat exchanger sections with a single-pass of hot gases from the combustion chamber to the stack, the boiler tested had heat exchanger sections which permitted horizontal flow of the combustion gases. In this design, hot gases flow horizontally to the end of the combustion chamber and are directed into four of six annular passages. The hot gases flow back to the front of the boiler and in turn are directed into the two remaining passages flowing to a collector at the rear of the boiler and onto the stack. The combustion chamber and stack gas passages are water cooled.

The seasonal efficiency for the unit tested was found to be 71.2% under conditions mentioned earlier in this report. The steady-state efficiency was 80.9% at an average water outlet temperature of 180°F.

It can be seen in Table 9 that the unit tested would use 1150 gallons of fuel oil annually, compared to 1455 gallons of fuel oil consumed under identical conditions by the "Baseline" boiler, a savings of about 21%. No comparison test was made with this voluntarily submitted unit using a conventional (LSNRH) burner and thus the apportionment of savings benefits between boiler and burner cannot be made.

Table 9

Boiler Test Comparison

Boiler Type	Boiler Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
			Stack	Jacket			
Special Wet-Base Cast Iron	P	HSRH D	14.8	4.3	9.7	71.2	1150
Baseline	Z	LSNRH J	25.7	5.1	13.0	56.2	1455

4. Boiler Stack Economizer (Heat Reclaimers) (Test Articles A, B, and C). 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, three stack economizers have been evaluated in the test facility. The concept used in all designs is identical, and a schematic of the economizer is shown in Fig. 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

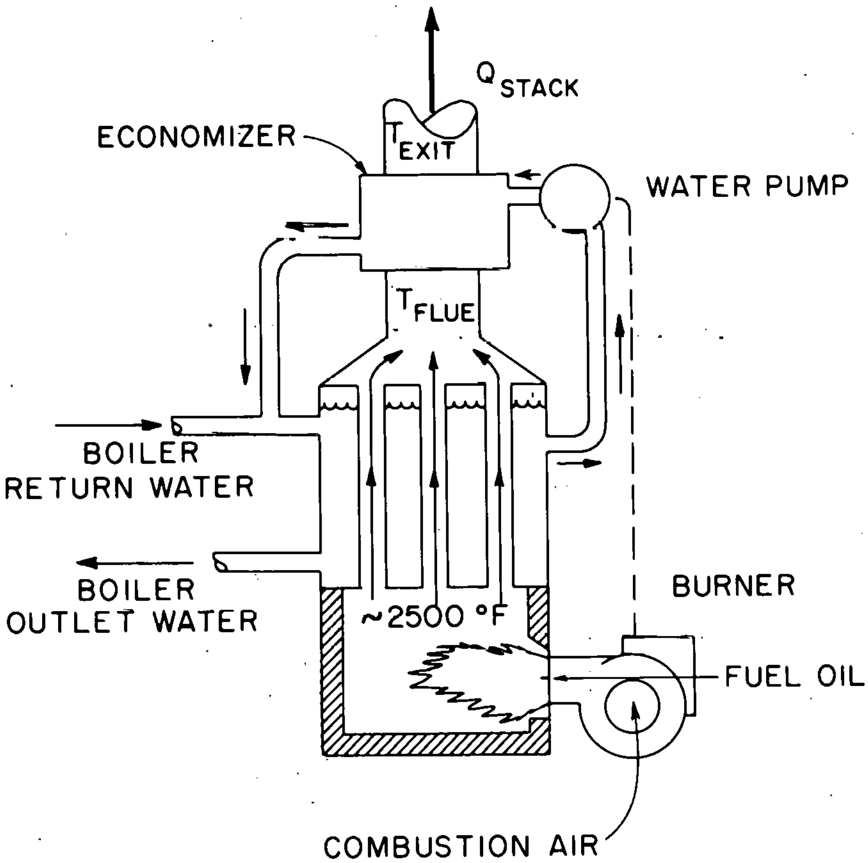

Figure 7. Economizer schematic.

burner operation by decreasing the temperature of exhaust gases vented through the chimney, and energy savings are 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.

In testing these 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 performance determined from laboratory tests appear in Tables 21, 22, and 23 of Appendix A for the models tested. Economizer A was of prototype design and provided good performance indicated by a 330°F drop in stack temperature, from 590° 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 sheet metal housing was acting to increase jacket losses through the economizer. Redesign to minimize such exposed surfaces might improve performance. The third unit was tested on a boiler of similar design to that used in testing the other economizers but of different manufacture. The stack temperature changed from 640°F without the economizer to 290°F with the unit installed. When all tests were concluded the annual fuel use computations showed an 11.7% reduction (from 1409 to 1244 gallons of oil per year) based on the same design requirements mentioned earlier.

One possible problem area observed with these units during the 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 study 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 firebox as the flue passage becomes restricted. Another area to be investigated is the possibility of equipment damage from flue gas condensation after economizer installation, if stack temperatures drop too low and condensation cannot be avoided. The third unit tested was the only one which was designed for such problems. The unit was built with isolation valves and unions which allowed the heat exchanger assembly to be removed from its housing in the flue. The heat exchanger could then be cleaned and reinstalled thus avoiding a major maintenance job.

It should be noted that the magnitude of fuel savings depends upon the burner/boiler combination on which the economizer is installed and the imposed heating load. For example, if a burner/boiler unit operates with a steady-state efficiency that is considerably higher than that of the test system, the amount of fuel that can be saved by stack economizer installation will be reduced. Similarly, if a burner/boiler system has a steady-state efficiency less than that of the test system (as observed for the average field-installed boiler), then annual fuel savings could be greater than indicated above. Measurement of the flue gas temperature can be used as a simple and effective indicator of the advisability of stack economizer installation on specific boilers. A higher stack temperature corresponds to a larger potential for fuel savings by stack economizer installation. The results of these economizer tests are summarized in Table 10.

