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Project Summary

Design Optimization and Field Verification of an Integrated Residential Furnace

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An experimental, oil-fired, residential furnace design developed by Rockwell International, under EPA sponsorship, was field-tested at six sites in Albany (NY) and Boston (MA) during the winters of 1977 through 1979. It was found that a 65-percent reduction of nitric oxide (NO) emissions can be sustained while maintaining control of carbonaceous pollutants. In addition, the low-pollution technology was compatible with enhanced furnace efficiency. Cycle-averaged efficiencies on the order of 70-80 percent were achieved, resulting in fuel savings of 10-15 percent, compared with conventional furnaces.

A short laboratory study was also performed to investigate the characteristics of the furnace when converted to natural gas. It was found that natural gas could be fired with nitrogen oxide (NO_x) levels slightly higher than those with oil-firing and acceptable CO and hydrocarbon emissions, with minor modification to the firebox.

U.S. Patent 4,138,986, covering the unique features of the furnace design, was issued, assigned to the U.S. Environmental Protection Agency (EPA). The National Bureau of Standards (NBS) method (NBSIR 78-1543) for determining the seasonal performance of residential furnaces was experimentally compared with a method devised by Rockwell and the EPA during this program. It was found that, both in the field and laboratory, the NBS method produced significantly higher steady state and cyclical efficiency values due to heat loss assumptions incorporated in the NBS method.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Low-NO_x design criteria were developed for No. 2 fuel oil-fired burners in research efforts conducted by Rockwell International for the U.S. EPA. The studies culminated in a developmental effort in which commercially feasible furnace design configurations, that integrated the low-NO_x technology with performance-enhancing features, were evaluated and a selected configuration field-tested. The prior studies indicated that the most favorable configuration for minimizing pollutant emissions was a tunnel-fired, hydronic heating system; however, considering the existing heating systems and current trends, a side-fired warm-air furnace was selected for further testing.

Efficient energy utilization was also a major concern in this low-NO_x furnace, and a detailed evaluation of system heat losses was conducted, along with a general evaluation of available performance-enhancement devices. The low-NO_x burner head had already been optimized to operate at low excess air conditions (i.e.,low flue heat loss), and generally all of the other performance-enhancing features considered were external devices with only minimal influence on the combustion zone. Thus the effects of these devices on the furnace were not detrimental to the emissions-reduction characteristics.

A laboratory prototype was constructed and tested with very favorable results. Consequently, a field test was conducted. The field test involved the construction of six prototype furnaces using techniques amenable to mass production assembly, national safety codes, and conventional maintenance practices, then testing the units in the northeastern U.S. for two complete heating seasons. Emphasis was placed on developing advanced technology that can be implemented by the U.S. heating industry with minimum departures from current manufacturing, distribution, installation, operation, and servicing practices. The field test performance goals were:

1) To reduce air pollutant emissions to or below the following levels, averaged over a typical duty cycle:
   a) NO_x 0.65 g (as NO)/kg fuel burned.
   b) CO, 1.0 g/kg fuel.
   c) Gaseous hydrocarbons, 0.1 g/kg fuel.
   d) Smoke, No. 1 on the Bacharach scale.

   (In comparison with average emission levels reported from a field survey of actual residential heating units, these goals would reduce NO_x emissions by 65 percent of the reported level while maintaining control of the carbonaceous pollutants.)
2) To increase cycle-averaged thermal efficiency by 10 percent or more above the mean achieved by existing installed heating units.

While primarily a long-term emissions reduction experiment, many conditions were amenable to determination of nominal efficiency for a NO_x-controlled oil-fired furnace. The long duration of the test offered a large number of measurements and a variety of firing conditions which provided samples of statistically significant size and permitted detailed studies of the parameters affecting furnace performance. An existing procedure for determining steady-state efficiency performance was modified and extended to accommodate cyclical operation by instituting an iterative measurement procedure. A computerized data logging system was utilized to measure a wide range of firing conditions and record the resultant data for a month or more on all of the test furnaces during each heating season.

This report describes the furnace configuration which evolved during this program and the results of the subsequent field and laboratory testing.

Background

The 1970 U.S. Census included a survey of installed residential space heating systems which showed that 22 percent of the residences were heated by fuel oil, and overall, about 25 percent of the systems were hydronic boiler systems. Combined then, more than 13 million residential warm-air furnaces and hydronic boilers were fired with fuel oil, predominantly No. 2 grade. A more recent survey shows that (in 1976) 3.58×10^{18} J (3.4×10^{15} Btu) of heat energy for residential use was provided by the equivalent of approximately 91×10^6 m^3 (575 million barrels) of oil.

Air Pollutant Emissions

Typically, two classes of combustion-generated air pollutants are of concern in the use of No. 2 fuel oil: (1) products of incomplete combustion, namely, CO, unburned hydrocarbons (UHC), and smoke; and (2) NO_x. Sulfur oxide (SO_x) emissions are minimal with this grade of fuel.

Generally, combustion is very nearly complete in properly tuned residential combustors so that concentrations of carbonaceous air pollutants are very low. Typically residential stack gas concentrations are less than 40 ppm CO, less than 10 ppm UHC, and little more than a faint trace of smoke (Bacharach 1 or 2).

NO_x emissions from conventional residential heating systems are formed, predominantly, by fixation of atmospheric nitrogen in the high-temperature flame zone. Their production is kinetically controlled, and their concentrations are far below equilibrium values for the flame zone conditions. A field survey of emissions from 34 residential heating units showed that: (1) NO_x are comprised of NO (nitric oxide) and NO_2 (nitrogen dioxide) in volumetric proportions of about 10 to 1, (2) the average NO_x emission level is about 1.8 g NO/kg, and (3) NO_x emissions are essentially unaffected by burner tuning. Approximately 80 percent of the units tested had NO_x emissions between 1.3 and 2.2 g NO/kg fuel burned.

Data from other studies indicate that oil-fired residential and commercial space heating systems contribute about 5 to 6 percent of the total combustion-generated NO_x emissions in the U.S. These sources may, however, cause a substantially greater air pollution problem because they are used only during the heating season, are concentrated in urban centers predominantly in two geographic areas (New England and Great Lakes states), and release their emissions at ground level.

Operating Efficiency

Furnace performance is presently estimated by measuring average steady-state values of net flue gas temperature and CO_2 content and applying those values to the standard tables of estimated heat losses. Minimum flue heat losses are about 14 to 15 percent; however, they are usually larger because flue temperatures commonly are well above the minimum needed to avoid condensation and because excess air is not minimized. Only minor losses (typically 0.5 to 1.5 percent) are conducted through the cabinet, etc., and radiated or convected to the surroundings during steady-state operation. Based on data from a number of sources, it is estimated that perhaps as many as 80 percent of existing installed residential oil-heating systems perform, at steady state, in a range as low as 67 percent (older units) to as high as 81 percent (newer units), averaging approximately 73 percent thermal efficiency.

