NBS BUILDING SCIENCE SERIES 163

# Potential Energy Savings in Residential Oil-Fired Heating ems in the U.S.



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ABSTRACT

Studies of the performance of residential oil-fired heating systems in the New England area from 1974-1977 demonstrated that significant energy savings are achievable through better maintenance and simple system modifications. These studies showed that annual tune-up of the furnace or boiler would improve the seasonal efficiency of most units, while considerable energy savings are possible by reducing the firing rate of the burner. Reduction in nozzle size with burner modification or with the installation of a new flame retention burner was found to reduce oil consumption substantially. In addition, more innovative equipment modifications such as the use of stack dampers, sealed combustion systems, and heat recovery devices also resulted in fuel savings, although to a lesser extent. Both experimental field data and results from computer simulations of furnace performance are presented.

Key words: Boiler; energy savings; firing rate; fuel efficiency; furnace; nozzle size; oil-fired; residential heating; sealed combustion; stack damper.

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# 1. INTRODUCTION

## 1.1 BACKGROUND

As a result of the need for greater energy conservation in buildings generated by the 1973 energy crisis, the Center for Building Technology (CBT) of the National Bureau of Standards (NBS) conducted a series of studies on the performance of residential heating and cooling systems. This research included both field studies of specific equipment modifications for improving performance and mathematical modeling for simulating dynamic and seasonal performance.

The bulk of this NBS research was sponsored by the Department of Energy (DoE) and its forerunners, the Federal Energy Office, the Federal Energy Agency, and the Energy Research and Development Administration. This research formed the part of the technical background and data base that was used by NBS to develop the DoE test and rating procedures for residential heating and cooling equipment. These procedures were mandated in the appliance labeling, energy targets, and minimum standards sections of the Energy Policy and Conservation Act (P.L. 94-163), the Energy Conservation and Production Act (P.L. 94-385), and the National Energy Conservation Policy Act (P.L. 95-619).

## 1.2 SCOPE

The present report summarizes the NBS studies of the performance of residential oil-fired heating equipment. These studies, performed between 1974 and 1978, focused on the energy performance of oil-fired furnaces and boilers used in single family residences. They were concerned with a variety of measures for improving the efficiency of these installations. Particular attention was paid to the energy savings potential of annual maintenance, equipment modifications, and the installation of add-on devices by qualified, trained personnel.

Work was conducted by a number of organizations under the direction of NBS. These included the Walden Research Division of Abcor, Inc., Honeywell, Inc. and Exxon Research and Engineering Company. The Walden Research Division performed the series of field tests [1, 2]* on residential oil-fired systems in the New England area during the winter heating seasons of 1974-75 and 1975-76. Field tests on some new innovative energy saving devices [3] were also performed by Walden during the 1976-77 heating season. The Honeywell Corporate Research Center, using data gathered in the New England field tests, used their computer model, HFLAME, to estimate seasonal efficiencies and potential energy savings analytically [4, 5]. Exxon participated in laboratory studies of furnace efficiencies under cyclic conditions [6].

In the following section, the operation of a furnace or boiler is discussed. Both steady-state and seasonal efficiency are defined, along with some of the factors affecting performance. In sections 3, 4, and 5, the results of field tests of heating systems in New England with different modifications are presented. The modifications range from simple tune-ups to reductions in

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* Numbers in brackets refer to references given in the reference section.

firing rate, to more innovative changes such as stack dampers and heat recovery devices. In addition, field results are compared with data from a computer simulation program modeling equipment performance. Conclusions are presented in section 6, with results from the various modifications indicating the possibility of significant energy savings for oil-fired residential heating equipment.

## 2. EFFICIENCY FACTORS IN RESIDENTIAL OIL-FIRED HEATING SYSTEMS

### 2.1 OVERVIEW

Subsequent sections of the present report document the results obtained from certain adjustments and modifications to oil-fired residential heating equipment. These changes were designed to improve the steady-state efficiencies and seasonal performance of the system. Both warm air and hot water systems were studied in a series of field tests. Modifications included burner adjustment and tune-up, reduction of firing rates by reducing nozzle size, reduction and modification or replacement of burners, the installation of hot water reserve storage tanks on tankless coil systems, and the use of stack dampers, sealed combustion systems and heat recovery devices. Data on the resulting changes in steady-state and seasonal efficiency are presented along with predicted data from a series of computer simulations of equipment performance. However, before presenting the results from the various studies, certain background information will be discussed in this section.

### 2.2 DETERMINATION OF STEADY-STATE AND SEASONAL EFFICIENCY

Because there exist a number of different furnace efficiency definitions, it is useful to define the meaning of the terms "seasonal efficiency" and "steady state efficiency" as they are used in this report. Seasonal efficiency is taken to be the ratio of the total useful heat delivered to the building by the heating system, as a result of the combustion process, to the total fuel energy used, over a full heating season. Steady state efficiency, on the other hand, is defined as the rate of energy input to the furnace by the fuel minus the rate at which energy is lost up the flue, divided by the rate of fuel energy input, under steady state operating conditions. The latter definition assumes that the combustion process itself is 100 percent efficient and that heat losses through the furnace jacket contribute useful heat. Because residential heating equipment operates on a cyclic basis, seasonal efficiencies are usually less than their steady state efficiencies. The losses associated with the operation of a furnace are discussed in greater detail below.

Figure 1 presents a schematic of the major components and processes common to most oil-fired systems. These form the basis for the NBS equipment performance modeling work [7, 8], and help to explain the operation of the furnace as described herein.

Several factors related to the design and operation of residential oil-fired heating equipment limit any real system from operating at 100 percent efficiency. First, for complete combustion, each fuel molecule must be in close proximity to air (oxygen) molecules. Although the typical oil burner finely atomizes the fuel and uses a blower to bring in and mix the fuel and combustion air, the combustion process is invariably less than complete, unless excess outside air is used. This excess combustion air must be heated to the flue gas temperature level, resulting in efficiency loss.

Another factor resulting in diminished efficiency is the heat lost up the chimney from the combustion by-products. Although this loss could be reduced

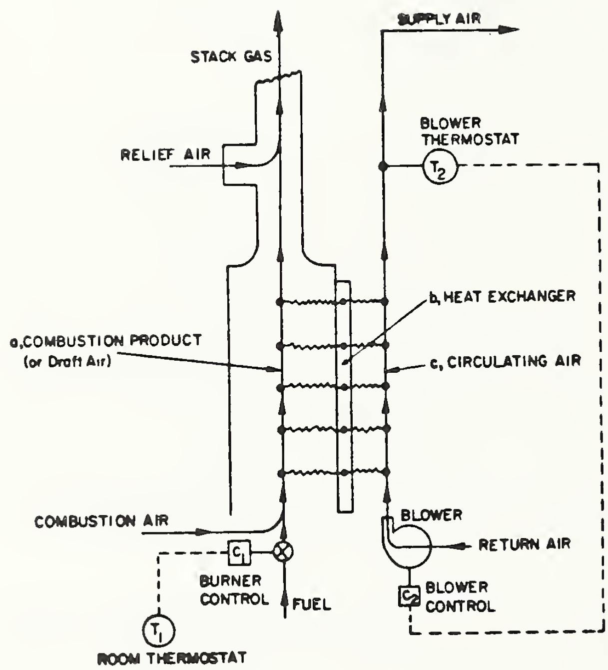


Figure 1. Schematic of furnace model

considerably by cooling the gas to room temperature, two practical limitations occur. First the use of combustion chambers at close-to-atmospheric pressure levels requires a certain flue gas temperature level above room temperature to exhaust the combustion products safely up the chimney. Secondly, certain condensables in the combustion gases, if allowed to cool, will liquify, creating severe corrosion problems.

In addition to combustion air and flue gas losses, there is usually an increase in building air infiltration due to the combustion air and the relief air required to maintain a constant draft condition in the combustion chambers. Neither this loss, nor the losses from the furnace jacket and distribution systems, are usually considered in a steady-state efficiency rating, although they are often considered in seasonal performance definitions of heating systems. However, the major factor contributing to reduced seasonal efficiency is the cyclic nature of residential heating systems. Unlike more expensive industrial equipment, residential systems do not modulate the fuel and air to meet changing load demands. Most residential systems operate either full on or full off. When heat is called for, the burner comes on at its full firing rate with combustion heat being transferred to the furnace mass itself until steady state equilibrium temperatures are reached. Once combustion stops, residual heat contained within the unit's mass continues to be transferred to any draft air flowing through the furnace and up the stack. Such draft losses can be reduced through the use of a power burner or automatic stack closure. These losses also become smaller if the percentage of off time is decreased by reducing the furnace firing rate to more closely match the heating load of the building. The effects of such modifications are discussed in subsequent sections.

Figure 2 provides a profile of changes in a typical residential furnace temperature as a function of time. Four different operational periods are identified. During the first period (burner-on/blower-off), the unit's heat exchanger is brought to a temperature level that will maintain a comfortable supply air temperature. Although a lot of the residual heat in the heat exchanger is recovered during the third period, the amount recovered usually does not completely offset the heat loss during period 1. During the second period (burner and blower both on) the blower transfers heat from the heat exchanger (which is still being heated) to the building. During the third period, the burner is shut off and the blower continues to distribute heated air to the building in an attempt to recover the residual heat of the unit's mass. The limit of this recovery process is timed so that the temperature of the supply air (water) does not result in uncomfortable space temperatures. Finally, both burner and blower are turned off. During both the third and fourth periods, the heat exchanger loses heat to the air that passes through the combustion chamber and up the chimney. The losses during the third and fourth periods described above tend to be larger if the heating unit is oversized. Since most residential furnaces in the United States tend to be at least 100 percent oversized, a large potential for energy loss exists. To reduce this loss and achieve the best seasonal efficiency for a particlar system, adjustments can be made to the furnace firing rate to match its output to the heating load of the residence.