Table 10

Economizer Test Comparison

Test Article	Boiler Code	Burner Code	Percent Operating Loss		Percent Off-Cycle	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
			Stack	Jacket			
Economizer A	Z	J	12.5	3.9	13.2	70.4	1163
Economizer B	Z	J	15.0	8.2	15.0	61.8	1324
Economizer C	S	A	15.3	5.3	13.6	65.8	1244
Baseline	S	A	24.8	7.2	9.9	58.1	1409
Baseline	Z	J	25.7	5.1	13.0	56.2	1455

5. Vapor Systems/Combination Air Humidification. To date five vapor systems have been accepted for testing and evaluated. These systems were alleged to increase combustion efficiency by introducing water vapor into part of the combustion air.

It was claimed for the first system (Test Article A) that the water vapor in combination with a chemical mixture acted as a catalyst to the combustion process thus improving combustion and heat transfer 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%. 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 consideration in evaluating the system's merits by a homeowner.

The manufacturer of the second unit tested (Test Article B) also claimed to improve 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 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 zone. The results of this test were very similar to those associated with the first unit; a fuel savings of 1.4% was observed, which again is considered negligible.

Advantages similar to those of the first two units were also claimed for the third unit (Test Article C). Its design included a single pipe system connected to the burner fan housing and it was powered by a small electric fan used to bubble air through a water reservoir and to feed this humidified air into the tube connected to the blower housing. Analysis of test results indicated a reduction in annual fuel consumption of 1.3%, again within the uncertainty of the measurement system.

In all five units tested, not one system could be found that had any significant effect on the efficiency of the equipment tested. A summary of the results is given in Table 11. The efficiency tests indicate that the vapor/humidified combustion systems can produce only negligible, if any, reduction in annual fuel use when used in conjunction with residential oil-fired heating equipment. To insure the correct application of the tested equipment and its adjustment, all setup and adjustment work was conducted by manufacturers and their official representatives.

6. Prototype Oil Burner Submitted Under Voluntary Program. A prototype burner designed to reduce electric energy consumption was tested. The fuel utilization efficiency was tested in the laboratory. The burner had a design firing range of 0.65 to 1.25 gallons per hour of fuel. Incorporated in the physical design was a low-horsepower combustion air blower with an independent solenoid oil pump. Steady-state and part-load efficiency tests were performed in the test facility, and annual fuel use was calculated by using the AFUE program. The unit was tested in conjunction with a dry-base single-pass vertical fire tube steel boiler. The steady-state efficiency of the burner in the boiler was measured to be 72.9%. The seasonal efficiency was found to be 63.6% (see Appendix A, Table 25) with a fuel consumption of 1287 gallons per year. A summary of the burner's performance in Table 12 reveals an 11.5% reduction in fuel use below that of the Baseline boiler with a conventional non-retention-head burner.

Table 11

Summary of Vapor/Humidified Combustion System Tests

	Vapor/Humidified Combustion System A	B	C	D	E**
Before System Installation					
Steady-State Efficiency	75.8	75.6	74.1	74.2	68.3
Seasonal Efficiency	67.2	65.3	65.7	65.5	-
Annual Fuel Use	1218	1254	1246	1249	-
CO_2, %	11½	10¼	11½	11½	8
T_{Net}*, °F	480	455	495	509	600
After System Installation					
Steady-State Efficiency	76.0	76.7	75.1	74.8	69.4
Seasonal Efficiency	68.1	66.2	66.6	65.8	-
Annual Fuel Use	1202	1236	1230	1243	-
CO_2, %	12	11	12½	11½	8
T_{Net}, °F	480	410	492	490	590
Reduction in Annual Fuel Use, %	1.3	1.4	1.3	0.5	

*T_{Net} is the net stack temperature used in flue gas analysis.

**System E was tested only in the steady-state mode.

Table 12

Prototype Burner Comparison

Test Article & Code	Boiler Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat)	Annual Fuel Use (Gallons)
		Stack	Jacket			
Burner G	Z	20.8	6.3	9.3	63.6	1287
Baseline Burner J	Z	25.7	5.1	13.0	56.2	1455

IV. WARM AIR FURNACE TEST FACILITY

A. Description of Furnace Test Stand

In the facility built to measure thermal efficiencies of various air furnace under identical conditions, it was necessary to provide means to control air flow rates and inlet air temperatures to accommodate furnaces of different designs (see Fig. 8). The following is a list of the major features of the test apparatus.

(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 under test is not used in this facility.

(2) Flow Control (Bypass) 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 and is maintained at constant temperature 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 (dump valve and block valve) are used to allow air flow to the furnace or to 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.

(6) 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. The quantities of interest are converted to digital values and displayed on readouts and four 4-channel printers. The most important feature of the computer is its 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