Efficiency is degraded during cyclical operation by some transient heat losses when the burner is not being fired (standby). A natural draft flow of air through the burner, firebox, etc., cools furnace components and convects heat up the flue, and these heat losses vary with cycle timing. At low utilization, the decrement may be greater than 15 percentage points. Cabinet heat losses continue during standby, making cyclical cabinet losses greater than they are measured during steady state. For warm-air furnaces, they may be doubled (1 to 2 percent). For hydronic boilers, they may be tripled or more (2 to 5 percent), because most boiler components are at nearly the same temperatures during standby as during firing.

Season-averaged efficiencies are rarely, if ever, measured but are estimated from shorter term cyclical testing. For example, one study suggested that a valid overall mean value of season-averaged residential furnace efficiencies may fall in the 60 to 65 percent range for units having 75 percent steady-state efficiency. In an effort to provide more meaningful information to the public, other government agencies are examining methods of evaluating the operating efficiency of furnaces under cyclical operation conditions. The method which appears closest to adoption is the National Bureau of Standards' "Test Procedures for Furnaces and Vented Home Heating Equipment," a method of estimating the flue heat losses based on periodic measurements of flue gas temperature and CO_2 composition. Since the technique was finalized after this program was underway, comparative tests were performed both in the field and laboratory to evaluate efficiency measurements using the NBS method and the method developed by Rockwell/EPA during this program.

Integrqted Furnace Construction

The experimental furnace design included considerations for both pollutant emissions control and efficiency performance enhancement. The features were integrated in a complementary manner. U.S. Patent 4,138,986 has been issued, covering the unique features of the design. It is assigned to the U.S. EPA.

Pollutant Emissions Control

The low-NO_x technology applied to the integrated furnace design involved hardware design changes only in the immediate vicinity of the combustion zone; i.e., the burner head and the firebox (see Figure 1).

Optimized Burner Head

The burner head's primary function is to mix the incoming air with the fuel oil, typically injected from pressure-atomizing nozzles, to achieve complete combustion. Typically, this is accomplished by swirl vanes to add a rotational component to the air flow and a "choke" plate with a central orifice to collect the flow toward the oil nozzle and increase the velocity of the air. This general configuration is referred to in the furnace industry as a "conventional" burner head as opposed to the newer "flame retention" heads that are steadily increasing in numbers in the new furnace inventory.

The flame-retention design utilizes an obstruction in the air stream (e.g., flat plate, cone) to create turbulence and recirculation eddies that promote rapid mixing and causes the flame to be "retained" by the device. The retained flame is thus more stable (i.e., less combustion noise) and less influenced by the configuration of, or conditions in, the firebox. An earlier study, however, showed that the flame-retention burners generally produced higher concentrations of NO_x emissions. The recirculating flow increases residence time at high temperatures without heat extraction, thus providing conditions more amendable to the formation of NO_x.

A conventional burner head configuration was optimized by using a variable geometry apparatus to obtain minimum NO_x emissions and complete combustion (i.e., minimal carbonaceous pollutants). The low-NO_x burner head incorporates large swirler vanes to ensure uniform flow rotation and a relatively low angle of the swirl vanes of 25° off the blast-tube centerline axis. The choke plate orifice diameter is a function of oil-firing rate based on a correlation established with the variable geometry hardware of:

$$D_{choke}\text{ (in.)} = \left[2.7 \times \dot{W}_{oil}\text{ (gal/h)}\right]^{0.4}$$

or,

$$D_{choke}\text{ (m)} = \left[2.65 \times 10^{-4} \times \dot{W}\text{ (ml/s)}\right]^{0.4}$$

where,

D_{choke} = choke plate orifice diameter

$\dot{W}_{oil}$ = oil nozzle firing rate

This configuration produces a minimal-turbulence mixing condition that approaches a "plug-flow reactor." The mixing is at a relatively slow rate, thus the combustion process is spread over a longer time period and larger physical volume. This reduces the peak gas temperatures and thereby results in less NO_x being formed. Additionally, the conditions are favorable for the inclusion of a cool-wall combustion chamber (firebox), thus further inhibiting peak temperatures.

Cooled Combustion Chamber

Common practice in the construction of the furnace combustion chamber, or "firebox," is to thermally insulate it, usually with a silica-fiber matting or solid brick insulator. The integrated furnace, however, utilizes an uninsulated finned firebox to extract approximately 20-25 percent of the heat directly from the combustion zone to reduce peak gas temperature and consequently reduce NO_x formation.

The firebox is 0.305 m (12 in.) in diameter, as opposed to the approximately 0.228- to 0.254-m (9- to 10-in.) diameter generally in use for 0.79- to 105-ml/s (0.75- to 1.00-gph) firing rates. This delays contact with the "cool" wall and avoids formation of carbonaceous pollutants resulting from premature quenching of the chemical reaction. The firebox cooling criteria were established with water-cooled apparatus, and the selection of an air-cooled configuration was to demonstrate the applicability of the criteria to all popular means of residential heating. Cast-iron fabrication was selected for its heat distribution, heat retention, and durability characteristics.

This burner/firebox combination resulted in a substantial reduction in NO_x in laboratory results. Nominally about 0.65 g of NO/kg of fuel burned was measured, approximately 0.4 g resulting from oxidation of free nitrogen in the combustion air, and the remainder formed from the conversion of the fuel-bound nitrogen, typically about 50-100 ppm in No. 2 fuel oil. The latter component, of course, varies with the fuel-boundnitrogen concentration.

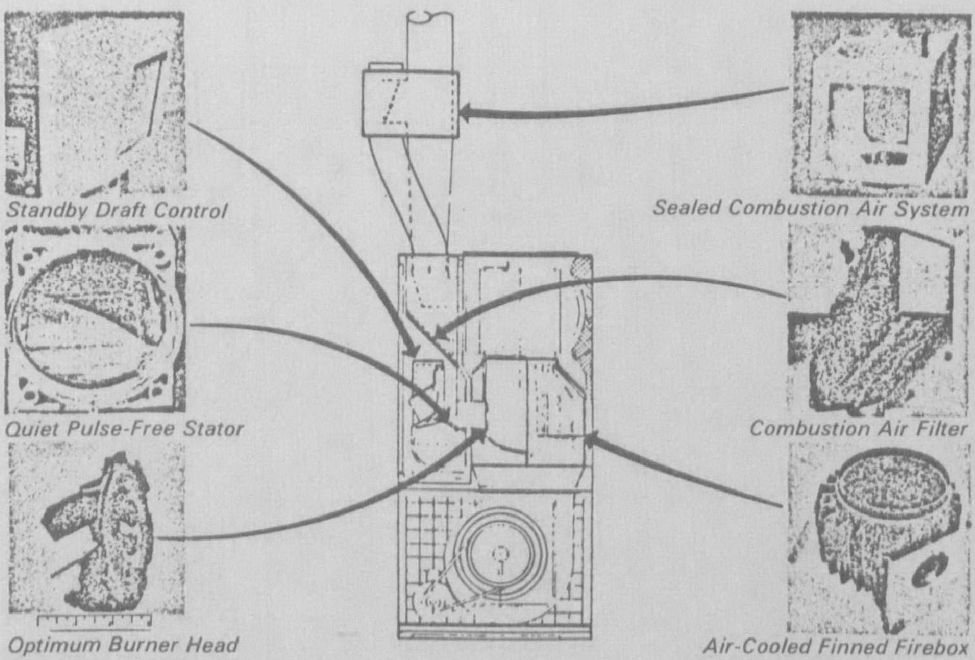

Figure 1. *Low-emission integrated furnace components.*

Performance Enhancement

Primarily, three considerations for maintaining high operational efficiency were incorporated into the furnace: low excess air operation, standby draft closure, and a sealed combustion air system.