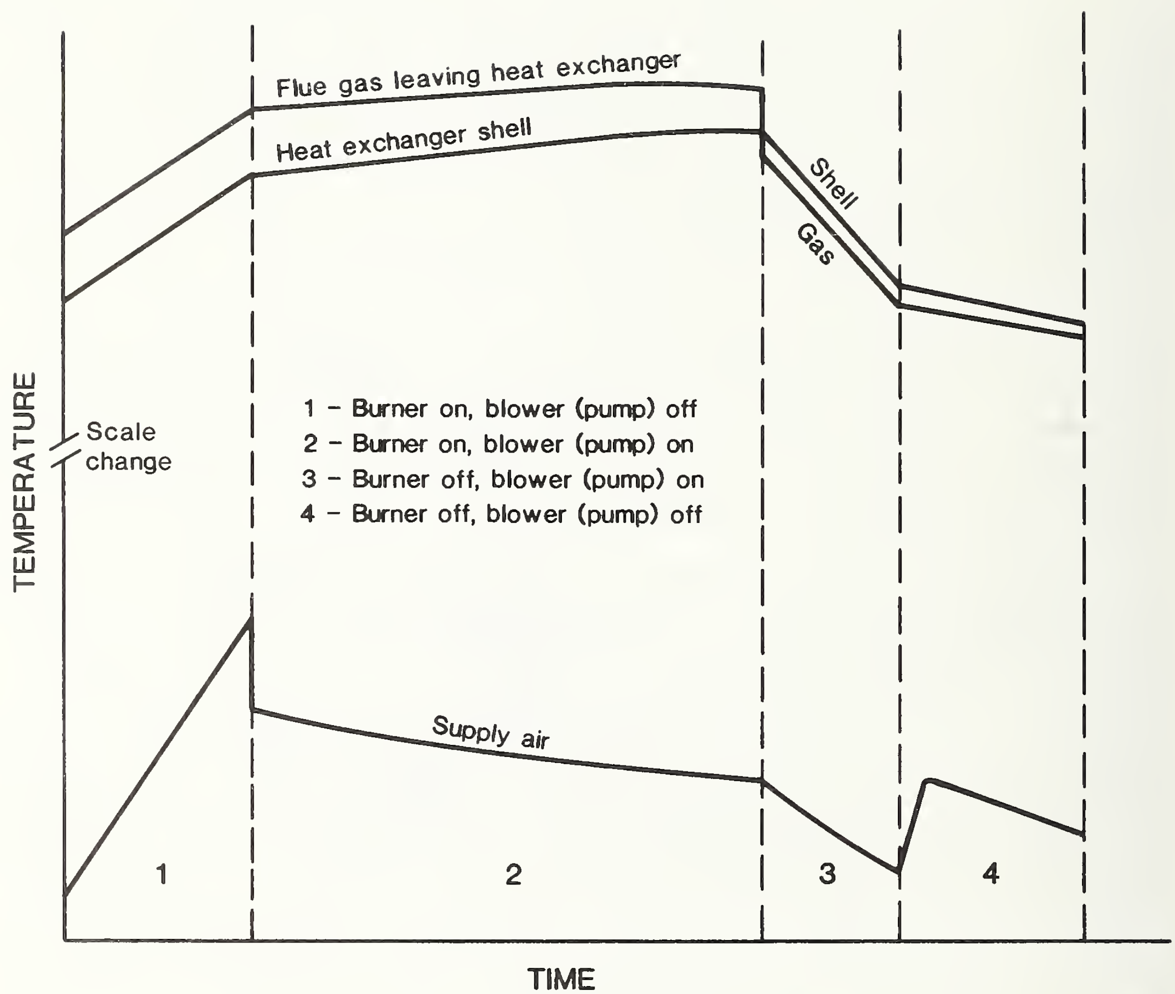


Figure 2. Temperature vs. time plots for a typical furnace

The heating load may be estimated using its K-factor, which is defined as the number of degree days occuring in a time period divided by the total number of gallons of oil consumed during the same period.

This K-factor provides a good approximation of the heating load of the residence under various conditions of outdoor temperature, wind condition, humidity, solar radiation and occupant habits. It also provides a good approximation of the seasonal efficiency of the heating system when the entire season is the time period used to determine the degree days and gallons used.

The winter K-factor can be used to calculate the minimum firing rate to minimize furnace off-period losses as follows:

$$FR = \frac{\Delta T_D}{24 \times K}$$

where FR is the firing rate of the furnace in gallons/hour and $\Delta T_D$ is the average indoor balance point temperature* minus the outdoor design temperature.

This formula assumes that the furnace output at steady-state operation matches the heating load of the residence at its greatest load (i.e., when the outdoor temperature equals the outdoor design temperature).

The use of the winter K-factor, therefore, serves as a guide toward which firing rates can be successively reduced while attempting to maintain satisfactory steady-state operation. As firing rates are reduced, the furnace efficiency should increase and the building load decrease slightly due to reduced infiltration losses. Hence, a new value for the K-factor may emerge which can become the basis for further iterations. The method for determining optimum firing rates, and the effectiveness of firing rate reduction procedures are described in subsequent sections of this report.

Several computer simulations currently exist for evaluating furnace seasonal performance and the effect of various design changes on annual energy consumption [7, 8]. One of these is HFLAME [9], developed by Honeywell Inc. This model accounts for heat loss during both the on-cycle and off-cycle mode and provides a method for predicting seasonal efficiency. It can predict the effects of excess air, flue gas temperature, off-cycle draft losses, and variations in firing rate upon seasonal efficiency. Other programs, developed at NBS, include DEPAB and DEPAF [7, 8], which simulate the operation of fossil fuel fired boilers and warm air furnaces under cyclic conditions. These programs provide a detailed time history of temperatures in the combustion chamber/stack, the heat exchanger and the heat distribution medium (air or water). These programs allow furnace efficiency to be calculated for different load and weather conditions. Estimates of building loads may also be obtained by using such load determination programs as NBSLD [11], DoE-2 [12], or BLAST [13].

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* Residential balance points are most often assumed to be 65°F (18°C); however, they can be considerably lower in well-insulated homes. See Petersen [10].

In the following sections, various modifications for improving furnace efficiency are presented. It should be noted, however, that the result of any energy saving modification is often specific to the installation and operating conditions of the individual heating system. As a result, prediction of specific energy use for one installation is somewhat risky.

# 3. EFFECTIVENESS OF TUNE-UPS ON THE PERFORMANCE OF OIL-FIRED FURNACES AND BOILERS

## 3.1 EFFECT OF ANNUAL TUNE-UPS ON STEADY-STATE EFFICIENCY

Steady-state efficiency measurements were carried out on 429 oil-fired heating systems in the New England area during the 1974-75 heating season. Interest in the steady-state efficiency of installed heating systems was promoted by the possibility that annual oil consumption in the U.S. could be reduced if heating systems were well maintained and serviced properly on an annual basis.

The tests were carried out on a rather large sample of installed units with the consent and cooperation of the homeowners. Most types of oil-fired heating systems were included in the sample, with the actual testing conducted by local heating system serice personnel and supervised by technical personnel of the Walden Research Division of Abcor. The structure of the test program and results are described below.

### 3.1.1 Field Test Measurements and Tune-Up Procedures

The sample of installed units consisted of systems that had not been tuned for approximately 1 year. The mix of types of units selected for testing is shown in table 1.

Table 1. Test Population Distribution for Field Test

| Burner Type | System Type<br>Warm Air | Hot Water | Steam |
|---|---|---|---|
| Conventional | 64 | 86 | 49 |
| Shell Head | 8 | 18 | 16 |
| Flame Retention | 17 | 65 | 31 |
| Low Pressure | 7 | 31 | 14 |
| Rotary | 9 | 8 | 6 |
| Sub-total | 105 | 208 | 116 |
| Total | | | 429 |

The distribution of units selected was based on statistical requirements, consideration of the population mix for the New England area, the availability of willing participants, and the growing use of flame retention burners.

Steady-state measurements were made on each of the 429 units before tune-up. These measurements were made by regular maintenance personnel from five oil distributors in the area. Steady-state efficiency was determined from the measurement of $CO_2$ and net stack gas temperature using a Bacharach Flue Finder efficiency chart. Following the initial steady-state efficiency measurements, the unit was adjusted and tuned to "best" operating condition by visual inspection of the burner flame and smoke readings. The following procedure was used:

- disassemble burner and clean. Change nozzle assembly if worn
- change oil filter
- lubricate draft adjustor
- vacuum clean heat exchanger, combustion area and vent pipes
- seal air leaks
- adjust draft regulator
- adjust combustion air
- change air filter on warm air systems

In addition to the tests performed by the regular service personnel, a more rigorous combustion air adjustment procedure was also performed on 25 units. This procedure was designed to assist in adjusting the ratio of excess air to obtain the highest steady state efficiency with an acceptable level of smoke. This procedure requires development of a plot of smoke as a function of $CO_2$ over a range of air settings as indicated in figure 3.

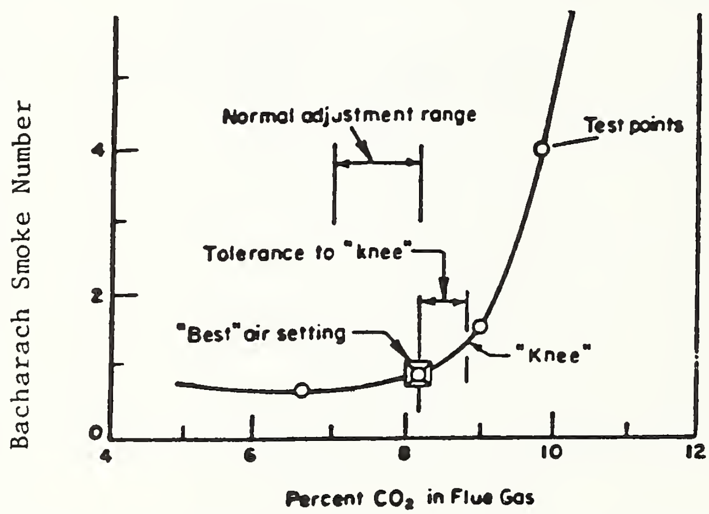


Figure 3. Typical smoke--$CO_2$ characteristics for a residential oil burner--with recommended air adjustment

The purpose of the smoke--$CO_2$ plot is to locate the "knee" of the curve (see figure 3) where the smoke number begins to rise sharply as the amount of excess air to the burner is reduced. The procedure is to adjust the air supply to a point on the curve slightly below the knee to provide a tolerance against possible shifts in the setting over time. The smoke--$CO_2$ plot can be quite effective in air adjustments provided that care is taken in obtaining the data points, and that other adjustment procedures, such as elimination of air leaks, have been carried out properly. The characteristic plot of smoke--$CO_2$ does, however, vary according to burner type, making the identification of the point of the "knee" more difficult for some types of burners.