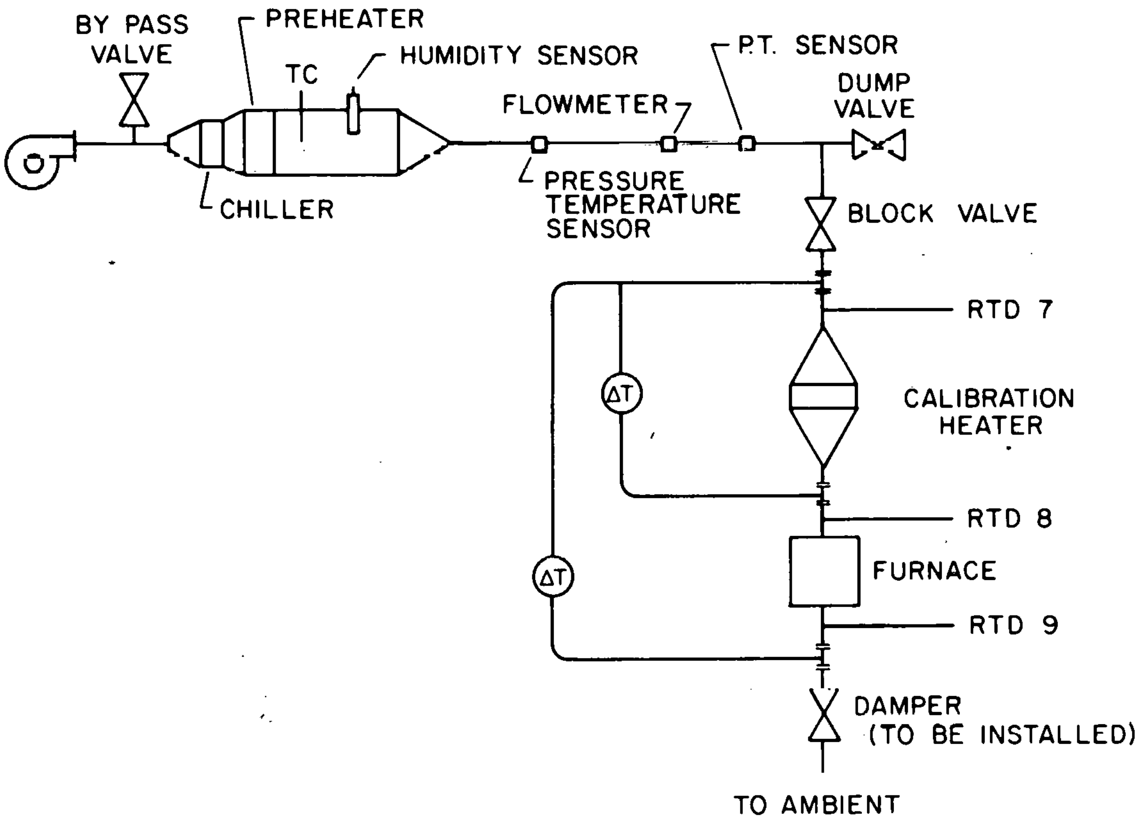

Figure 8. Schematic of Furnace Test Stand

heat values. The only alternative method requires manual integration of areas under curves (e.g., the ΔT time curve) which is time consuming and a large source of error.

Ambient air is drawn into the test stand system by a centrifugal blower. The blower delivery rate is controlled with a motor-driven bypass valve enabling the operator to manually control the air flow through the system. After leaving the blower, the air is dehumidified in a cooler and reheated to 70^{o}F in a preheater which is automatically controlled. Located in the duct following the preheater are sensors for measuring humidity, pressure, and temperature. A vortex shedding flow meter is used to measure the air flow through the system to the furnace. Downstream of the flow meter, additional pressure and temperature sensors are installed. A pair of motor-driven butterfly valves are used to simultaneously "block" the flow from the test furnace and "dump" the flow to ambient. This arrangement permits repetitive cycling of the test furnace air flow without disturbing the conditioning of the incoming air. Before reaching the test furnace, the air is passed through a calibration heater which is used to calibrate the air flow meter. The air is at this point delivered to the air inlet of the test furnace. Temperature instrumentation in the form of thermopiles are located across the calibration heater and the test furnace. Platinum resistance temperature detectors are located at critical points to permit calibration of the thermopiles.

B. Calibration

The test facilities at BNL were designed and built to produce 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.

To maintain a high degree of accuracy, calibration checks of all measured quantities 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_1). 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:

$$\dot{m}_{air} = \frac{\dot{Q}_{in}}{C_p \Delta T_1}$$

(4) ΔT_1 & ΔT_2 - The temperature rise of the air across the calibration heater and across the test furnace are each measured using a twenty (20) element differential temperature thermopile. This thermopile is checked by electronics and by comparison to calibrated platinum resistance thermometers (RTD7, RTD8, and RTD9).

C. Test Procedure

1. 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 $155^{\circ}F$ ($\pm 5^{\circ}$) outlet temperature while the inlet temperature is maintained at $70^{\circ}F$ ($\pm 5^{\circ}$). 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.

2. 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 set at 5.0 minutes while the air flow (fan "on") time is set at 10 minutes. To begin a cycle, the burner and the air flow through the furnace start simultaneously. At the end of the burner firing period (5 minutes), the air flow is allowed to continue until the total blower "on" time of 10 minutes 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 become constant from cycle to cycle.

The amounts of heat into and out of the furnace are 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 in both steady-state and cycle-efficiency tests.

D. Test Results

An oil-fired central furnace with a nameplate output of 84,000 Btu/hr and .75 gph firing rate was tested. This furnace, as received, is a "Hi-Boy" furnace fitted with a high-speed retention-head burner. The original blower in the equipment was removed and the test stand blower used in its place. A hot wire anemometer was used to assure that the flow patterns and velocities within the furnace were not changed. To this end, internal sheet metal was installed to duplicate the original blower housing. All seams in the furnace's sheet metal housing were sealed with duct tape or silicone rubber. Air leaks in the furnace or system will have the effect of inflating the measured efficiency of the furnace if they are downstream of the test systems flow meter.

The furnace was tested as a packaged unit and the results are shown in Table 13.

Table 13

Overall Efficiency vs Burner On-Time

% Burner On-Time	Overall Efficiency
5	-
10	72.0
15	75.0
20	77.1
25	78.2
30	79.3
40	80.8
100	81.7

E. Future Work

The testing of commercially available oil-fired furnaces will be continued with the results subjected to annual fuel use and seasonal efficiency computation. Changes to the existing experimental setup are in progress to allow a quicker turnaround and minimal down time. With the oncoming testing of prototypes and developmental units, this effort should increase productivity.

The increasing use and familiarization with the test system has produced improvements in procedures and operation with corresponding improvements in the accuracy and reproduction of the test results.

V. SUMMARY AND CONCLUSIONS

During Fiscal Year 1979, approximately 37 laboratory tests were completed. Of these tests, 28 have been discussed in this report. The remaining 9 tests constitute additional Baseline and experimental tests which are not reportable but rather provide further technical support for the results presented in this report. Many of the results of all these tests will be used to prepare topical reports. The testing included 11 boilers with several combinations of retention-head, non-retention-head, and blue-flame burners. Additional tests were made of stack gas economizers, vent dampers, and humidified combustion systems augmenting areas already covered in previous annual reports.[1,4,6]

By far, the most exciting results of the work to date has been the identification of several commercially available packaged boilers which appear to have high performance capability. The basic criterion of high performance by BNL's standards was the achievement of a computed seasonal efficiency of at least 70%. The 9 packaged boilers are listed in Table 14.