The burner head, in addition to achieving low NO_x emissions, was also designed to operate at low excess air (nominally 20 percent). Additional heat transfer surface obtained from the use of a finned firebox assisted in maximizing heat extraction from the combustion gases. Additionally, the fan stator was modified to reduce air flow pulsation and a combustion air filter was added.

A standby draft inhibitor was added to the furnace to reduce the loss of heat stored in the firebox and heat exchanger during the standby periods. The improvement in the retention of heat also provides favorable conditions for restart, resulting in notable reductions in the start "spikes" of both CO and UHC concentrations. The furnace cabinet was also fully insulated to reduce heat losses through the housing, especially in an outdoor installation.

Outside combustion air was provided through a sealed-air system to reduce the loss of heated humidified air from the dwelling through the burner or flue barometric control valve. The sealed-air system improves the heat loss characteristics of the dwelling, not the furnace, but the effect of utilizing cold air on the emissions performance was of great interest; therefore, it was included in the integrated furnace system experiment.

Field Verification

A field test was organized to observe the integrated furnace system under real conditions. Six Lennox Model 011-140 furnaces were modified to incorporate the features noted earlier and were installed in host residences in the Albany (NY) and Boston (MA) areas, representing continental and maritime influence climates, respectively. The test period included the two complete and consecutive heating seasons of 1977-78 and 1978-79.

Field Test Monitoring Methods

Pollutant Emissions

The pollutant emissions were monitored periodically, generally at 4- to 6-week intervals, from September through June. A mobile emissions measurement laboratory was used to measure flue gas emissions at each site; readings were recorded with the furnace operated on a 4-minute-on/8-minute-off firing cycle.

Flue gas sampling was continuous throughout the firing cycle, and average readings were recorded. Parameters which were monitored are shown in Table 1.

Table 1. *Mobile Laboratory Instrumentation*

Species	*Range*	*Measurement Method*
CO	0-1500 ppm	Infrared
CO_2	0-15%	Infrared
NO/NO_x	0-1000 ppm	Chemiluminescent
O_2	0-25%	Polarographic
UHC	0-3000 ppm	H_2 Flame Ionization
Smoke	0-9 Bacharach	Hand Pump
Temperature[a]	0-500°F	Thermometer

[a]To convert to metric units, use °C = 5/9 (°F − 32).

Furnace Efficiency

A cycle-averaged, heat-delivered/heat-input measurement scheme was devised. It is a derivative of American National Standards Institute (ANSI) Z91.1-1972, Section 6, "Performance Requirements for Oil-Powered Central Furnaces," modified to improve measurement accuracies and extended to evaluate cyclical furnace operations. The cycle-average thermal efficiency is determined by direct measurement of heat delivered to the dwelling's distribution system during the operating cycle, normalized by the amount of heat input into the furnace by the burner. The total heat output is simply determined by a cumulative measurement of warm-air weight flow rate and temperature rise during each cycle. The heat input for each cycle is derived by timing the burner during each firing and, in the subsequent data reduction procedure, by applying a period-average oil flow rate.

Two modifications to the ANSI method improved its accuracy (see Figure 2): (1) a series electrical arrangement with individual reference junctions was chosen for the nine-thermocouple-output thermal grid instead of the specified parallel arrangement, and (2) a calibrated air-flow measurement element was added for determining warm-air throughput.

A computer-controlled data logger (H/P System 3051A) was used to record the test parameters during each furnace firing cycle. A schematic of the complete monitoring system is shown in Figure 2.

Channel 1 senses burner power to determine the boundary of the firing cycle and the duration of heat input. Channel 2 senses warm-air fan power, which is only used as a signal for measurement of heat output parameters. Channel 3 is return air temperature, required for both air flow rate and temperature gain calculations. Channel 4 is a series matrix of nine thermocouples to determine average output air temperature. Channel 5 monitors maximum flue gas temperature during burner firing and is used in

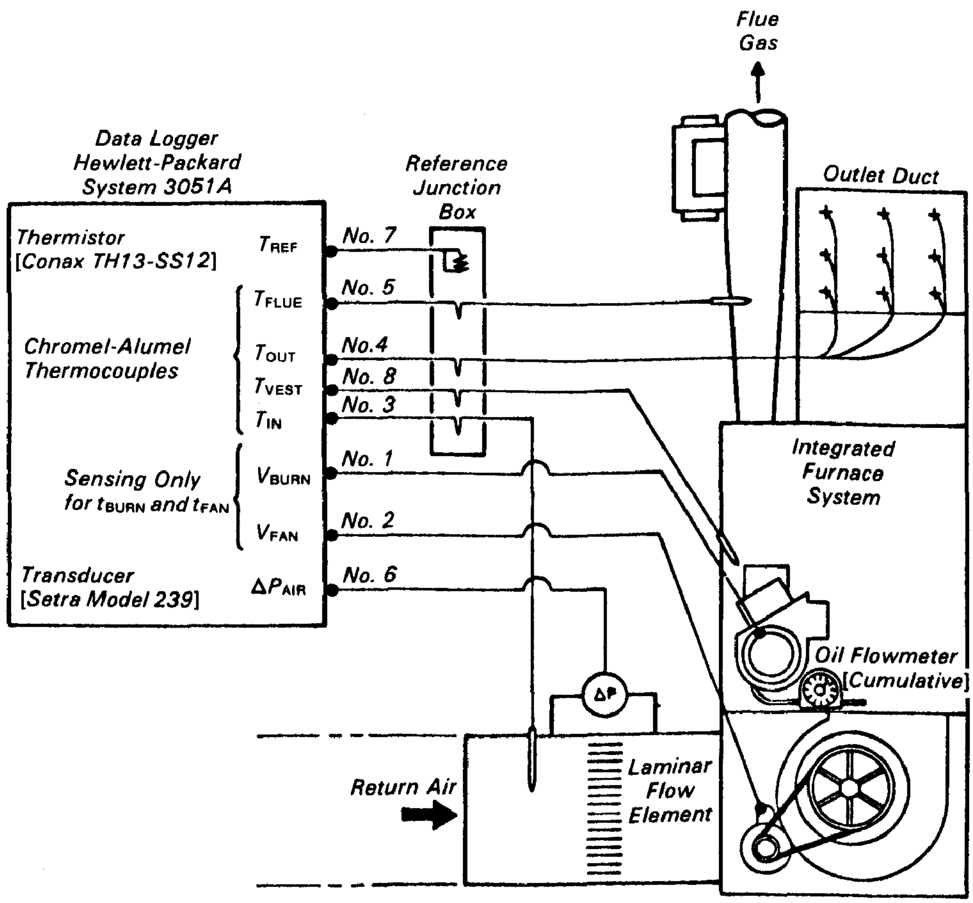

Figure 2. *Schematic of the automatic field test furnace efficiency data acquisition system.*