The results of carrying out this more rigorous combustion air adjustment procedure were not conclusive because of the small number of units involved and the difficulty experienced in obtaining sufficiently smooth plots to identify the "knee" of the curve. However, on the 22 units studied, the average efficiency was increased 1.2 percent over that obtained by the simpler adjustment procedure usually employed. The average smoke number was reduced from 1.0 to 3.0. The development of a continuous-reading $CO_2$ device could facilitate the development of a more useful $CO_2$ smoke plot for field installations, and would probably be cost-effective in view of the higher efficiencies obtainable.*

### 3.1.2 Annual Tune-Up Test Results

Figures 4 and 5 show the distribution of steady-state efficiencies before and after tune-up, respectively, for the 429 units tested. The average steady-state efficiency before tune-up was 74.2 percent and 76.1 percent after. The median efficiency before tune-up was 74.8 percent and 76.5 percent after tune-up. In examining these distributions, however, it should be noted that 79.2 percent of the units were more than 70 percent efficient after tune-up. This indicates that some 40 units were brought up to a more reasonable level of steady-state efficiency as a result of tune-ups. It should also be noted that this summary data includes 14 units that were determined to be in need of replacement and could not be properly tuned.

In table 2 below, a summary of the before and after measurements for the steady-state efficiency calculation is shown.

Table 2. Summary of Efficiency Measurements

| | Before Tune-Up | After Tune-Up |
|---|---|---|
| Number of Units | 429 | 429 |
| Percent $CO_2$ | 8.2 | 8.3 |
| Net Stack Temperature | 521°F | 482°F |
| Mean Steady-State Efficiency | 74.2 | 76.1 |
| Smoke Reading | 1.9 | 0.9 |

* Since the completion of this study, a continuous reading $O_2$ and temperature instrument equipped with a microprocessor for computing $CO_2$ and efficiency has been introduced onto the market.

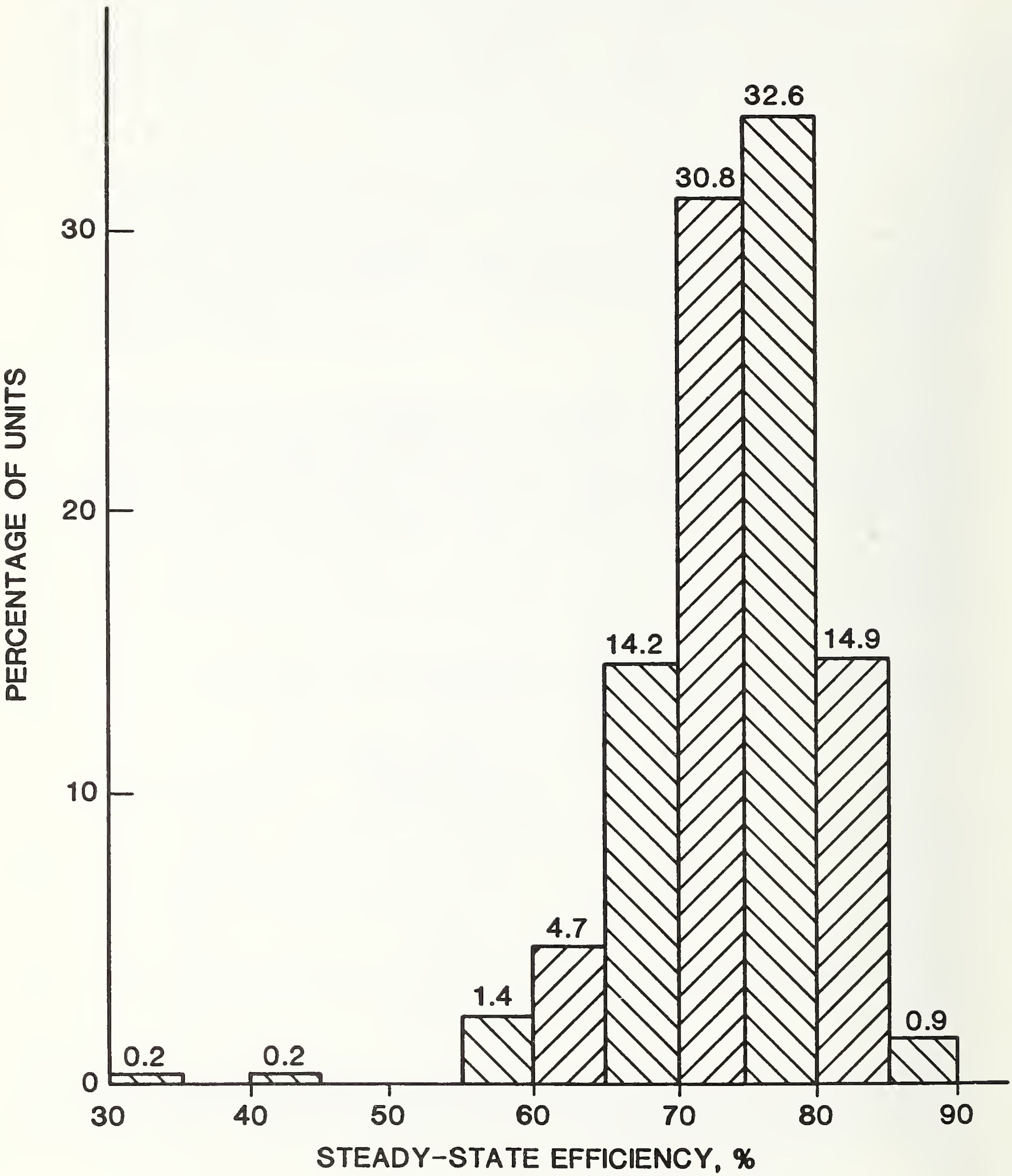


Figure 4. Distribution of efficiency before tune-up

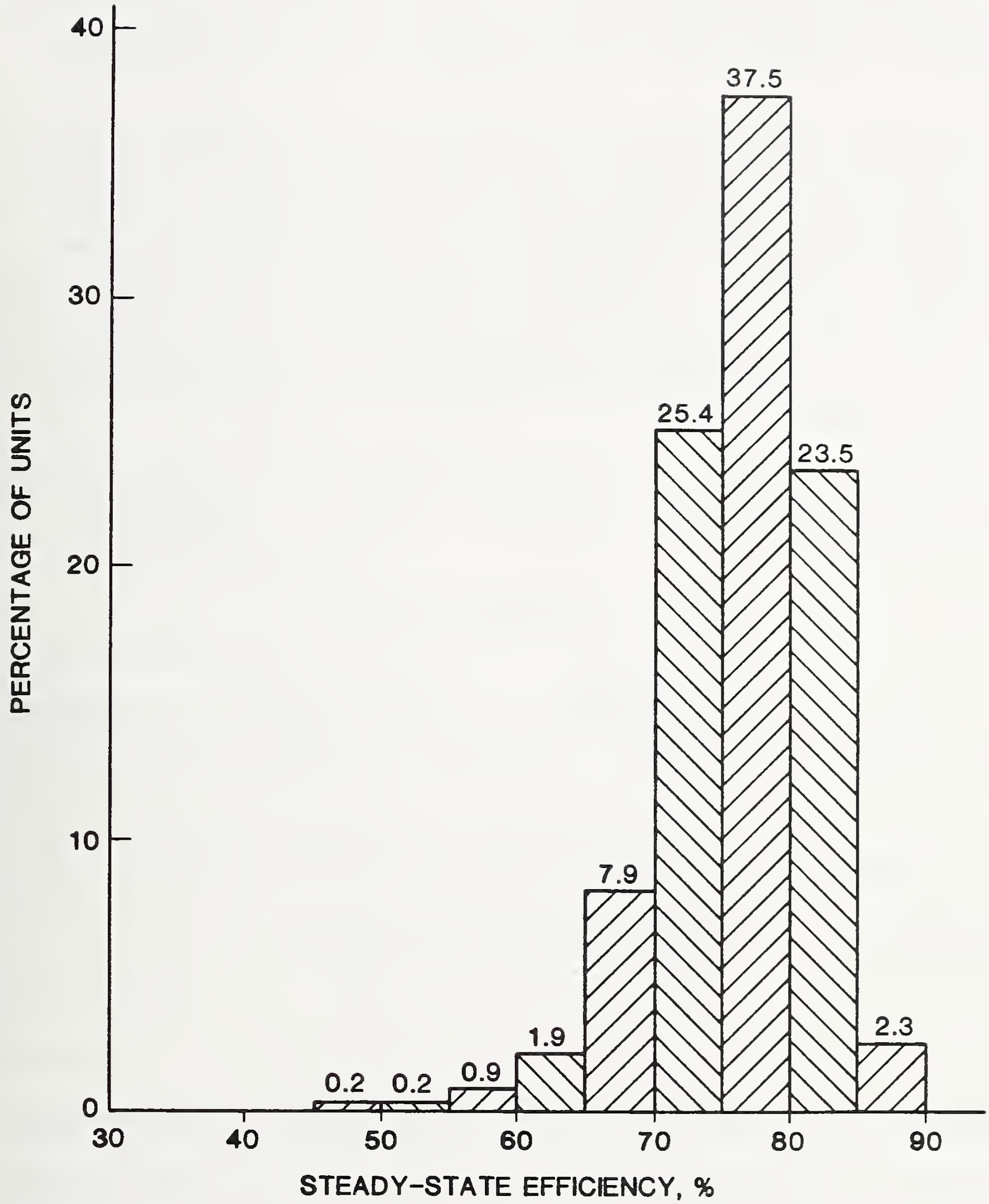


Figure 5. Distribution of efficiency after tune-up

The effect of an annual tune-up was to increase the average efficiency by about two percentage points, corresponding to a relatively small increase in $CO_2$ (0.1 percent) and small decrease in net stack temperature (39°F), as shown in table 2. The effect of reducing smoke number from 1.9 to 0.9, however, was quite dramatic.

Three months after the tune-ups had been performed, the steady-state efficiency of 183 of the original 429 units was again measured. The objective of this measurement was to determine if there had been any degradation in performance during this time period. The average efficiency of the 183 units immediately after tune-up was 76.5 percent, and the average efficiency three months later was also found to be 76.5 percent, indicating no deterioration in efficiency over a 3 month period. Although these results indicated that the units had maintained their efficiency levels for 3 months, the test performed on the original 429 units which had not been tuned-up for a year, would tend to indicated that there is likely to be some degradation in steady state performance over the entire heating season.

It is interesting to examine, at this point, the percentage of units in different regions which receive annual tune-ups. Table 3 presents the results of a summary of oil distributor service [1, 3].