Table 14

High-Efficiency Boilers

Boiler Type	Boiler Code	Burner Type & Code	Percent Operating Loss		Percent Off-Cycle Loss	Percent Seasonal Efficiency (Useful Heat	Annual Fuel Use (Gallons)
			Stack	Jacket			
Wet-Base Steel	L	[c]	18.8	(Total)	6.6	74.6	1098
	M	HSRH A	16.5	1.4	8.0	74.1	1104
	J	Recirculating[a] Gas-Blue-Flame	14.0	3.6	8.2	74.2	1104
	N	HSRH A	13.0	4.9	11.1	71.0	1153
	A	HSRH[a] A	14.5	3.2	8.2	74.1	1105
	O	[c]	15.6	(Total)	12.1	72.3	1132
Wet-Base Cast-Iron	B	HSRH[b] B	17.3	1.3	10.3	71.1	1151
	B	HSRH[a,b] C	18.0	1.0	5.7	75.3	1087
	P	HSRH D	14.7	4.4	9.7	71.2	1150
Dry-Base Cast-Iron	Q	HSRH N	11.7	4.4	13.4	70.5	1161

[a]Tested in Fiscal Year 1979 and reported herein.
[b]These packaged units consisted of the same boiler with different retention-head burners.
[c]Integral burner with induced draft fan.

It must be recognized that tests of such refit options as economizers and vent dampers have revealed that they are effective only when fitted to the more inefficient boiler/burner combinations. These refit options may have only small effects when coupled with most of the packaged units shown in Table 11.

With the exception of two units with induced draft systems, the average steady-state net stack temperature of the packaged boilers was about 390°F, ranging from 230° to 440°F. Stack gas economizers tested generally have been able to reduce stack gas temperatures, in steady-state, by about 50° to 350°F when exposed to stack temperatures in excess of 600°F. Substantially lower gains could be achieved using such economizers on the listed boilers and, in fact, the application might present difficulties in homes which have high-mass masonry chimneys. Condensation of the water vapor in the stack gas could take place and lead to boiler and heat exchanger corrosion.

The application of vent dampers to the above units may have limited gain in that the additional savings in off-cycle losses are small over those already obtained with a retention-head burner. It must be presumed that the off-cycle losses shown in Table 11 are largely due to (and reflected by) jacket heat loss.

The evaluation of humidified combustion systems is completed. The results have indicated that the technology has little application in residential heating systems using light oil. The applicability of such systems in the commercial area utilizing heavy oil has yet to be completely resolved and is outside the present scope of BNL's program.

To this date, the characterization test program has virtually only begun. The work will continue and will reflect the knowledge gained from the evaluated test results through changes in the programs, planning, and procedures.

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APPENDIX A

AFUE Computation Analysis and
Efficiency Data for Hydronic Equipment

	Tables
Characterization Boiler Tests	1 to 16
Blue-Flame Combustion Boiler Tests	17 to 19
Special Wet-Base Cast-Iron Boiler Tests	20
Stack Economizer Tests	21 to 24

NOTE:

(1) All computations of Annual Fuel Use and Efficiency (AFUE) correspond to a design heating load of 50,000 Btuh for a home located in New York City with 40 gallons of domestic hot water used per day and operating with an overfire ratio of 2 (100% overfired), conditions typical of the installations in the field in this area. The abbreviation HSRH and LSNRH, high-speed-retention head and low-speed-non-retention head respectively, are used in describing the type of burner used in each test.[3,4,5]

(2) Some of the heating units indicated on the Code Guide Sheet were tested in other Fiscal Years. These results are not in this report.

CODE GUIDE SHEET

Oil Burners Tested

Code	Type	Make	Model No.
A	HSRH	Beckett	AF
B	HSRH	Sunray	FC
C	HSRH	Wayne	MH
D	HSRH	Carlin	100CRD
E	HSRH	Riello	MEC-3KA
F	HSRH	Stewart-Warner	HPR135
G	Prototype	Wayne	'S' Prototype
H	LSRH	Beckett	SR
J	LSNRH	Weatherall	XLA-1A
K	LSNRH	Beckett	S
L	LSNRH	Wayne	OE
M	Blue-Flame	M.A.N.	RE1
N	HSRH	Beckett	Preproduction

Boilers Tested

Code	Type	Make	Model No.
A	WBST	New Yorker	FR147
B	WBCI	Burnham	V-14
C	WBCI	Weil-McLain	P-366
D	WBCI	Slant Fin	78-106
E	DBST	Burnham	HE24
F	DBST	Columbia	FT30
G	DBCI	Slant Fin	MS100
H	DBCI	Utica	PBOt3
J	WBST	Blueray	BR75
K	WBCI	Breda	Syst.91
L	WBST	Axeman-Anderson	87CPO
M	WBST	Axeman-Anderson	87PO
N	WBST	Dynatherm	24

CODE GUIDE SHEET

Boilers Tested-cont'd.

Code	Type	Make	Model No.
O	WBST	Oil King	EF-124W
P	WBCI	Tasso	T4
Q	DBCI	Ultimate	KT5Y
R	Pulse Combustion	Turbopulse	Prototype
S	WBST	New Yorker	S-98-AP
Z	DBST	Federal	XL76

Economizers Tested

Code	Make	Model
A	Maxi Heat Engineering	Prototype
B	Macc Energy Corp.	Flue Pak
C	Energy Savings Devices, Ltd.	Thermastack

Humidified Combustion

Code	Make	Model
A	ECS	#200
B	Vapormid	H-800
C	Energy Pak	EP800
D	Save Fuel	None
E	Aftco	Pyromid

Table 1

Boiler A, Wet-Base, One-Pass Horizontal Fire Tube, Steel Construction, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 74.1%

Annual Fuel Use (Gallons/Year) 1105

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
1.5	0	0
3.0	49.2	40.5
4.0	62.1	51.1
5.0	69.9	57.5
7.0	78.7	64.8
10.0	85.3	70.2
12.0	87.9	72.3
15.0	90.5	74.5
20.0	93.1	76.6
25.0	94.6	77.9
40.0	99.3	81.7
60.0	99.5	81.9
100.0	100.0	82.3

Average Steady-State Efficiency at 180°F Outlet Temperature: 82.3

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 85½%

Percent CO_2 11%

Net Stack Temp. 306°F

Table 2

Boiler A, Wet-Base, One-Pass Horizontal Fire Tube, Steel Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 67.3%