conjunction with Channel 8, burner inlet air temperature, for calculating a net flue gas temperature. The temperature in the reference junction enclosure is monitored by a thermistor device on Channel 7, and the resulting temperature measurement is provided as a reference junction correction for all of the thermocouple readings. Channel 6 is connected to a very low differential pressure transducer, 0 to 138 Pa (0 to 0.5 in. W.C.), which measures the pressure differential across a laminar flow element in the return air ducting. This, in conjunction with the return air temperature (Channel 3), enables the weight flow rate of heated air to be calculated. All channels are scanned every 4.5 sec; however, the measurements are retained only during their appropriate sequence in the firing cycle, thereby avoiding errors induced by accumulation of residual values.

The retained values are stored cumulatively until the next burner start is sensed which signals the end of the present firing cycle (and start of a new cycle). The appropriate calculations are executed on the stored values to result in seven values that are recorded: three on the console printer and four on magnetic tape. The printed values display current activities, presenting the updated totals of: (1) the number of firings monitored, (2) burner-on time (used for establishing average oil flow rate), (3) burner-off time. The magnetic tape records individual firing cycle information: (1) duration of firing, (2) duration of standby period, (3) total heat delivered, and (4) maximum flue gas temperature. This information enables the calculation of the heat delivery efficiency of each firing and provides precise furnace utilization information.

The primary data logger system was supplemented by cycle-time recording data loggers which accurately record the utilization of the remaining test furnaces when they are not being monitored by the primary system. This provided a complete record of utilization throughout the field test period for use in computing average operating efficiency over the entire heating system.

Table 2. *Summary of the 1977-78 and 1978-79 Integrated Furnace Field-Test Pollutant-Emission Averages*

	Test Goals	*Stoich. Ratio*	*CO g/kg*	*NO g/kg*	*UHC g/kg*	*Smoke Bacharach*
	Field Test Site	*1.20*	*≤1.00*	*≤0.65*	*≤0.100*	*≤1.0*
Boston Area	*Woodbine*	*(1.23)*[a]	*(0.70)*	*(0.688)*	*(0.064)*	*(0.6)*
		1.25	*0.67*	*0.860*	*0.051*	*1.7*
	Richard	*(1.26)*	*(0.96)*	*(0.536)*	*(0.042)*	*(0.2)*
		1.23	*0.54*	*0.794*	*0.045*	*0.6*
	Pond	*(1.23)*	*(0.55)*	*(0.584)*	*(0.039)*	*(0.4)*
		1.28	*0.68*	*0.776*	*0.044*	*0.6*
Albany Area	*Gravon*	*(1.26)*	*(0.57)*	*(0.572)*	*(0.045)*	*(0.1)*
		1.25	*0.51*	*0.764*	*0.042*	*0.6*
	Stovepipe	*(1.22)*	*(0.99)*	*(0.509)*	*(0.036)*	*(0.1)*
		1.21	*0.55*	*0.634*	*0.032*	*0.5*
	Fissette	*(1.20)*	*(1.05)*	*(0.535)*	*(0.090)*	*(0)*
		1.24	*1.12*	*0.659*	*0.071*	*0.4*

[a]*( ) 1977-78 Heating Season.*

Field Test Results

Pollutant Emissions

The experimental furnaces performed relatively trouble-free with only minor shakedown problems during the first season. Following completion of the first heating season, each furnace received a typical annual servicing, including installation of a new oil spray nozzle and line filter. Results of the monitoring are shown in Table 2, summarized by heating season.

The stoichiometric ratio was set at the beginning of each heating season very close to S.R. = 1.20 (20 percent excess air) and left unchanged through the season. Generally, the stoichiometric ratio drifted upward during the season, which appeared to be caused by slight reductions in the oil flow rate. The Woodbine and Richard furnaces were inadvertently adjusted to below design conditions early in the first season, but thereafter all units nominally maintained design stoichiometric ratio conditions.

The CO and UHC concentrations were generally well below their respective target levels. The first season averages for the Woodbine and Richard sites were biased upward by the period of mistuned operation (i.e., S.R. <1.20). The Stovepipe and Fissette furnaces had a start-up characteristic during warmer weather of producing large emissions concentration spikes at start-up, which was later related to the spark electrode position causing a slight delay in ignition. The CO and UHC emission goals were based on the average of existing furnaces, and achieving these emission goals demonstrates that NO_x control is not compromising the control of the other pollutants.

The smoke emission goal was met at all test sites during the first test period; however, in the second heating season (1978-79), there were spot shortages in the general supply of oil to the Northeast, and the oil received was not of consistent quality. Very dark colored oil, more bottom contaminants, water, etc., were occasionally noted at some of the sites, resulting in a higher-than-average smoke emission for the second season. The Woodbine site, however, was the only site that exceeded the smoke emission goal; all other sites remained well below the No. 1 Bacharach smoke scale limit.

The NO emission results shown in Table 2 show that the concentration averages during the first period were notably below the field test goal of 0.65 g/kg; only the Woodbine site averaged close to that level. A significant rise in the second season averages was recorded at all sites. Analysis of the oil at several sites revealed that some of the oil being delivered during the second season (and once at Woodbine during the first season) were significantly higher in fuel-bound nitrogen content. At these levels of concentration, conversion of fuel-nitrogen to NO_x is nearly 100 percent. The low-NO_x burner/firebox configuration influences the formation of thermal NO_x but does not impede the chemical conversion process. Nevertheless, the second season average of all six sites still accomplished nearly a 60 percent reduction in NO emissions compared to the average of existing furnaces.

Furnace Efficiency

Steady-State Efficiency

The steady-state efficiency of the integrated furnaces was measured in the field by the flue-gas loss method for purposes of general comparisons and were found to be between 83 and 84 percent (includes an assumed 2 percent cabinet loss), very close to the maximum achievable efficiency for noncondensing-flue furnace systems. These values are gross efficiency values based on the higher heating value of No. 2 fuel oil, and all efficiency values reported are computed on this basis.

Cycle-Averaged Efficiency Results

To characterize all six test furnaces, the primary data logger system monitored each furnace for a minimum of 1 month, recording more than 500 firing cycles on each furnace during each heating season. Although the monitoring periods for each test unit were at different phases of the winter season, the 24-hr/day monitoring technique resulted in measurement of a wide range of furnace utilization levels at all of the installations, from long "morning warmup" firings to short midday firings.