Table 3. Oil Burner Service

| | Annual Overhaul Service Contract | Annual Overhaul No contract | No Annual Overhaul |
|---|---|---|---|
| New England | 37% | 45% | 18 |
| Metro New York | 54 | 21 | 25 |
| Other Mid-Atlantic | 32 | 40 | 28 |
| South Atlantic | 24 | 26 | 50 |
| Midwest | 27 | 26 | 47 |
| West | 17 | 21 | 62 |

## 3.2 DETERIORATION OF STEADY-STATE EFFICIENCY OVER A SERIES OF HEATING SEASONS

The field tests to determine efficiencies before and after tune-up on 429 units resulted in a small average increase in steady-state efficiency for this sample. However, most of the units tested were regularly maintained by the oil distributor servicemen. It is of interest to know how well steady-state efficiency is maintained over several heating seasons. In other words, are regular tune-ups important to the maintenance of good steady-state efficiencies? To determine the change of steady state efficiency with time, 57 units in the New England area that had not been tuned-up in the previous 3 years were selected for tests. The mix of heating systems selected is shown in table 4.

Table 4. Mix of Heating Systems

| Burner Type | Warm Air (System Type) | Hot Water (System Type) | Steam (System Type) |
|---|---|---|---|
| Conventional | 11 | 14 | 7 |
| Shell Head | 2 | 4 | 2 |
| Flame Retention | 3 | 4 | 4 |
| Low Pressure | 1 | 3 | 2 |

For each installation the following measurements were taken:

- $CO_2$ in dry flue gas
- $O_2$
- Draft over the fire
- Smoke number
- Net stack temperature
- Nozzle firing rate

The steady-state efficiency was calculated from the $CO_2$ concentration and the net stack temperature.

The results of these efficiency tests were compared to the measurements taken before and after tune-up on the 429 units in the 1974-75 field tests. The results are shown in table 5.

Table 5. Comparison of Serviced and Unserviced Units

| | Annually Serviced Units | | |
|---|---|---|---|
| | After Tune-Up | Before Tune-Up | Unserviced Units |
| Number of Units | 429 | 429 | 57 |
| $CO_2$ percent | 8.3 | 8.2 | 7.4 |
| Net Stack Temp. | 482°F | 521°F | 590°F |
| Steady-State Eff. | 76.1 | 74.2 | 69.9 |
| Smoke No. | 0.9 | 1.9 | 3.3 |

Unfortunately time and money did not permit the tune-up of the 57 unserviced units. However, from the types of units in this study, there is no reason to believe that a tune-up would not bring their average steady state efficiency up to the same level obtained after tune-up for the 429 units. Assuming this is correct, the data in table 5 is an indication of the general deterioration over time of all the measured parameters. This deterioration in performance is believed to result from the following factors;

- soot accumulation on the heat exchanger inhibiting efficient heat transfer
- carbonizing of the nozzle tips interfering with the atomization and spray angle of the fuel
- dust accumulation on air fans and air inlet shutter altering the air-fuel ratio.

## 3.3 VARIABLES AFFECTING STEADY-STATE EFFICIENCY

Extensive statistical analyses were performed on the steady-state efficiency data for the 429 units tested in an attempt to relate efficiencies to variables in the test population. The most significant variable, was burner type which explained 10.9 percent and 14.5 percent of the total variance in the steady-state efficiencies before and after tune-up, respectively. However, these small numbers, when compared with the small differences in average efficiencies, appear to have little practical value.

## 3.4 CONCLUSION

Regular servicing of oil-fired furnaces and boilers is essential to maintaining them at a high level of performance. The results of the field studies cited in sections 3.1 and 3.2 would tend to indicate that the average unit's steady state performance deteriorated at a rate of approximately two percentage points a year. While some units deteriorated faster than others, there does not appear to be any significant relationship between steady state efficiency (or change in steady state efficiency as a result of tune-up) and any of the variables typically used to describe a heating system (e.g., burner type, type of system, nozzle size, age, etc.).

Based upon these results, it is recommended that annual efficiency tests be carried out on all oil-fired residential heating systems. (This could be combined with a safety evaluation to assure that the units have not developed any potentially dangerous malfunctions.) A low steady state efficiency or a significant drop in steady state efficiency from previous values should be the criteria that is employed to determine if a tune-up would be cost effective.

## 4. EFFECTIVENESS OF REDUCING FIRING RATES

### 4.1 THE PROBLEM OF OVERSIZED HEATING SYSTEMS

The magnitude of the problem of oversized heating systems was determined in the New England field tests conducted during the 1975-76 heating season. For each of the 429 units tested, the magnitude of oversizing was determined by the following formulas:

$$\text{Design nozzle size} = \frac{\text{seasonal efficiency}}{\text{steady state efficiency}} \times \frac{\Delta T\ \text{design}}{24\ \text{hr/day}} \times \frac{1}{K}$$

$$\%\text{Oversized} = \left( \frac{\text{actual nozzle size}}{\text{design nozzle size}} - 1 \right) \times 100$$

where

the design nozzle size = nozzle firing rate (in gph) required to meet the heating load of the house at the outdoor design temperature

K = average winter K-factor in degree days per gallon determined from the oil supplier's record

$\Delta T$ design* = (indoor temperature - outdoor design temperature)

seasonal efficiency = assumed value of 60 percent

steady-state efficiency = unit's measured steady-state efficiency

Based upon the above, it was found that of the 429 units tested, 416 or 97 percent** were oversized with respect to the design heating requirement of the building and that the average oversizing was 168 percent. Figure 6 shows the distribution of the 429 units according to the percentage of oversized units.

Statistical analysis of the data showed that:

- the larger the heating system, the more likely it will be oversized,
- hot water systems are more likely to be oversized than warm air systems, but steam systems are more likely to be oversized than either of these.
- Oversizing appears to be an industry-wide phenomenon regardless of the oil distributer.

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* Note that this definition of $\Delta T$ design differs slightly from the definition of $\Delta T_D$ given previously.

** Actually, a more detailed look at some of the units which were supposedly under-sized or properly-sized revealed that almost all of these units were really oversized and that the oil supplier had underestimated the K-factors for these installations.

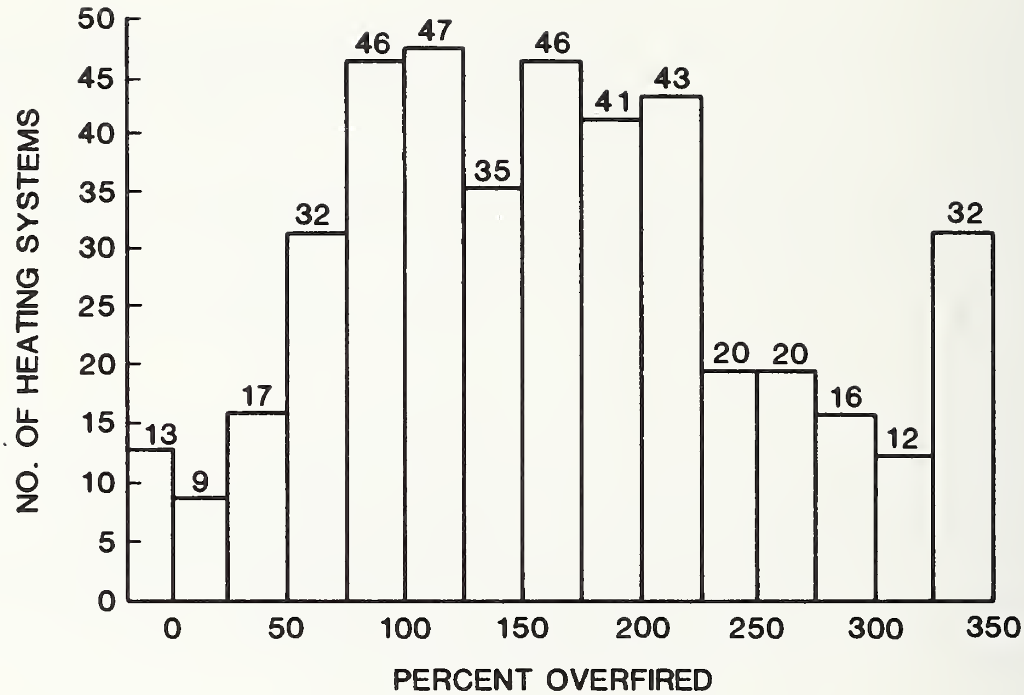


Figure 6. Frequency distribution of percentage of oversized units

Another study of 40 units, in which the oversizing was determined from measured values of on-time, daily average outdoor temperature, and average indoor temperature, resulted in an average oversizing of 208 percent. When the oversizing was calculated for these same units using the oil supplier's K-factors and the so-called properly-sized or under-sized units were eliminated, the average calculated oversizing was 200 percent and the average measured oversizing (based on actual on-time) was 218 percent. This indicates that given the correct K-factor, the formulas presented above give reasonably good results for determining which units are oversized and by what percent they are oversized.

## 4.2 GUIDELINES FOR OPTIMIZING NOZZLE SIZE REDUCTIONS

While the above findings provide a measure of the magnitude of the problem of oversizing, they do not provide any information on the degree of reduction in oversizing which can realistically be achieved in the field or on the potential energy savings of such reductions. While it might in theory be desirable to adjust the firing rate on all field installations to make them properly sized or just slightly over-sized, in practice a reduction in firing rate will usually alter other design factors, such as air-fuel ratio or heat transfer of the heat exchanger, which may be only partially correctable, or perhaps correctable at only a prohibitive cost. This section deals with these aspects as they relate to reductions in nozzle size, while section 4.3 addresses the benefits of combining simple burner modifications with nozzle size reductions.

Initial attempts to reduce nozzle sizes on furnaces and boilers in the New England field tests quickly demonstrated the interactive effects of various furnace design factors on both steady-state and seasonal efficiency. Therefore, field tests were carried out during the 1974-75 heating season to develop sound procedures (see appendix) for reducing nozzle firing rates in order to achieve the best seasonal fuel savings considering the cost of modifications to the heating system. The effect of nozzle size reductions on steady-state parameters was observed in the steady-state data collected for 27 units before and after nozzle size reductions were carried out. The average values before and after were:

| | % $CO_2$ | Net Stack Temperature | Smoke No. | Steady-State Efficiency |
|---|---|---|---|---|
| Before Nozzle Reductions | 8.2 | 533°F | 0.8 | 73.6 |
| After Nozzle Reductions | 7.5 | 472°F | 1.0 | 75.2 |

The observed reduction in average net stack temperature is to be expected, based on the reduction in heat flow rate through the combustion chamber. This reduction in temperature is responsible for the average increase in steady-state efficiency, in spite of the increase in excess air as shown by the $CO_2$ readings. A more detailed analysis of the steady-state data demonstrated the importance of reducing excess air when nozzle size is reduced. Fuel savings for those units where the percent $CO_2$ was actually decreased amounted to 1.8 percent, compared to 7.8 percent savings for those units where the percent $CO_2$ was maintained at the same level or increased. Excess air, therefore, is one of the major parameters which must be watched when nozzle air reductions are undertaken. Procedures for reducing firing rates must address the problem of adjusting the equipment to minimize excess air, while at the same time, assuring that the combustion efficiency is not adversely affected by excessive firing rate reductions which result in a mismatch between the burner flame and the size and/or shape of the combustion chamber.