Annual Fuel Use (Gallons/Year) 1217

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.5	0	0
3.0	18.4	14.4
5.0	52.5	41.0
7.0	67.1	52.3
10.0	78.1	60.9
12.0	82.3	64.2
15.0	86.6	67.5
20.0	90.8	70.8
25.0	93.4	72.9
30.0	95.1	74.2
40.0	98.1	76.5
60.0	99.4	77.5
100.0	100.0	78.0

Average Steady-State Efficiency at 180°F Outlet Temperature: 78.0%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 82 1/8%

Percent CO_2 8 3/4%

Net Stack Temp. 345°F

Table 3

Baseline Boiler (Z), Dry-Base, Vertical Fire Tube, Steel Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 56.2%

Annual Fuel Use (Gallons/Year) 1455

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_c \times \eta_c$ %
4.2	0	0
5.0	18.8	13.0
7.0	45.2	31.3
8.0	53.5	37.0
10.0	65.0	45.0
12.0	72.7	50.3
16.0	82.4	57.0
20.0	88.2	61.0
25.0	92.8	64.2
30.0	95.8	66.3
40.0	98.3	68.0
70.0	99.3	69.0
100.0	100.0	69.2

Average Steady-State Efficiency at 180°F Outlet Temperature: 69.2%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 74½%

Percent CO_2 8%

Net Stack Temp. 538°F

Table 4

Boiler B, Wet-Base, Four-Section, Cast-Iron Construction, with HSRH Burner C

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 75.3%

Annual Fuel Use (Gallons/Year) 1087

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
1.7	0	0
5	70.2	56.9
10	88.2	71.4
15	94.2	76.3
20	97.2	78.7
25	99.0	80.2
30	100.0	81.0
35	100.0	81.0
40	100.0	81.0
50	100.0	81.0
75	100.0	81.0
85	100.0	81.0
100	100.0	81.0

Average Steady-State Efficiency at 180°F Outlet Temperature: 81.0%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 82%

Percent CO_2 11½%

Net Stack Temp. 440°F

Table 5

Boiler B, Wet-Base, Four-Section, Cast-Iron Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 63.6%

Annual Fuel Use (Gallons/Year) 1286

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.3	0	0
4.0	18.4	14.0
5.0	36.2	27.6
7.0	56.5	43.1
10.0	71.7	54.7
12.0	77.6	59.2
15.0	83.5	63.7
20.0	89.4	68.2
25.0	93.0	71.0
30.0	95.3	72.7
40.0	96.0	73.2
60.0	97.3	74.2
100.0	100.0	76.3

Average Steady-State Efficiency at 180°F Outlet Temperature: 76.3%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 77¼%

Percent CO_2 8 3/4%

Net Stack Temp. 490°F

Table 6

Boiler C, Wet-Base, Three-Section, Cast-Iron Construction, with HSRH Burner C

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 68.5%

Annual Fuel Use (Gallons/Year) 1195

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.1	0	0
4.0	50.2	38.2
5.0	61.4	46.7
7.0	74.2	56.4
10.0	83.8	63.7
12.0	87.6	66.6
15.0	91.3	69.4
20.0	95.1	72.3
25.0	97.3	73.9
30.0	98.8	75.1
40.0	99.6	75.7
60.0	99.7	75.8
100.0	100.0	76.0

Average Steady-State Efficiency at 180°F Outlet Temperature: 76.0%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 81½%

Percent CO_2 11½%

Net Stack Temp. 471°F

Table 7

Boiler C, Wet-Base, Three-Section, Cast-Iron Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency	65.4%
Annual Fuel Use (Gallons/Year)	1251

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.0	0	0
3.0	14.2	10.8
5.0	50.6	38.4
7.0	66.2	50.2
10.0	77.8	59.0
12.0	82.4	62.5
15.0	86.9	65.9
20.0	91.5	69.4
25.0	94.2	71.4
30.0	96.0	72.8
40.0	97.6	74.0
60.0	98.9	75.0
100.0	100.0	75.8

Average Steady-State Efficiency at 180°F Outlet Temperature:	75.8%
Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses):	79 3/4%
Percent CO_2	9½%
Net Stack Temp.	444°F

Table 8

Boiler D, Wet-Base, Three-Section, Cast-Iron Construction, with HSRH Burner B

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 62.9%

Annual Fuel Use (Gallons/Year) 1301

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.8	0	0
4.0	31.2	23.5
5.0	45.4	34.2
7.0	61.5	46.4
10.0	73.6	55.5
12.0	78.3	59.0
15.0	83.1	62.7
20.0	87.8	66.2
25.0	90.6	68.3
30.0	92.5	69.7
40.0	96.4	72.7
60.0	99.5	75.0
100.0	100.0	75.4

Average Steady-State Efficiency at 180°F Outlet Temperature: 75.4%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 79½%

Percent CO_2 10%

Net Stack Temp. 477°F

Table 9

Boiler E, Dry-Base, Single-Pass, Vertical Fire Tube, Steel Construction, with HSRH Burner C

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency	67.6%
Annual Fuel Use (Gallons/Year)	1211

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.2	0	0
3.0	27/4	20.9
4.0	46.8	35.7
5.0	58.4	44.6
7.0	71.7	54.7
10.0	81.7	62.3
12.0	85.5	65.2
15.0	89.5	68.3
20.0	93.3	71.2
25.0	85.6	72.9
30.0	97.2	74.2
60.0	99.9	76.2
100.0	100.0	76.3

Average Steady-State Efficiency at 180°F Outlet Temperature:	76.3%
Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses):	83 3/4%
Percent CO_2	11½%
Net Stack Temp.	389°F

Table 10

Boiler E, Dry-Base, Single-Pass, Vertical Fire Tube, Steel Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 64.3%

Annual Fuel Use (Gallons/Year) 1272

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.4	0	0
3.0	21.0	15.0
5.0	54.3	40.2
7.0	68.5	50.7
10.0	79.2	58.6
12.0	83.3	61.6
15.0	87.5	64.8
20.0	91.7	67.9
25.0	94.2	69.7
30.0	95.8	70.9
40.0	97.8	72.4
60.0	99.3	73.5
100.0	100.0	74.0

Average Steady-State Efficiency at 180°F Outlet Temperature: 74.0%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 82%