Preliminary evaluations of the dynamics of the standby losses showed that this effect can be characterized by some function of the ratio of total cycle time (off and on) to on-time, the inverse of furnace utilization. The measurements were analyzed statistically, using least-squares curve-fitting methods to identify the correlating parameters affecting the efficiency of the furnace in cyclical operation. An inverse form of furnace utilization produced the most consistent results in terms of the index of determination (r^2) over all six test installations. Better results were found by using cycle times based on the preceding off-time, as opposed to the following off-time, in calculating the furnace utilization parameter. Although the extraction of heat occurs in the off-period following the firing, the amount of heat extracted is controlled by an internal thermostat, essentially fixed from firing to firing. Therefore, the major difference between firings is the thermal state of the furnace at the beginning of the firing cycle, and this is determined by the standby losses in the preceding off-period.

Figures 3 and 4 show the efficiency data for the 1978-79 winter period from the Boston and Albany installations, respectively. The graph for each installation also shows the cyclical operation efficiency correlations associated with each data set. Expectations were that the performance of the six identically assembled furnaces with draft inhibitor devices would be unaffected by site variations and that an overall correlation of the entire data set could be obtained; however, as can be seen in Figures 3 and 4, performance characteristics do vary from site to site.

Although the integrated furnace design incorporates a standby draft inhibitor, the device is located on the air inlet of the burner so the furnace is not fully isolated from the flue system during off-periods and the differences in performance drop-off characteristics are believed to be caused primarily by differences in the sites' flue systems. It is interesting to note the differences in the data between the two test areas of Boston (Figure 3) and Albany (Figure 4). The Boston installations were all multistory (i.e., tall chimneys), and the Albany area installations were all one-story. The dropoff in performance with lower utilization is more significant in the taller flue installations, which supports the "flue system influence" theory. Also notable is the greater scatter in data from the taller flue installations. No significant instrumentation installation differences

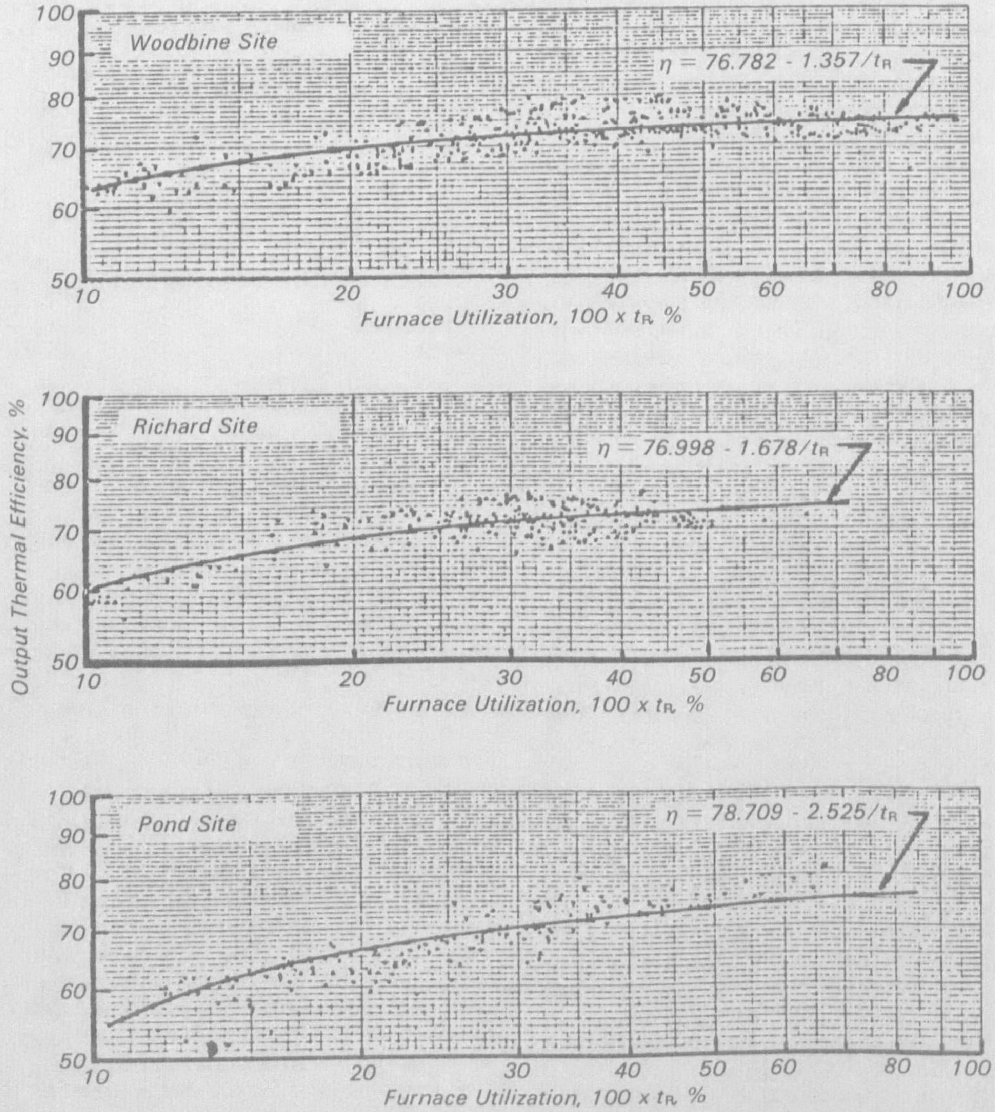

Figure 3. *Integrated furnace installed cycle-average output thermal efficiency performance as a function of utilization for the Boston-area sites.*

were noted at these sites, and it is suspected that the higher stacks, rising above the surrounding obstacles, were also more directly exposed to wind, resulting in greater fluctuations in standby losses.

As noted, all six furnaces' steady-state efficiency performances, determined by the flue gas loss method, were very close, on the order of 83 to 84 percent. The measured output efficiency data from the Albany sites (Figure 4) show close agreement; the data for all three sites appear to be approaching those values at 100 percent utilization (i.e., steady state). The measured output efficiency data from the Boston area sites generally indicate a lower steady-state output efficiency performance in the high 70 percent region, the cause of which has not been identified.