## 4.3 FUEL SAVINGS RESULTING FROM COMBINING NOZZLE SIZE REDUCTION WITH BURNER MODIFICATIONS

### 4.3.1 The New England Field Tests

Extensive firing rate reductions were carried out on 36 overfired heating systems in the New England area during the 1975-76 heating season. These tests were an extension of the 1974-75 heating season tests to evaluate the energy savings of various firing rate reduction procedures. The 1974-75 tests, as discussed in the previous section, involved reducing the nozzle size and adjusting excess air without making any modifications to the burner, the combustion air handling equipment, or the combustion chamber. The objective of the 1975-76 heating season tests was to evaluate the fuel savings resulting from the following modification procedures:

- nozzle size reduction accompanied by modifications to combustion air handling equipment and/or the combustion chamber as necessary

- installation of new burners with reduced firing rate

- addition of domestic hot water reserve storage tanks plus reduced firing rates on hot water heating systems employing tankless coils to supply domestic hot water.

The mix of the 36 heating systems selected for these tests is shown in table 6.

Table 6. Type of Equipment in 1975-76 Test

| | Heat System Type | |
|---|---|---|
| Burner Type | Warm Air | Hot Water |
| Conventional | 8 | 12 |
| Shell Type | 1 | 2 |
| Flame Retention | 3 | 9 |
| Low Pressure | 0 | 1 |

The field measurements were made by Walden Corp. technicians, with local oil burner servicemen performing the actual modifications to the equipment.

Steady-state and dynamic operating parameters were measured both before and after the firing rate reductions and modifications were carried out.

The steady-state measurements included:

- Percent of $CO_2$ in dry flue gas
- Net stack temperature
- Draft over the fire
- Smoke number
- Firing rate in gallons per hour from which steady-state efficiencies were calculated.

The dynamic measurements included:

- Electrical usage of auxiliary equipment
- On and off-times
- Warm-up and cool-down flue gas temperature profiles
- Indoor temperature, 24 hour average
- Outdoor temperature, 24 hour average*
- Wind speed, 24 hour average*
- Solar radiation, daily average*.

The measured on-times and firing rate was used along with the outdoor temperature data to calculate the K-factor before and after each modification. The fuel savings resulting from each modification was then determined using:

$$\text{fuel savings} = 100\left(\frac{\dfrac{1}{K\ \text{initial}} - \dfrac{1}{K\ \text{final}}}{\dfrac{1}{K\ \text{initial}}}\right)$$

In addition, under contract, Honeywell Inc. used their HFLAME (see section 3) model to determine the estimated seasonnal efficiencies before and after a change. The results are described in the following sections.

### 4.3.2 Reduced Firing Rates with Burner Modifications

Firing rate reductions were carried out on 18 of the 36 units in the test program. The study was performed in two phases. In the first phase, the minimum firing rate that provided satisfactory combustion wihout modifying the combustion air handling equipment was determined. In the second phase, the smallest firing rate that provided satisfactory combustion with modified air handling equipment was determined. These tests provided a comparison for evaluating the effectiveness of air handling equipment modifications. The comparison is shown in table 7, which shows the minimum firing rate achieved with and without air handling equipment modifications.

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* The outdoor temperature, wind speed, and solar radiation were measured at several centrally located weather stations.

Table 7. Effectiveness of Combustion Air Handling Equipment Modifications

| System No. | Minimum Nozzle Size (without air Mod's) | Minimum Nozzle Size (with air Mod's) |
|---|---|---|
| 4 | 1.20 gal/hr | 1.00 gal/hr |
| 5 | 1.10 | 0.75 |
| 7 | 1.10 | 0.85 |
| 8 | -- | 0.85 |
| 11 | 1.10 | 0.75 |
| 15 | 1.00 | 0.85 |
| 19 | 1.75 | 1.35 |
| 20 | 1.10 | 1.00 |
| 21 | 1.10 | 0.85 |
| 22 | 1.20 | 1.00 |
| 23 | 0.90 | 0.65 |
| 24 | -- | 0.85 |
| 25 | 1.20 | 0.85 |
| 29* | 1.10 | 0.85 |
| 34 | 1.10 | 0.50 |
| 35 | 1.00 | 0.60 |
| 37* | 1.50 | 1.10 |
| 38 | 0.85 | 0.50 |
| Average | 1.14 | 0.84 |

* Combustion chamber liners were also installed on units 29 and 37 as a part of the air handling equipment modification because both units could not achieve the reduced firing rate criteria due to inadequate combustion chamber design.

The nozzle size reductions in the first column amounted to an average 14.5 percent reduction in firing rate from the original nozzle size. The corresponding average reduction in firing rate with air handling equipment modifications was 36 percent.

The combustion air handling equipment modifications were necessarily tailored to the type of burner as follows:

Conventional High Pressure Gun Type

Installed flame retention end cones or available modernization kits to improve the blast tube--air cone configuration.

Flame Retention Burners

Installed the appropriately sized end cone for the reduced nozzle size.

Shell Type Burners

Adjusted the primary air control ring which serves as a vacuum breaker inside the cone.

Modification of the combustion air handling equipment allowed the percentage of excess air to be maintained or decreased as the firing rate was reduced. This resulted in an increase in the steady-state efficiency, a longer burner on-time, and an improved seasonal efficiency. The effect on these parameters is shown in table 8.

As indicated in table 8, firing rate reductions with burner modifications resulted in an average increase in the steady-state efficiencies of 10.7 percent. The average decrease in excess air was 1.4 percent, with a range of a 55.8 percent reduction to a 15.5 percent increase in excess air. The increase in excess air occurred on unit number 35, which had a very high initial $CO_2$ reading of 13 percent which produced excessive smoke (5 on the Bacharach smoke scale). It was necessary to reduce the $CO_2$ to 10 percent during the modification procedure to minimize this smoke problem.

The significant finding to note in table 8 is that fuel consumption was reduced in all units. The fuel savings, as determined from the HFLAME model using the dynamic test data as input, averaged 14.0 percent, which shows good agreement with the 14.5 percent savings determined for the 10 day test period after rates were reduced.

The relative change in seasonal fuel savings, steady-state efficiency, excess air, and firing rate as a function of burner type is shown in table 9.

Table 8. Change in Performance from Reduced Firing Rates and Burner Modifications

| Unit No. | Steady-State Eff. Increase % | Excess Air Reduction % | Firing Rate Reduction % | Fuel Savings % 10-day Experiment | Fuel Savings % Predicted by HFLAME |
|---|---|---|---|---|---|
| 4 | 8.6 | 0 | 39.3 | 18.7 | 22.9 |
| 5 | 11.4 | 24.3 | 50.7 | 17.8 | 20.6 |
| 7 | 7.0 | 13.6 | 31.8 | 9.6 | 8.5 |
| 8 | 15.8 | 23.2 | 48.4 | 18.2 | 19.7 |
| 11 | 9.6 | 11.9 | 43.2 | 7.6 | 13.2 |
| 15 | 2.9 | 0 | 29.3 | 10.6 | 5.6 |
| 19 | 0.9 | (15.4 increase) | 25.1 | 8.6 | 6.2 |
| 20 | 3.4 | 0 | 30.2 | 5.8 | 10.7 |
| 21 | 10.0 | 0 | 30.9 | 17.0 | 11.1 |
| 22 | 4.3 | 0 | 25.6 | 9.2 | 3.8 |
| 23 | 19.1 | 0 | 39.6 | 22.7 | 21.8 |
| 24 | 27.2 | 24.2 | 29.2 | 19.6 | 21.0 |
| 25 | 5.3 | 12.9 | 28.1 | 11.3 | 5.6 |
| 29 | 0.6 | 12.5 | 29.6 | 9.5 | 1.3 |
| 34 | 17.0 | 0 | 64.6 | 22.1 | 22.6 |
| 35 | 7.9 | (15.5 decrease) | 55.8 | 11.8 | 13.8 |
| 37 | 21.9 | (32.9 increase) | 55.8 | 11.8 | 13.8 |
| 38 | 19.2 | 55.8 | 40.7 | 16.2 | 24.6 |
| Average Change | 10.7 | 1.4 | 36.0 | 14.5 | 14.0 |

Table 9. Change in Performance by Burner Type

| Burner Type | No. of Units | Steady-State Eff. Increase | Excess Air Decrease | Firing Rate Reduction | Fuel Consumption Decrease* |
|---|---|---|---|---|---|
| Conventional | 10 | 12.7% | 9.6% | 36.9% | 14.7% |
| Shell Head | 1 | 2.9 | 0 | 29.3 | 5.6 |
| Flame Retention | 7 | 8.9 | (17.3 increase) | 41.3 | 14.2 |

Conventional burners showed the greatest increase in steady-state efficiency, with an average reduction in fuel consumption of 14.7 percent. Although conventional burners are difficult to modify for improved burner air handling, their relatively poorer condition and greater age offer significant potential for improvement. Shell type burners offer limited possibility for air adjustment (adjustment of the primary air control ring) and the one unit tested showed a fuel savings of only 5.6 percent. Flame retention burners facilitate relatively large reductions in firing rates due to the flexibility and ease in modifying the air handling characteristics of these burners by simply changing flame retention rings. The seven flame retention units tested showed an average fuel savings of 14.2 percent.