Percent CO_2 10¼%

Net Stack Temp. 408°F

Table 11

Boiler F, Dry-Base, Single-Pass, Vertical Fire Tube, Steel Construction, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 63.4%

Annual Fuel Use (Gallons/Year) 1392

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.1	0	0
4.0	22.3	17.2
6.0	49.2	38.0
8.0	62.7	48.5
10.0	70.8	54.7
12.0	76.1	58.8
15.0	81.5	63.0
20.0	86.9	67.2
25.0	90.1	69.6
30.0	92.3	71.3
40.0	94.4	73.0
60.0	96.2	74.4
100.0	100.0	77.3

Average Steady-State Efficiency at 180°F Outlet Temperature: 77.3%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 84¼%

Percent CO_2 10¼%

Net Stack Temp. 335°F

Table 12

Baseline Boiler (Z), Dry-Base, Vertical Fire Tube Steel Construction, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 61.9%

Annual Fuel Use (Gallons/Year) 1323

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.0	0	0
4.0	26.7	19.5
5.0	42.5	31.1
7.0	60.7	44.4
10.0	74.3	54.3
12.0	79.6	58.2
15.0	84.9	62.1
20.0	90.2	65.9
25.0	93.4	68.3
30.0	95.5	69.8
40.0	97.1	71.0
60.0	98.1	71.7
100.0	100.0	73.1

Average Steady-State Efficiency at 180°F Outlet Temperature: 73.1%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 80%

Percent CO_2 10%

Net Stack Temp. 466°F

Table 13

Boiler G, Dry-Base, Three-Section, Cast-Iron Construction, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 70.0%

Annual Fuel Use (Gallons/Year) 1169

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.1	0	0
3.0	33.1	25.9
5.0	61.9	48.4
7.0	74.2	58.0
10.0	83.5	65.3
12.0	87.0	68.0
15.0	90.7	70.9
20.0	94.2	73.7
25.0	96.4	75.4
30.0	97.8	76.5
40.0	98.5	77.0
60.0	99.0	77.4
100.0	100.0	78.2

Average Steady-State Efficiency at 180°F Outlet Temperature: 78.2%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 83%

Percent CO_2 12%

Net Stack Temp. 430°F

Table 14

Boiler G, Dry-Base, Three-Section, Cast-Iron Construction, with LSNRH Burner L

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 67.9%

Annual Fuel Use (Gallons/Year) 1205

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.1	0	0
3.0	29.6	22.7
5.0	59.4	45.6
7.0	72.3	55.5
10.0	81.8	62.8
12.0	85.6	65.7
15.0	89.3	68.6
20.0	93.0	71.4
25.0	95.3	73.2
30.0	96.8	74.3
40.0	98.0	75.3
60.0	98.7	75.8
100.0	100.0	76.8

Average Steady-State Efficiency at 180°F Outlet Temperature: 76.8%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 80 3/4%

Percent CO_2 9 3/4%

Net Stack Temp. 432°F

Table 15

Boiler H, Dry-Base, Four-Section, Cast-Iron Construction, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 64.5%

Annual Fuel Use (Gallons/Year) 1269

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_c \times \eta_c$ %
2.5	0	0
3.0	16.7	12.6
5.0	51.1	38.6
7.0	65.9	49.8
10.0	76.9	58.1
12.0	81.2	61.4
15.0	85.5	64.6
20.0	89.8	67.9
25.0	92.4	69.9
30.0	94.1	71.1
40.0	96.6	73.0
60.0	98.5	74.5
100.0	100.0	75.6

Average Steady-State Efficiency at 180°F Outlet Temperature: 75.6%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 81½%

Percent CO_2 10%

Net Stack Temp. 417°F

Table 16

Boiler H, Dry-Base, Four-Section, Cast-Iron Construction, with LSNRH Burner J

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 58.4%

Annual Fuel Use (Gallons/Year) 1402

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.1	0	0
4.0	22.8	16.1
5.0	39.1	27.6
7.0	57.6	40.7
10.0	71.5	50.5
12.0	76.9	54.3
15.0	82.3	58.1
20.0	87.7	61.9
25.0	91.0	64.2
30.0	93.1	65.7
40.0	95.9	67.7
60.0	98.4	69.5
100.0	100.0	70.6

Average Steady-State Efficiency at 180°F Outlet Temperature: 70.6%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 76 3/4%

Percent CO_2 9¼%

Net Stack Temp. 524°F

Table 17

Blue-Flame Burner/Boiler (J) System Developed Under DOE Funding, Steel Boiler Construction, with Horizontal Fire Tubes

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 74.2%

Annual Fuel Use (Gallons/Year) 1104

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
1.8	0	0
3.0	13.3	11.0
4.0	57.9	47.7
5.0	66.8	55.0
7.0	77.1	63.5
10.0	84.7	69.8
15.0	90.7	74.7
20.0	93.6	77.1
25.0	95.4	78.6
30.0	96.6	79.6
4.0	100.0	82.4
60.0	100.0	82.4
100.0	100.0	82.4

Average Steady-State Efficiency at 180°F Outlet Temperature: 82.4%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 86%

Percent CO_2 13%

Net Stack Temp. 332°F

Table 18
Blue-Flame Burner/Boiler (K) System Developed in Italy, Cast-Iron Boiler Construction, with Horizontal and Annular Heat Exchanger

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 78.5%

Annual Fuel Use (Gallons/Year) 1,042

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
1.3	0	0
2.0	37.9	31.7
3.0	59.9	50.1
4.0	70.8	59.3
5.0	77.4	64.8
6.0	81.8	68.5
8.0	87.3	73.1
10.0	91.6	76.7
15.0	94.9	79.4
20.0	97.1	81.3
25.0	98.4	82.4
30.0	99.3	83.1
100.0	100.0	83.7

Average Steady-State Efficiency at 180°F Outlet Temperature: 83.7%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 88 1/8%

Percent CO_2 14%

Net Stack Temp. 256°F

Table 19

West German Blue-Flame Burner (M) Tested in Boiler A, Steel Boiler Construction, Wet-Base, with Horizontal Fire Tubes