Season-Averaged Efficiency Results

The cycle time data loggers provided utilization records of all six test furnaces through the field test period. The efficiency characteristic correlations which described the performance of the furnaces as functions of utilization were applied to their respective utilization histories to determine the nominal level of performance over the winter heating season. Results of the season-averaged computations are presented in Table 3, along with furnace utilization information. The nominal operating efficiency for the integrated furnaces appears to be about 73.5 percent, well above the 60 to 65 percent level suggested earlier for existing furnaces. Very little comparative data on measured, installed efficiency on oil-fired residential furances are available; however, other investigators are

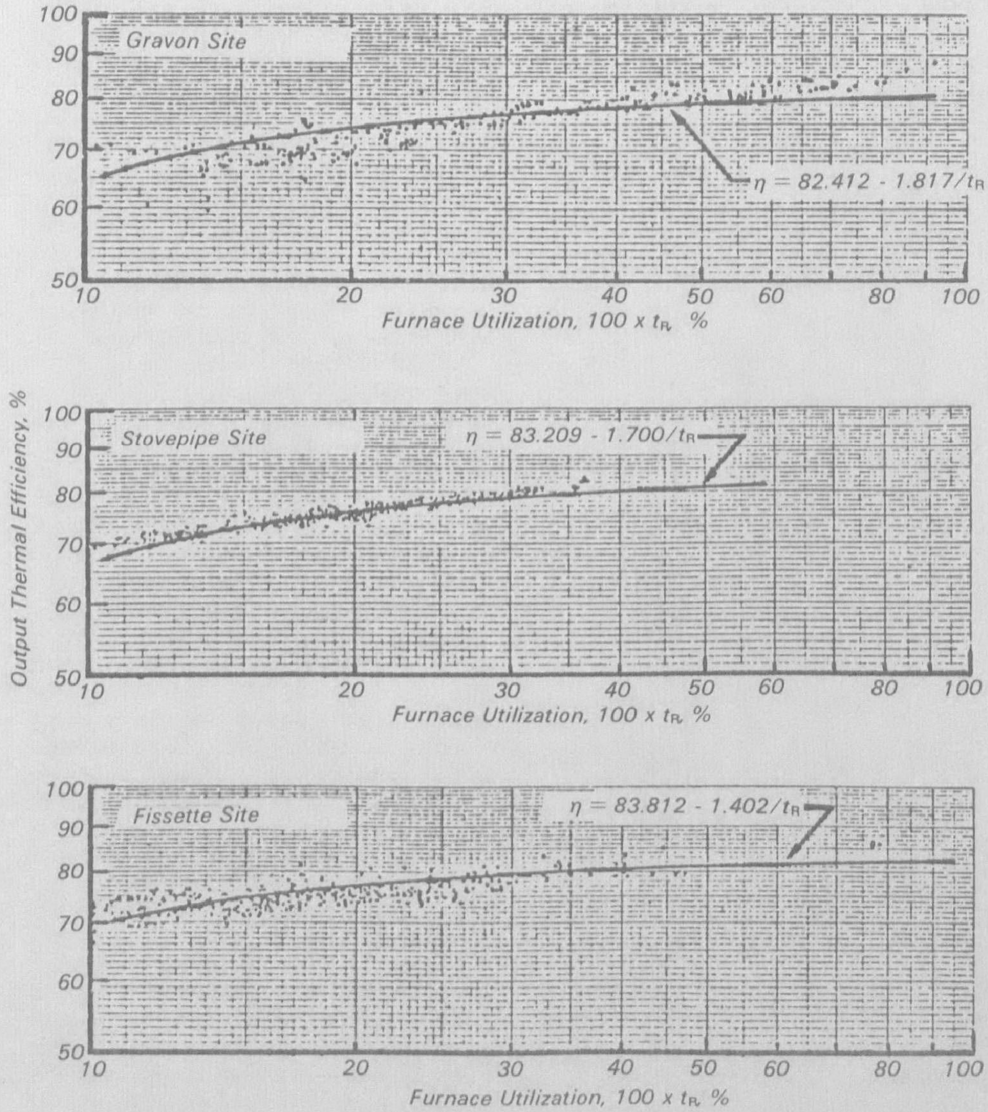

Figure 4. Integrated furnace installed cycle-average output thermal efficiency performance as a function of utilization for the Albany-area sites.

using similar methods for evaluating operating efficiency of furnaces and should provide comparative data on a wide range of furnaces.

Fuel Utilization

The sealed-air system on the integrated furnace provided unheated outside air to the burner and the flue barometric control. This eliminated the ejection of the heated indoor air to the outdoors and thus reduced heat losses from the dwelling. Although the overall performance of the furnace system is improved, the improvement cannot be determined by measurement of the heat output from the furnace. Therefore, the fuel consumption of the host dwellings was recorded (along with degree-day information) and compared with the fuel consumption history of the dwellings. This was done primarily to confirm that unanticipated losses were not being introduced by the outside air system. The normalized fuel consumption histories were simply compared with the field test results without rigorous efforts to establish exact baseline conditions. The results of the comparisons are shown in Table 4. The improvement in fuel consumption averages over 15 percent.

NBS Seasonal Performance Rating Procedure

The National Bureau of Standards (NBS) furnace performance rating procedure was also conducted on two of the integrated furnaces at their field sites for general comparison. Although the procedure is laboratory-oriented, the flue height specification of 1.52 m (5 ft) was the only significant deviation in the field from the NBS test requirements. The flue heights at the field sites were on the order of 6.1 to 9.1 m (20 to 30 ft), and this greater natural draft potential would likely lower the performance results, in comparison to a laboratory-conducted test.

The NBS procedure results are shown in Table 5, along with equivalent data (i.e., same utilization level of 22.5 percent) from the measured heat output efficiency data for the respective sites, and laboratory data that will be discussed later. Note that, in both comparisons of average seasonal efficiency performance, the NBS efficiency ratings are significantly higher than the Rockwell/EPA measurements, and also that the unit with the significantly lower measured performance (Pond site) resulted in the higher NBS rating. The primary cause of these discrepancies is the definition of "useful heat." The Rockwell/EPA method defines it as "that heat delivered to the dwelling;" while the NBS procedures assumes it to be "all heat that is not lost through the flue pipe." The NBS definition often leads to unusual calculated results, as seen in Table 5, where in both cases the average performance over the whole heating season is higher than the steady-state performance.

Supplementary Laboratory Tests

The final effort conducted in the program involved testing two of the furnaces from the field under controlled-laboratory conditions. This testing was conducted at the Rockwell facility in Canoga Park, CA. This program was aimed at: (1) obtaining laboratory data on both emissions and furnace efficiency for comparison with the previously measured field data, and (2) investigating the conversion of the integrated furnace to natural gas fuel. The two furnaces tested were from the Pond and Gravon sites.

Laboratory Fuel Oil Test Results

The two furnaces were tested in the laboratory in two conditions: (1) as received from the field after two heating seasons service, and (2) renovated to "like new" condition.

Emission Results

The same instrumentation used in the field was utilized to sample and analyze the flue gases in the laboratory tests. Results are shown in Table 6, along with field test data obtained during the final site visit to each furnace. NO emissions are notably lower in the laboratory tests because the laboratory stock of fuel oil contained lower nitrogen concentrations than the oil delivered to the sites during the later months of the field test. Results

Table 3. *Summary of Estimated Season-Averaged Thermal Efficiency Performance of the Integrated Furnaces*

Furnace Test Site	Firing Cycle Timing Data: Average Furnace Usage (t_R, %)	Firing Cycle Timing Data: Average Burner-On Time (Min)	Estimated Season Efficiency (%)
Woodbine Street MA (Unit 5)	42.4	12.8	(81.0)[a]
Richard Road MA (Unit 4)	44.7	13.3	(79.3)
Pond Avenue MA (Unit 1)	30.0	5.7	70.4
Gravon Road NY (Unit 2)	21.2	11.0	69.7
Stovepipe Road NY (Unit 6)	30.7	10.2	77.2
Fissette Drive NY (Unit 3)	31.3	10.8	75.8
	1977-78 Overall Average		73.3 (75.6)
Woodbine Street Newton, MA	38.8	13.94	71.82
Richard Road Needham, MA	22.1	9.16	70.80
Pond Avenue Brookline, MA	33.5	8.80	70.24
Gravon Drive Delmar, NY	28.4	15.10	75.63
Stovepipe Road Clarksville, NY	28.4	8.76	76.06
Fissette Drive Feura Bush, NY	22.0	6.87	76.34
	1978-79 Overall Average		73.65

[a]( ) = Fuel feed problems encountered during measurement period.

with the original laboratory oil stock show the familiar levels of NO (<0.65 g/kg) upon which field test goals were based. The CO and UHC concentrations for both furnaces remain well under the test goals of 1.00 and 0.10 g/kg, respectively.