### 4.3.3 Reduced Firing Rates with New Burners

Installation of a new burner in a heating system is a major alteration which costs considerably more than the modifications covered in the previous section. The choice of the type of replacement burner involves consideration of not only the size and range of the burner, but also the physical configuration of the burner and the costs of mounting, rerouting electrical service, compliance with fire codes, required modifications to the combustion chamber, etc. In practice, the decision by the homeowner to replace a bad burner is often based on economy, i.e., will the estimated fuel savings provide a reasonable payback period for the cost of replacing the burner? In the tests described herein, the criteria for selecting burners to be replaced were first developed. Then the new burners were installed and the firing rates reduced. Finally, the fuel savings was determined by comparing the fuel consumption during two ten day periods before and after each burner replacement and by using the computer simulation model, HFLAME. In this section, the criteria for burner replacement and subsequent fuel savings are presented.

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* Based on 10 day test period before and after burner modification.

The criteria for selecting burners for replacement were as follows:

- Low Combustion Efficiency

  If the steady-state efficiency after adjustment and tune-up could not be raised above 60 percent, the burner should probably be replaced. Three units were selected on this basis.

- High Smoke Levels

  If the steady-state efficiency after adjustment and tune-up is between 60 and 70 percent with a smoke number in excess of 3 on the Bacharach scale, the burner should probably be replaced. Two units met this criterion.

- Inability to Reduce Firing Rate

  If the reduced firing rate procedure results in shifting to larger and larger nozzle sizes until the original nozzle size was again reached, the burner should probably be replaced. Five units were selected on this basis.

After installation of a new burner, the procedures for calculating minimum nozzle size and determining the minimum acceptable nozzle size based on $CO_2$ level and steady-state efficiency were essentially the same as described in the previous sections.

New burners were installed on 10 units and the steady-state and dynamic data were measured as for the other firing rate reduction tests. Data for only seven of the units are presented here because the large distortions exhibited in the data from three units resulted in unrealistic values for fuel consumption. The distortions in the results appeared to be due to weather factors which could not be accounted for in either the manual or simulation model (HFLAME) analytical procedures.

Table 10 shows the changes in steady-state parameters and fuel consumption for the seven units.

As expected, all units showed an increase in steady-state efficiency and reduction in excess air as the firing rates were reduced. Again, as in the previous section, the fuel savings calculated by the HFLAME model using the 10-day dynamic measurements, corresponded quite closely to the fuel savings calculated during the 10-day experimental run. The average firing rate reduction achievable was 42.8 percent and the average fuel savings measured was 29.2 percent, with a range of 44.8 to 14.2 percent. The fuel savings did not appear to be dependent on the criteria used for deciding on burner replacement. These results indicate that replacing bad burners while also reducing firing rate offers significant potential for fuel savings.

Table 10. Change in Performance with New Burners

| Unit No. | Steady-State Eff. Increase % | Excess Air Reduction % | Firing Rate Reduction % | Fuel Savings % 10-day Experiment | Fuel Savings % Predicted by HFLAME |
|---|---|---|---|---|---|
| 1 | 28.4 | 32.8 | 40.5 | 21.6 | 43.1 |
| 2 | 54.5 | 66.7 | 44.9 | 38.1 | 36.4 |
| 6 | 18.9 | 41.2 | 42.7 | 28.7 | 31.0 |
| 9 | 14.2 | 23.1 | 37.6 | 14.2 | 14.0 |
| 27 | 45.4 | 83.7 | 49.6 | 44.8 | 38.5 |
| 31 | 15.1 | 32.6 | 37.7 | 18.3 | 23.7 |
| 36 | 24.2 | 83.7 | 46.9 | 38.5 | 25.9 |
| Average | 28.7 | 52.0 | 42.8 | 29.2 | 30.4 |

### 4.3.4 Tankless Coil Hot Water Systems

The 1975-76 heating season field study also involved eight hot water systems which provided domestic hot water by means of tankless coils located within the heat exchanger of the furnace. Demand for domestic hot water caused the burner to come on, irrespective of the demand for heat and prevented the firing rate from being reduced by any significant amount. Reserve storage tanks were installed to satisfy the demand for hot water, while the firing rate of the system was reduced to more nearly match the heating load of the residence. The change in performance of the eight boilers is shown in table 11.

Firing rate reductions averaging 33.6 percent were successfully carried out on all eight systems. It had been shown in previous field tests that firing rates of at least 1.25 gallons per hour are necessary to provide enough hot water for typical households with systems having tankless coils. The installation of the reserve hot water tanks permitted lowering of the minimum firing rate while still providing sufficient hot water for a typical household. As noted from table 11, the firing rate reductions for the eight systems ranged from 9.4 to 52.0 percent. The data demonstrate again, as in the previous firing rate reduction studies, that if excess air can be reduced with a consequent increase in steady-state efficiency, then seasonal fuel savings will be realized. The fuel savings measured during the tests averaged 13.4 percent, while that predicted by HFLAME was 12.4 percent.

It should be noted that the fuel savings determined in these tests was for the heating season only. Since domestic hot water is required year-round, it is probable that reduced firing rates would also cause a reduction in fuel consumption during the summer months. This possibility was not, however, investigated in the field program. Moreover, the effects of reducing the boiler water

Table 11. Change in Performance of Hot Water Systems with the Installation of Reserve Storage Tanks and Reduction in Firing Rates

| Unit No. | Steady-State Eff. Increase % | Excess Air Reduction % | Firing Rate Reduction % | Fuel Savings % Experiment | Fuel Savings % HFLAME |
|---|---|---|---|---|---|
| 10 | 1.7 | 0 | 9.4 | 7.5 | 3.9 |
| 12 | 8.2 | 33.8 | 31.8 | 6.5 | 14.6 |
| 13 | 8.2 | 0 | 40.2 | 6.4 | 18.2 |
| 14 | 3.2 | 34.4 | 33.1 | 41.0 | 6.1 |
| 16 | 9.2 | 0 | 52.0 | 1.1 | 16.7 |
| 17 | 12.9 | 13.6 | 28.3 | 10.4 | 16.2 |
| 26 | 12.6 | 15.2 | 42.7 | 34.2 | 21.7 |
| 30 | 0.2 | 79.5 (Increase) | 31.4 | 0 | 1.4 |
| Average | 7.0 | 2.2 | 33.6 | 13.4 | 12.4 |

temperature, and the role of piping and tank insulation is critical and would have to be carefully investigated in any future study to determine the effect of this modification on summer fuel consumption.

While the installation of reserve storage tanks accompanied by reduced firing rates resulted in heating season fuel savings, the modification costs are considerably higher than for other modifications proposed. The higher costs and the uncertainty of summer fuel savings currently leave these modifications in question.

5. EFFECTIVENESS OF HEATING EQUIPMENT MODIFICATIONS

## 5.1 ADDITIONAL FIELD TESTS

### 5.1.1 Objective and Scope of Tests

A third field study was carried out on a mix of steam, hot water, and warm air heating systems in the New England area during the 1976-77 heating system to determine the potential fuel savings of several innovative technologies. Among the new technologies investigated were:

- Stack dampers to close off the stack when the furnace is not firing and thereby reduce the flow of warm air from the heat exchanger and draft control device going up the stack during off-periods.

- Sealed combustion systems in which outside air is piped directly to the furnace to provide air for combustion and draft control. This incoming air may or may not be preheated by the exiting flue gases.

- Heat recovery devices to reclaim heat from the hot stack gases for use in combustion air, or in direct heating of the residential space.

The three devices discussed above were studied in a variety of combinations. The objective of the tests was to determine the seasonal fuel savings that could be achieved by measuring fuel consumption before and after the modifications to the existing heating systems. A brief description of the innovative devices tested and the test procedures employed are given below.

### 5.1.2 Description of Modifications

#### 5.1.2.1 Stack Dampers

A stack damper is an automatically activated valve that can be readily installed downstream from the draft control device on existing fossil fuel-fired heating equipment. Its purpose is to reduce off-cycle convective flue loss and minimize the contribution of chimney flow to building infiltration. Two types of electrically activated automatic stack dampers, having slightly different operating modes, were evaluated in this study.

One of the models tested was spring-loaded in the open position and activated to the closed position by de-energizing the burner controls. The unit used a 2.5 $\pm$ 1 minute delay in closing the damper after burner shutdown to allow for the evacuation of residual combustion products. When a call for heat occurred, the gear motor was de-energized and the coiled spring drove the damper to the open position. When the heat demand was satisfied, the burner controls were de-energized and the gear motor drove the damper to the closed position. If power to the unit was disrupted for any reason, the damper would spring open. This operation, when coupled with the burner operating switch, functioned as a fail-safe mechanism. A later modification, which was not included on the test units, included optional 3/4" knockouts in the damper to help alleviate potential odor problems.

The second type of automatic vent damper studied was a power-open/power close device. It consisted of two primary components: the damper assembly and the control box. The control box, which contained all of the necessary controls, was mechanically connected to the cast aluminum casing and stainless steel damper and shaft. The control assembly was activated when the burner controls were energized so that a high torque gear motor rotated the damper to a fully open position. This caused a microswitch and relay to complete the burner circuit and allow the burner to fire. When the heat demand was satisfied, the burner control was de-energized and the gear motor drove the damper plate to the closed position, at which time the motor stopped. This unit incorporated a 15 second delay mechanism to allow for the evacuation of residual combustion products. Unlike the first model, which completely covered the stack cross-sectional area (with the exception of the new knockouts), the second model covered approximately 80 percent of the cross-sectional area thus allowing continuous low flow exhaust of the flue products.

#### 5.1.2.2 Sealed Combustion Systems

With the exception of the mobile home market, sealed combustion systems were not, at the time of this study, in general use in the U.S. Nevertheless, such systems offer the potential for reducing heating system losses. In sealed combustion systems, outdoor air is piped directly to the furnace to provide air for combustion and barometric draft control. By piping air directly from outside the residence, two sources of potential heat loss are reduced. During the on-period, the air infiltration into the residence, caused by replacing the vented, heated flue gases, is reduced. During off-cycle, the convective flow of air from inside the residence through the heat exchanger and draft control device is eliminated. The extraction of heat from the warm heat exchanger during the off-period may, however, be increased, since this heat loss depends upon a difference in temperature and outdoor air is considerably colder than inside air. In addition, the use of cold outdoor air for combustion air reduces the overall efficiency of the combustion/heat exchanger process during the on-period. Part of the purpose of this study was to bypass these conflicting theories and actually measure the fuel savings from the installation of several sealed combustion systems on existing oil-fired furnaces and boilers.

The sealed combustion systems employed in the program were designed and fabricated by Walden personnel since no commercially available units could be adapted to the unique configurations required at each residence. A total of nine sealed combustion systems were installed, of which six incorporated a preheat device which transferred heat from the flue gases to the incoming combustion and draft control air by means of heat pipes. Outdoor air was passed through a window pane via a smoke pipe to the barometric damper and burner. A sheet metal Tee was used to bring the combustion air to a sealed metal box surrounding the burner.