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 68.1%

Annual Fuel Use (Gallons/Year) 1201

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.7	0	0
4.0	8.3	7.2
5.0	26.7	23.3
7.0	47.7	41.6
10.0	63.5	55.4
12.0	69.6	60.8
15.0	75.7	66.1
20.0	81.8	71.4
25.0	85.5	74.6
30.0	87.9	76.7
40.0	95.3	83.2
60.0	98.9	86.3
100.0	100.0	87.3

Average Steady-State Efficiency at 180°F Outlet Temperature: 87.3%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 90½%

Percent CO_2 13¼%

Net Stack Temp. 138°F

Table 20

Special Wet-Base, Cast-Iron Boiler (P), with HSRH Burner (D), Cast-Iron Boiler Construction, with Two Pass, Horizontal Wet-Base Heat Exchanger
AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 71.2%

Annual Fuel Use (Gallons/Year) 1150

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.8	0	0
4.0	33.1	26.8
5.0	48.4	39.2
6.0	58.6	47.4
8.0	71.3	57.7
10.0	78.9	63.8
12.0	84.0	68.0
15.0	89.1	72.1
20.0	94.2	76.2
25.0	97.2	78.6
40.0	100.0	80.9
70.0	100.0	80.9
100.0	100.0	80.9

Average Steady-State Efficiency at 180°F Outlet Temperature: 80.9%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 85¼%

Percent CO_2 12%

Net Stack Temp. 330°F

Table 21
First Hydronic Stack Economizer (Test Article A) of Prototype Design Tested on the Baseline Boiler (Z), with LSNRH Burner (J)

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 70.4%

Annual Fuel Use (Gallons/Year) 1163

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.7	0	0
4.0	33.4	27.9
5.0	47.2	39.4
6.0	56.4	47.2
8.0	67.8	56.7
10.0	74.7	62.4
12.0	79.3	66.3
15.0	83.9	70.1
20.0	88.4	73.9
25.0	91.2	76.2
40.0	96.9	81.0
70.0	98.7	82.5
100.0	100.0	83.6

Average Steady-State Efficiency at 180°F Outlet Temperature: 83.6%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 87½%

Percent CO_2 9%

*Net Stack Temp. 190°F

*Measured Downstream of Stack Economizer

Table 22

Second Hydronic Stack Economizer (Test Article B), Commercially Available, Tested on the Baseline Boiler (Z) with LSNRH Burner (J)

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 61.8%

Annual Fuel Use (Gallons/Year) 1324

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.6	0	0
4.0	11.1	8.5
5.0	29.8	22.9
6.0	42.3	32.5
8.0	57.9	44.5
10.0	67.2	51.6
12.0	73.5	56.4
15.0	79.8	61.3
20.0	86.0	66.0
25.0	89.7	68.9
40.0	93.5	71.8
70.0	96.4	74.0
100.0	100.0	76.8

Average Steady-State Efficiency at 180°F Outlet Temperature: 76.8%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 85%

Percent CO_2 9%

Net Stack Temp. 270°F

Table 23

Third Stack Economizer (Test Article C), Tested on Boiler S, Steel Construction Boiler, with HSRH Burner (A)

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 65.8%

Annual Fuel Use (Gallons/Year) 1244

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
3.7	0	0
4.0	8.8	7.0
5.0	29.0	23.0
6.0	42.5	33.7
8.0	59.3	47.1
10.0	69.4	55.1
12.0	76.1	60.4
15.0	82.9	65.8
20.0	89.6	71.1
25.0	93.7	74.4
40.0	96.6	76.7
60.0	97.7	77.6
100.0	100.0	79.4

Average Steady-State Efficiency at 180°F Outlet Temperature: 79.4%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 84 3/4%

Percent CO_2 9½%

Net Stack Temp. 290°F

Table 24

Boiler S, Dry-Base, Vertical Fire Tube, Steel Construction Boiler, with HSRH Burner A

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 58.1%

Annual Fuel Use (Gallons/Year) 1409

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.8	0	0
4.0	31.2	21.2
5.0	46.1	31.3
6.0	56.1	38.1
8.0	68.4	46.5
10.0	75.9	51.6
12.0	80.8	54.9
15.0	85.8	58.3
20.0	90.7	61.7
25.0	93.7	63.7
40.0	97.8	66.5
60.0	98.5	67.0
100.0	100.0	68.0

Average Steady-State Efficiency at 180°F Outlet Temperature: 68.0%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 75¼%

Percent CO_2 10½%

Net Stack Temp. 640°F

Table 25

Prototype Oil Burner (G) Submitted Under Voluntary Program tested with the Baseline Boiler (Z)

AFUE COMPUTATIONAL ANALYSIS

Seasonal Efficiency 63.6%

Annual Fuel Use (Gallons/Year) 1287

EFFICIENCY DATA

Burner Fractional "On" Time %	Cycle Efficiency %	Overall Efficiency $\eta_s \times \eta_c$ %
2.2	0	0
4.0	46.3	33.8
6.0	65.1	47.5
8.0	74.5	54.3
10.0	80.1	58.4
12.0	83.9	61.2
15.0	87.7	63.9
20.0	91.4	66.6
25.0	93.7	68.3
30.0	95.1	69.3
40.0	98.9	72.1
60.0	99.3	72.4
100.0	100.0	72.9

Average Steady-State Efficiency at 180°F Outlet Temperature: 72.9%

Average Steady-State Efficiency by Stack Gas Sampling (Neglecting Jacket Losses): 79¼%

Percent CO_2 10 3/4%

Net Stack Temp. 525°F

APPENDIX B

HYDRONIC FACILITIES DESCRIPTION AND TECHNIQUE

A. Efficiency Measurement Technique

A heat flow measurement technique provides a direct, fundamental physical measurement of heating equipment efficiency 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 as 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 was developed 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 quantitites that are measured include (see Figure B-1):

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

(b) ΔT - temperature rise across the boiler

$$\Delta T = T_{outlet} - T_{inlet} \quad (^{o}F)$$

(c) $\dot{m}_{oil}$ - 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.

$$\dot{H} = \dot{m}_w \times C_p \times \Delta T. \quad (C_p \text{ - heat capacity of water})$$

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.

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

The efficiency is the ratio of these two quantities accumulated over time.

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

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.

B. Efficiency Definitions

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.

Cyclic 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.