Efficiency Measurement Results

The two furnaces were installed in the laboratory using a 1.52 m (5 ft) stack, as specified in the NBS procedure. Performance characteristics were determined for each furnace: first in the condition it was returned from the field, and then with the heat exchangers cleaned to return the configuration to a "like new" condition. Approximately 1.7 and 1.2 kg of contaminants, primarily iron oxide, were removed from the Pond and Gravon heat exchangers, respectively.

The test results are presented in Table 5. Again, the NBS rating procedure produced estimates of seasonal performance well above the Rockwell/EPA method results and, in fact, above measured steady-state efficiency. The differences between the two measurement procedures, as noted earlier, stem primarily from differences in the definition of "useful heat." The results show no reliable correlation between the two methods.

Natural Gas Conversion

Alternate fuel experiments, conducted in Phase I of this program, with the integrated furnace system included tests with natural gas. The tests used a commercially available, powered, gas burner in place of the optimized oil burner. The gas burner, a Mid-Continent (Midco) DS5850 burner, incorporated state-of-the-art features such as direct-spark ignition and solid-state electronics.

Pollutant Emissions

The furnace, a cleaned Gravon unit, was fired at an equivalent rate of 31,630 W (108,000 Btu/hr). These experiments indicated that the finned firebox extracted too much heat for natural gas/air combustion and was quenching the reaction, thus producing low-NO concentrations but unacceptable CO and UHC concentrations. Additional testing investigated if simple modification of the heat transfer characteristics of the finned firebox could improve the CO and UHC emissions to an acceptable level.

A 0.305-m (12-in.) diameter disc of Pyroflex insulation, covering about 20 percent of the inside surface of the firebox, was placed on the bottom of the combustor to inhibit heat extraction from the combustion zone. Acceptable CO and UHC concentrations were obtained at a reasonably efficient operating condition of SR ≈ 1.28; however, the NO emissions increased to approximately 1.0 g/kg, significantly higher than that of the optimized oil burner. A small disc of 0.22 m (8.5 in.) diameter, half the surface area of the first disc, was then installed in the firebox. Table 7 shows that the resultant compromise provided favorable tradeoffs, with acceptable levels of CO and UHC emissions at SR ≈ 1.28, with an approximate 30 percent reduction in NO emissions in 4-minutes-on/8-minutes-off cyclical operation. The NO emission concentrations are slightly higher than those produced by the optimized oil burner.

The results of the natural-gas-fired pollutant emission experiments demonstrated that only a very minor modification is required to achieve acceptable pollutant emissions at efficient operating conditions in converting the oil-fired integrated furnace system to natural gas. The experiments indicated that the benefits of the cooled firebox can be utilized by natural gas burners; results showed NO concentrations about 20-30 percent lower than the levels shown by earlier data.

Note that the gas burner was unmodified; additional development to match the flame characteristics to the firebox and to optimize the burner/air fuel ratio could result in even further improvement in the emissions' performance.

Efficiency Performance

The optimized, natural-gas-firing integrated furnace was then fired at its best stoichiometric ratio condition of 1.28 and at a less efficient SR condition of 1.64 to obtain information of its NBS-estimated seasonal performance ratings and its output efficiency performance characteristics.

Results of the NBS furnace rating procedure are presented in Table 8, along with

Table 4. Effect of Integrated Furnace on Fuel Oil Consumption

Test Site	Consumption History Two-Season Average (gal./D-D)[a, b]	Integrated Furnace Two-Season Average (gal./D-D)[a, b]	Net Improvement (%)
Woodbine Street Newton, MA Unit 5	0.2837	0.2284	19.5
Richard Road Needham, MA Unit 4	0.1276	0.1045	18.1
Pond Avenue Brookline, MA Unit 1	0.1244	0.1101	11.5
Gravon Drive Delmar, NY Unit 2	0.0890	0.0782	12.1
Stovepipe Road Clarksville, NY Unit 6	0.0953	0.0746	21.7
Fissette Drive Feura Bush, NY Unit 3	0.0871	0.0775	11.0
		Overall Average	15.7

[a]Degree-Day, °F-Day (reference temperature: MA = 65°F, NY = 70°F).
[b]To convert to metric units, use: 1 gal. = 3.79ℓ, and °C = 5/9(°F −32).

comparative oil-fire test data. Both steady-state and the estimated seasonal performance level decreased with the increase in excess air throughput to 77.05 and 75.22 percent, respectively, at SR = 1.64.

When fired over a range of utilization at the two selected stoichiometric ratio conditions, measurements of the thermal efficiency characteristic, the data shown in Figure 5 were obtained.

The oil-fired efficiency performance is generally slightly higher than the natural-gas-fired results by about 6 or 7 percentage points at the higher utilization levels. This is caused primarily by the higher flue gas latent-heat losses (higher water vapor content in the product gas) and, secondarily, by inhibited heat transfer resulting from the partially insulated firebox and lower reaction temperatures.

Conclusions

With the integrated furnace, a 65 percent reduction of NO emissions can be achieved and sustained in the field while maintaining control of carbonaceous pollutants.

The integrated furnace design for NO_x control is compatible with furnace features which enhance efficiency. Cycle-averaged efficiencies on the order of 70-80 percent were achieved, resulting in fuel savings of 10-15 percent. The integrated furnace design is amenable to conversion to natural-gas firing with only minor modification to the cooling characteristics of the firebox. The NBS method (NBSIR 78-1543) for determining the seasonal performance of residential furnaces produces significantly higher steady-state and cyclical efficiency values than those measures by the Rockwell/EPA method developed during this program. This is the result of heat loss assumptions incorporated into the NBS method, which tend, in some cases, to produce unrealistically high results.

Recommendations

Making available the integrated furnace technology developed during this program, to manufacturers of residential furnaces, could lead to its commercialization. Making available more information on available furnace technology to consumers could prompt market demand for more efficient low-polluting furnaces.