A pre-installation survey was required to measure the overall dimensions of the burner, the size of a window, the distance from the window to the barometric draft regulator, the distance from the barometric draft regulator to the burner, and stack pipe diameter.

#### 5.1.2.3 Heat Recovery Devices

Flue gas heat reclaimers recover waste heat from flue or stack gases through the process of heat exchange. They can vary from simple air-to-air heat exchangers to heat pipes, which use a vaporizing-condensing fluid to transfer heat from the flue to a supply air stream. The performance of three heat pipe units and one air-to-air heat exchanger were analyzed in this study.

The heat pipe heat-recovery device is designed with four or five heat pipes which are individually charged with a suitable transfer media and permanently sealed. Heat from the flue gas evaporates the liquid in the heat pipes, and the vapor flows to the other end of the pipe (room air or supply air), where the lower temperature causes the vapor to condense. A wick transports the fluid back to the evaporator end to complete the cycle. Since the method takes advantage of the latent heat of vaporization, a relatively high rate of heat transfer can be expected. For the units studied, the condenser end of the pipes was located within a circular duct that housed a fan, which was activated by a thermostat to move air over the heat transfer unit. The temperature sensor was located within the housing of the device so that the fan was controlled by the temperature of the air after it was heated by the heat pipe heat exchanger.

The air-to-air heat reclaimer was a homemade device designed for the residence in which it was installed. It consisted of 3/4 inch electrical conduit, each about 12" long, mounted in two flanges which were covered with shrouds. A fan drew room air into the shroud and conduits, and then distributed the heated air via ducts to the living space.

### 5.1.3 Field Test Procedures

Measurement of the steady-state operating parameters and dynamic flue gas temperature rise and decay profiles were gathered on 21 selected residential oil-fired heating installations. Fuel consumption and weather information was obtained for test periods, which were at least 10 days long, before and after installation of the vent dampers. The rate of fuel consumed by each residence was monitored in the following manner:

1) The oil flow rate to the nozzle tip was determined at each installation by connecting an oil-filled graduated cylinder to the burner pump inlet and measuring the oil flow for a limited time period. A two minute start-up was provided prior to measurement to allow for stabilization of oil flow rates.

2) The on-off cycling rate was monitored for each 10 day period with a voltage recorder connected across the power supply to the burner. The strip chart records were later digitized to obtain the daily burner operating time and the number of burner operating cycles.

3) Indoor house temperature was monitored with circular temperature recorders to note any disturbances to the normal routine and to provide daily average indoor temperatures.

4) Outdoor weather data (daily temperature, wind speed, and insolation) were obtained throughout the measurement period at three meterological stations located within the test region.

These data were then used to calculate daily K-factors for each 24-hour period using the equation:

$$K = \frac{(65° - \text{average outdoor temp. in 24-hour period}) \times 60 \text{ min/hr}}{(\text{total burner on-time in minutes in 24-hour period}) \times \text{nozzle flow rate in gal/hr}}$$

The average K-factor for each test period was then determined. Days which were overtly nonrepresentative of the average conditions existing during a test period were excluded. The determination of the days to be excluded was based upon records kept by the homeowner, meterological data and indoor temperature measurements. Days were excluded only when it was obvious that something extraordinary had happened (e.g., a homeowner went on vacation and lowered his thermostat setting).

The experimental fuel savings attributable to each modification was then determined using the formula:

$$\% \text{ fuel savings} = 100\left(\frac{\frac{1}{K_1} - \frac{1}{K_2}}{\frac{1}{K_1}}\right) = 100\left(\frac{K_2 - K_1}{K_2}\right)$$

where $K_1$ and $K_2$ are the average K-factor for the test periods before and after a modification, respectively.

5.1.4 NBS-Developed Calculation Procedure

The use of the above procedure for determining the fuel savings resulting from a furnace or boiler modification depends upon the existence of similar heating loads and weather conditions during the before and after test periods. In order to remove these effects and to generalize the results to weather conditions and installation practices which are more typical of the nation as a whole, some of the field results were also analyzed using procedures recommended by the National Bureau of Standards for determining the seasonal performance of residential central furnaces and boilers [14, 15].

The above mentioned procedures formed the basis for the test procedures published by the Department of Energy in the Federal Register, Vol. 43, No. 91, May 10, 1978. These are currently used by manufacturers of residential furnaces and boilers to test and rate their appliances. The test procedures require carrying out the following four tasks: 1) measuring the flue gas temperature and $CO_2$ concentration during steady-state operation, 2) obtaining data on the shape of the flue gas temperature-vs-time curves as the unit cools down and warms up from steady-state conditions, 3) assigning appropriate values to various factors which describe the off-period air flow rates through the flue and stack, and 4) carrying out a step-by-step calculation procedure to determine the various on-period and off-period losses and seasonal efficiency of a furnace or boiler.

The information for tasks 1) and 2) was measured during the field study, while the factors assigned in task 3) were the values (recommended in reference 2) for units equipped with power burners, barometric draft control devices, and installed with or without automatic vent dampers. The part-load efficiency of all the units was calculated for the average weather and oversize load conditions which existed during the test period. These results were then used to predict the energy savings resulting from the installation of automatic stack dampers and sealed combustion systems, which were then compared with the measured energy savings. In addition, the energy savings for these two devices for conditions corresponding to an average national climate was also determined, based upon the assumption that each furnace or boiler was oversized by 70 percent at an average outdoor design temperature of 5°F (-15°C).

To predict the heat reclaimed by the heat recovery devices and the percent increase in seasonal efficiency attributable to these devices, a simulation model was developed and employed by Walden [3]. The model used the results of tests performed on each unit, together with weather information, to predict the heat reclaimed over the entire heating season. Although the values used for the initial seasonal efficiencies were approximate, the percent increase in seasonal efficiency attributable to the heat reclaimer was relatively insensitive to the exact value used.

## 5.2 EFFECTIVENESS OF STACK DAMPERS

As a result of the installation of 21 automatic vent dampers, the average experimental fuel savings during the test period attributable to these devices was found to be 6.5 percent. The predicted fuel savings during the same period was 6.2 percent. The predicted fuel utilization efficiency averaged 69.9 percent in the test period prior to the modification and 74.4 percent in the test period with the vent damper functioning. Table 12 provides a summary of the individual fuel utilization efficiencies and the fuel savings based on both the experimental determination and the NBS calculation procedure. Excluding unit 14, which had a wide variation in average outdoor temperature between the before and after test periods, a regression analysis of the paired data (experimental vs. predicted model results) yields a correlation coefficient of 0.862.

Since the predicted and measured fuel savings during the test periods were in such good agreement, the calculation procedure was used to find the expected annual fuel savings for an average U.S. climate. An average annual fuel savings of 8.2 percent was calculated based upon the assumption that all units were 70 percent oversized.

As shown in table 13a, installations with the power-open/power-close dampers had average measured and predicted fuel savings for the test periods of 6.1 and 5.3 percent, respectively, whereas installations with the spring-loaded damper test had average measured and predicted fuel savings during the test period of 7.7 and 9.1 percent, respectively. The average seasonal fuel savings associated with the installation of the power-open/power-close dampers and the spring loaded dampers were predicted to be 7.5 and 10.5 percent, respectively, when based on an average U.S. climate and a 70 percent oversizing factor.

Table 12. Fuel Savings Resulting from the Installation of Motorized Stack Dampers

| Unit | Predicted Fuel Utilization Efficiency for Test Period[1] (%) | | Fuel Savings Prediction for Test Period[1] (%) | Experimentally Determined Fuel Savings (%) | Seasonal Fuel Utilization Efficiency for Average U.S. Climate[2] (%) | | Predicted Seasonal Fuel Savings for Average U.S. Climate[2] (%) |
|---|---|---|---|---|---|---|---|
| | As Found | With Stack Damper | | | As Found | With Stack Damper | |
| 1 | 65.2 | 75.4 | 13.5 | 10.0 | 67.9 | 74.8 | 9.2 |
| 2 | 72.4 | 77.0 | 6.0 | 7.8 | 72.1 | 76.5 | 5.8 |
| 3 | 64.2 | 69.7 | 7.9 | 5.3 | 64.5 | 69.2 | 6.8 |
| 4 | 55.6 | 62.6 | 11.2 | 12.5 | 53.9 | 64.0 | 15.8 |
| 5 | 70.3 | 73.5 | 4.4 | 2.2 | 67.4 | 74.5 | 9.5 |
| 6 | 63.7 | 67.2 | 5.2 | 4.6 | 63.6 | 67.9 | 6.3 |
| 7 | 62.0 | 67.6 | 8.3 | 8.6 | 60.6 | 68.2 | 11.1 |
| 8 | 69.3 | 71.5 | 3.1 | 5.7 | 65.6 | 70.6 | 7.1 |
| 9 | 61.4 | 63.7 | 3.6 | 5.6 | 58.1 | 63.8 | 8.9 |
| 10 | 75.1 | 77.0 | 2.5 | 3.5 | 73.7 | 77.8 | 5.3 |
| 11 | 70.7 | 72.9 | 3.0 | 3.4 | 68.3 | 76.6 | 10.8 |
| 12 | 75.9 | 78.7 | 3.6 | 3.5 | 77.0 | 82.8 | 7.0 |
| 14 | 75.4 | 77.1 | 2.2[3] | 8.9[3] | 75.8 | 81.0 | 6.4 |
| 15 | 63.2 | 70.8 | 10.7 | 8.6 | 60.7 | 70.2 | 13.5 |
| 16 | 82.2 | 83.7 | 1.8 | 2.4 | 83.1 | 86.7 | 4.1 |
| 17 | 80.4 | 81.2 | 1.0 | 5.3 | 78.3 | 83.3 | 6.0 |
| 18 | 66.3 | 73.7 | 10.0 | 9.5 | 65.8 | 73.9 | 11.0 |
| 20 | 59.7 | 68.3 | 12.6 | 11.2 | 62.9 | 69.7 | 9.8 |
| 21 | 79.8 | 82.1 | 2.8 | 3.2 | 78.5 | 83.9 | 6.4 |
| 22 | 81.6 | 85.7 | 4.8 | 6.2 | 82.2 | 86.2 | 4.6 |
| 23 | 73.0 | 82.4 | 11.4 | 8.1 | 75.6 | 81.6 | 7.4 |
| Avg. | 69.9 | 74.4 | 6.2 | 6.5 | 69.3 | 75.4 | 8.2 |

[1] Predicted by the NBS calculation procedure using average measured values of outdoor temperature, indoor temperature, and on-and off-cycle times for test periods.