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

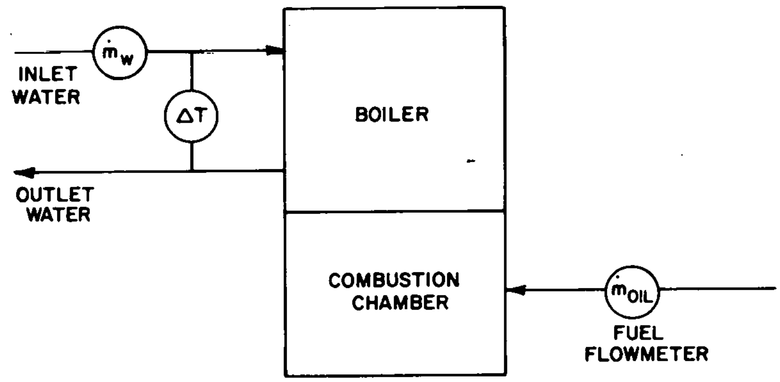
$$\eta_{overall} = \eta_{steady\text{-}state} \times \eta_{cycle}$$

For example, if $\eta_{ss} = .70$ and $\eta_{cycle} = .70$ for a particular burner load, then the overall efficiency is equal to (.70) x (.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 ($\eta_c = 1.0$) and the overall efficiency equals the steady-state efficiency.

C. 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 50853, 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.



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 = $\dot{m}_{OIL} h$

$$\text{EFFICIENCY} = \frac{\dot{m}_w \Delta T}{\dot{m}_{OIL} h}$$

Figure B-1. Brookhaven National Laboratory Boiler Efficiency Measurement Schematic

APPENDIX C

INVESTIGATION OF ALTERNATIVE TESTS METHODOLOGY

An effort was initiated to develop some simplified testing procedures which could reduce the length of time and cost normally required in producing computed seasonal efficiency of oil-fired hot water boilers.

It has been observed that the rate of rise of boiler water temperature is approximately constant in time, once a cold residential boiler is heated by a steady combustion source and after a brief initial transient period. The boiler in question served no external load. It has also been observed that the boiler cool-down period (after achievement of a peak desired temperature) corresponds to an exponential decay of boiler water temperature with time. The purpose of this study is to examine the gross heat transfer, thermal storage, and energy release rate mechanisms which underlie these observations.

The heating of a cold boiler "to temperature" by a quasi-steady combustion process involves time-dependent heat transfer within and thermal energy storage in the nonuniform, nonisothermal boiler. In the usual accepted sense, the process is nonsteady. This, despite the quasi-steady combustion process. Nevertheless, the reported observations indicate certain regularities in major portions of the time periods which describe the "heat-up" and "cool-down" processes. It is important to understand the physical nature of these regularities and their relation, if any, to the boiler's steady-state characteristics (e.g., steady-state efficiency).

It is also known that boiler's cycle efficiency is related to its "cool-down" characteristics. Accordingly, it is important to examine the relations, if any, between "cool-down" irregularities and "cycle efficiency."

A typical residential boiler consists of a nonuniform distribution of material elements. Each element has its own thermophysical properties. At initial time, the system is taken to be isothermal (cold) and its total enthalpy and enthalpy distribution can be calculated once its detailed internal structure and material constituency are known. Immediately after ignition, the boiler as a system is highly nonisothermal and nonsteady. Nevertheless, its instantaneous elemental and total enthalpy is well defined and deducible if the complete time-dependent temperature field is not sufficiently well investigated to be "known." It is therefore necessary to study the gross physical features of the boiler's heat-up and cool-down periods and to examine whether certain approximations are implied by the observations described above.

A procedure was developed to evaluate the merits of testing a residential boiler using the variation with time of the boiler water temperature, under certain operating and nonoperating conditions.

The test requires that the approximate thermal capacity of the boiler be known. This can be approximately determined in two ways.

The first is to actually weigh the boiler empty and then filled with water. The approximate thermal capacity can be determined by summing the products of mC_p for each major component of the boiler. In this case there would be two major components under consideration, namely, water and steel (cast-iron for the appropriate boiler). Thus $\left[\overline{mC_p}\right]B$, the approximate thermal capacity, can be represented by

$$\left[\overline{mC_p}\right]B = m_s\, C_{p,s} + m_w\, C_{p,w}$$

where the subscripts s and w refer to steel and water respectively.

In the second method, an electric heater is used to heat the boiler under test. Since the heat rate is known,a measurement of the time variation of boiler water temperature permits a computation of the approximate thermal capacity as

$$\left[\overline{mC_p}\right]B = \frac{\dot{Q}}{\dot{\Delta}_t},$$

where $\dot{Q}$ is the heat rate input watts of the electric heater and $\dot{\Delta}t$ is the temperature rise over time of the boiler. This latter method utilizes the apparent linear boiler temperature rise and will be verified through comparisons with the weighing method.

The actual determination of an efficiency for the boiler will require accurate measurement of the fuel consumed over the duration of firing. The efficiency as measured may or may not be equivalent to firing steady-state efficiency as measured by the direct heat flow method and is therefore subject to verification. This efficiency is

$$\eta_q = \frac{\left[\overline{mC_p}\right] B\, \dot{\Delta}_t}{\dot{m}_f\, \Delta H_c},$$

where $\dot{m}_f$ is the fuel consumed over time and ΔH_c is the heating value of the fuel consumed.

The determination of cycle efficiency requires a knowledge of the heat retained within a boiler at the end of a given standby period. It may be that such a figure of performance can be derived from the characteristic cool-down boiler temperature data. The cycle efficiency can be defined, for these purposes, as the ratio of the heat remaining in a boiler to the amount stored at the end of the firing period. This can be expressed as

$$\eta_c = \frac{\text{heat remaining}}{\text{heat stored}} = \frac{(T_r - T_i)}{(T_p - T_i)}$$

$$\eta_c = \frac{(T_r - T_i)}{(T_p - T_i)},$$

where T_p is the peak boiler temperature reached at burner shutdown and T_r is the boiler temperature at the end of a given standby period.

Testing to determine the degree of correlation that these efficiencies have with those developed under the direct measurement program will be completed in early Fiscal Year 1980 and the results summarized in the next annual report.