Table 5. Comparison of the Results of the NBS Furnace Rating Procedure for the Pond and Gravon Furnaces in the Field and in the Laboratory

System	Pond (Unit 1)			Gravon (Unit 2)		
Efficiency Performance	Field Test %	Laboratory Test %	(Cleaned HX)[a] Laboratory %	Field Test %	Laboratory Test %	(Cleaned HX)[a] Laboratory %
Steady-State Operation						
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss	-9.90	-9.30	-6.80	-9.20	-9.00	-7.60
η_{SS}	83.60	84.20	86.70	84.30	84.50	85.90
Cyclical Operation						
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss						
On	-7.50	-4.96	-4.17	-6.27	-5.29	-4.38
Off	-0.10	-0.12	-0.09	-0.1	-0.12	-0.10
$\eta_{NBS\ Seasonal}$	85.90	88.42	89.24	87.12	88.09	89.02
$\eta_{Rockwell/EPA}$[b]	65.0	65.5	70.0	73.5	73.0	70.0

[a]HX = heat exchanger.
[b]Measured Output Efficiency, Test Data at t_R = 22.5%.

Table 6. *Cycle-Averaged Pollutant Emission Concentrations from the Pond and Gravon Integrated Furnaces Tested in the Laboratory*

	Run No.	Stoic. Ratio	CO2 %	O2 %	CO ppm	NO ppm	UHC ppm	CO g/kg	NO g/kg	UHC g/kg	Bach. Smoke
2 Seasons	1	1.25	12.5	4.5	30	31	4	0.50	0.549	0.036	1.1
	2	1.24	12.6	4.4	31	30	4	0.53	0.529	0.036	1.1
SS	3	1.23	12.6	4.3	20	36	2	0.33	0.631	0.019	0.8
POND	4	1.26	12.4	4.6	31	32	4	0.53	0.571	0.038	0
Clean HX[a]	5	1.25	12.5	4.6	31	32	4	0.53	0.570	0.036	0
SS	6	1.25	12.6	4.5	20	37	2	0.33	0.655	0.019	0
	11	1.32	12.0	5.5	40	33	4	0.70	0.618	0.040	1.0
2 Seasons	12	1.32	12.0	5.6	40	32	4	0.70	0.602	0.040	1.0
SS	13	1.32	12.0	5.5	20	39	2	0.35	0.730	0.020	1.0
GRAVON	14	1.30	12.2	5.4	38	32	3	0.66	0.594	0.035	0
Clean HX[a]	15	1.31	12.2	5.5	35	31	3	0.61	0.578	0.035	0
SS	16	1.31	12.2	5.5	20	38	2	0.35	0.709	0.020	0

[a] HX = heat exchanger.

Table 7. *Pollutant Emission Concentrations from the Natural Gas-Fired Integrated Furnace with a 0.22-m Diam Insulator Installed in the Firebox in a 4-Minute-on/8-Minute-off Cyclic Operation*

Run No.	Stoic. Ratio	CO2 %	O2 %	CO ppm	NO ppm	UHC ppm	CO g/kg[a]	NO g/kg[a]	UHC g/kg[a]	Bach. Smoke	Net TFG[b] °C
54	1.41	8.1	6.4	53	45	8	0.88	0.799	0.076	0	
55	1.28	9.2	5.0	55	46	7	0.83	0.740	0.060	0	
56	1.22	9.7	4.1	105	44	6	1.50	0.672	0.049	0	
57	1.25	7.3	3.5	105	46	7	1.54	0.721	0.058	0	
58	1.07	10.1	1.5	≥1599	35	120	≥20.02	0.469	0.858	0	
59	1.22	7.5	3.2	242	43	32	3.47	0.658	0.261	0	
60	1.27	8.5	4.5	45	44	9	0.67	0.704	0.077	0	
61	1.36	8.0	5.6	39	46	11	0.62	0.790	0.101	0	
62	1.55	7.1	7.5	157	36	25	2.89	0.706	0.261	0	
63	1.68	6.4	8.4	290	30	45	5.78	0.639	0.511	0	
64	1.30	8.7	5.0	30	64	2	0.46	1.044	0.017	0	
65	1.43	7.8	6.5	85	40	9	1.43	0.722	0.087	0	179
66	1.51	7.3	7.1	95	39	7	1.69	0.743	0.071	0	189
67	1.56	7.0	7.6	115	38	10	2.13	0.753	0.106	0	198
68	1.70	6.5	8.8	167	34	35	3.38	0.735	0.404	0	
69	1.64	6.9	8.5	220	33	35	4.27	0.686	0.388	0	

[a] 1 kg = heat equivalent of 1 kg of No. 2 fuel oil.
[b] TFG = temperature, flue gas.

Table 8. *Comparison of the Results of the NBS Furnace Rating Procedure for the Gravon Furnace Fired with No. 2 Fuel Oil and with Natural Gas*

System	Oil-Fired	Natural-Gas-Fire	
Efficiency Performance	S.R. = 1.32 %	S.R. = 1.28 %	S.R. = 1.64 %
Steady-State Operation			
Latent Heat Loss	-6.50	-9.55	-9.55
Sensible Heat Loss	-6.80	-9.65	-13.40
$\bar{\eta}_{SS}$	86.70	80.80	77.05
Cyclical Operation			
Latent Heat Loss	-6.50	-9.55	-9.55
Sensible Heat Loss			
On	-4.17	-5.04	-8.43
Off	-0.09	-4.84	-6.80
$\bar{\eta}_{NBS\ Season}$	89.24	80.57	75.22
$\bar{\eta}_{Rockwell/EPA}$[a]	70.0	67.0	65.0

[a] *Measured Output Efficiency, Test Data at t_R = 22.5%.*

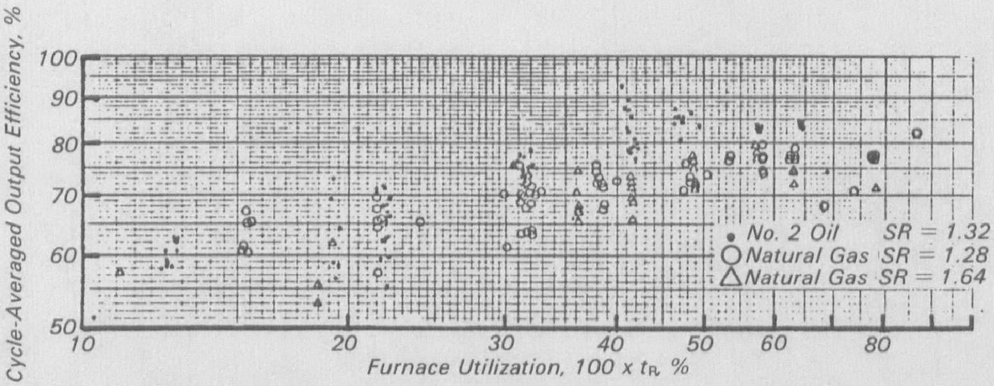

Figure 5. *Comparison of efficiency performance of oil-fired and natural-gas-fired integrated furnaces.*

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The complete report, entitled "Design Optimization and Field Verification of an Integrated Residential Furnace," (Order No. PB 84-153 246; Cost: $17.50, subject to change) will be available only from:

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