[2] Predicted by the NBS calculation procedure using an average U.S. climate and assuming that all units were oversized by 70 percent at an outdoor design temperature of 5°F (-15°C).

[3] For this unit the average outdoor temperatures during the before and after test periods were considerably different. This tends to explain the large discrepancy between measured and predicted fuel savings.

Table 13. Fuel Savings as a Function of Equipment Type

13a. Fuel Savings as a Function of Damper Type

| Damper Type | Number of Units | Fuel Savings for Test Periods (%) Experimental Data | Fuel Savings for Test Periods (%) NBS Procedure | Predicted Seasonal Fuel Savings for Average U.S. Climate[1] (%) |
|---|---|---|---|---|
| Power open/power close | 16 | 6.1 | 5.3 | 7.5 |
| Spring Loaded | 5 | 7.7 | 9.1 | 10.5 |

13b. Fuel Savings as a Function of System Type

| System Type | Number of Units | Fuel Savings for Test Periods (%) Experimental Data | Fuel Savings for Test Periods (%) NBS Procedure | Predicted Seasonal Fuel Savings for Average U.S. Climate[1] (%) |
|---|---|---|---|---|
| Steam | 6 | 8.9 | 8.7 | 10.3 |
| Forced Hot Water | 9 | 5.9 | 6.8 | 8.0 |
| Forced Warm Air | 7 | 4.7[2] | 2.7[2] | 6.5 |

13c. Fuel Savings as a Function of Burner Type

| Burner Type | Number of Units | Fuel Savings for Test Periods (%) Experimental Data | Fuel Savings for Test Periods (%) NBS Procedure | Predicted Seasonal Fuel Savings for Average U.S. Climate[1] (%) |
|---|---|---|---|---|
| Flame Retention | 8 | 6.5 | 6.8 | 7.5 |
| Conventional | 13 | 6.5 | 5.8 | 8.7 |

[1] Predicted by the NBS calculation procedure using an average U.S. climate and assuming that all units were oversized by 70 percent at an outdoor design temperature of 5°F (-15°C).

[2] Excluding unit 14, the average experimental and predicted fuel savings for forced warm air systems during the test period were 4.0 and 2.8 percent, respectively.

The slightly lower fuel savings associated with the power-open/power-close damper could be due to longer off-cycle convective losses, since the damper plate did not completely cover the stack area. The spring loaded units, operating with a post-purge period to evacuate combustion products, employed a damper plate that effectively covered the stack area and thus eliminated most off-cycle convective losses. However, odors caused by unburned hydrocarbons might be more likely to occur with this latter type of automatic damper. Perhaps as a result of this, the spring-loaded dampers are now being produced with knockout holes in the damper plate to eliminate odors.

Similarly, it was found that the fuel savings also varied as a function of the heating plant configuration, as shown in table 13b. The average measured and predicted fuel savings resulting from the installation of automatic vent dampers was highest for steam boilers, somewhat lower for forced hot water boilers, and lowest for warm air furnaces. Warm air furnaces operate with a low, purgeable thermal mass so that off-cycle heat transfer from the heat exchanger is smaller and more rapid. Boilers, however, function with a large stored thermal mass, so that off-cycle heat transfer is continuous and more substantial.

It was thought that the burner type might affect the fuel savings potential of automatic vent dampers; however, this was not evident from the results of this field study (see table 13c). The average measured fuel savings resulting from the installation of automatic vent dampers on units with flame retention burners and units with conventional burners was the same, 6.5 percent. It was expected that automatic vent dampers might produce greater fuel savings in heating plants with conventional burners than in heating plants with flame retention burners. This expectation was based upon the belief that the combustion head on a flame retention burner might tend to choke the air stream at the air tube outlet, thereby reducing the off-cycle convective flue flow. However from the results of this study alone, it is not clear whether other factors such as stack height, boiler/furnace configuration, heating plant type, or other unmeasured parameters may have played a more significant role in the determination of relative fuel savings which could overwhelm the effect of burner type.

Information was also obtained from this field test on problems associated with the installation and operation of automatic vent dampers on oil-fired heating equipment. It was found that the proper installation of these devices is critical to the long-term, maintenance-free, and safe operation. Old or partially deteriorated flue pipes cannot support the additional weight of the damper assembly, and should be replaced with new flue pipe, securely fastened with sheet metal screws and firmly supported with wire or perforated metal strapping ceiling loops. Under cyclic operation, the flue pipe and damper assembly were found to resettle due to contraction and expansion which caused a shifting of the damper plate alignment. If, during the installation, the flue pipe and damper assembly were not securely supported, the likelihood of "no heat" calls was significantly increased. During the field study, six service calls were required to release damper plates that hung up on the flue pipe. Table 14 summarizes the operational problems encountered in this study that were associated with the automatic stack dampers. These were all the result of inadequate installation procedures.

Table 14. Installation and Operational Problem Associated with Motorized Stack Dampers

| Unit | Odor Problems | Other Problems | Comments |
|---|---|---|---|
| 1 | No | Yes - smoke pipe collapsed as a result of weight of stack damper. | Supported flue from ceiling, strengthened flue pipe with sheet metal screws. Continued to operate damper after test. |
| 2 | Yes - severe | Yes - insulation on stack damper motor control leads melted and burned out damper transformer | Drilled holes and cut ends of damper plate, dropped barometric damper below flue pipe, installed solenoid on oil line. Disconnected damper after test due to odor problem |
| 3 | Yes - slight | No | Disconnected damper after test due to odor problem |
| 4 | Yes - slight | No | Continued to operate damper after test |
| 5 | Yes - moderate | No | Disconnected damper after test due to odor problem |
| 6 | No | Yes - control relay field, damper plate hung up on flue pipe | Continued to operate damper after test |
| 7 | No | No | |
| 8 | No | Yes - damper plate hung up on fire pipe | Continued to operate damper after test |
| 9 | No | Yes - damper plate hung up on flue pipe. | Smoke pipe strengthened with sheet metal screws and supported flue from ceiling. Continued to operate damper after test |
| 10 | Yes - moderate | No | Installed solenoid in oil line. Disconnected damper after test due to odor problem |
| 11 | No | No | Continued to operate damper after test |
| 12 | No | No | Continued to operate damper after test |
| 13 | Yes - severe | Yes - damper plate hung up on flue pipe | Disconnected damper after test due to odor problem |
| 14 | Yes - slight | No | Dropped barometric damper, sealed flue pipe and leaks. Disconnected damper after test due to odor problem |
| 15 | Yes - very slight | Yes - damper plate hung up on flue pipe | Continued to operate damper after test |
| 16 | Yes - very slight | No | Continued to operate damper after test |
| 17 | No | No | Continued to operate damper after test |
| 18 | Yes - moderate | No | Disconnected damper after test due to odor problem |
| 19 | Yes - moderate. | No | Installed solenoid on oil line, sealed smoke pipe. Disconnected damper due to odor problem, test discontinued |
| 20 | No | No | Continued to operate damper after test |
| 21 | No | Yes - damper plate hung up on flue pipe and casting | Disconnected damper after test at owner's request |
| 22 | No | No | Continued to operate damper after test |
| 23 | No | No | Continued to operate damper after test |

In addition to problems associated with the installation of automatic vent dampers, certain operational concerns developed during the program. Two electrical failures occurred; one resulting from motor control leads shorting out, which in turn burned out the damper transformer, and one failure of the control relay. But more significantly, following installation of the stack dampers, 11 residences experienced some level of odor ranging from very slight traces to severe, noxious odors. Ultimately, eight out of the 23 stack dampers initially installed were disconnected or removed due to odor problems which could not be eliminated and two of these eight disconnections resulted in incompleted tests.

It is believed that the odor is caused by oil in the nozzle and jet tube expanding from the heat of the combustion chamber after burner shut-down. The oil then drips out of the nozzle and into the hot chamber, where it vaporizes and produces unburned hydrocarbons. Since the draft has been significantly reduced or entirely removed by the motorized stack damper, the natural escape route up the chimney is closed off. The unburnt hydrocarbons then escape out of any hole, especially the draft regulator.*

A portable hydrocarbon analyzer was employed in the field to ascertain the particular locations in the heating system where leaks occurred. The primary sources of leaks were the barometric damper, the connection between the flue pipe and boiler/furnace, and any obvious holes or loose seams. Several attempts were made to eliminate or at least reduce the odor. The first procedure entailed patching all visible leaks with furnace cement and asbestos rope. Partial success was encountered with this procedure. The second method was to modify the draft regulator positioning by adding a 2-foot extension and droping the regulator below the flue pipe. No change was noticeable from this alteration. Finally, solenoid valves were installed on the oil line to interrupt the oil flow to the nozzle when power to the burner ceased. Again, this was not overly successful.

## 5.3 EFFECTIVENESS OF SEALED COMBUSTION SYSTEMS

The experimental field data and NBS predicted values for the fuel savings resulting from the installation of nine sealed combustion systems showed poor correlation. The results are presented in table 15. Unit No. 7 was excluded from the average because of the large unaccountable discrepancy between predicted and experimental data.

Extreme variations in the estimated seasonal fuel savings were generally obtained for both the predicted and experimentally determined fuel savings. These discrepancies resulted from unique characteristics inherent in each calculation procedure. In the case of the experimental data, if similar test parameters (in particular, outdoor temperature and indoor temperature) were maintained during the before and after test periods and if these parameters

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* Since the completion of this study, it has been common practice to install solenoid valves in the fuel line to the burner, with the installation of the stack damper, to immediately stop the fuel flow when the damper closes.

Table 15. Summary of Fuel Savings for Sealed Combustion Systems

| Unit | Preheat Unit | Fuel Savings Predicted for Test Period (%) | Experimentally Determined Fuel Savings (%) |
|---|---|---|---|
| 2 | Yes | 4.4 | -11.5 |
| 4 | No | -1.6 | -2.2 |
| 5 | Yes | 10.7 | 1.4 |
| *7 | Yes | -11.5 | 30.6 |
| 8 | Yes | 5.6 | 9.4 |
| 9 | No | 1.9 | 11.7 |
| 14 | No | 5.4 | 11.0 |
| 16 | Yes | 4.3 | 4.5 |
| 17 | Yes | 6.1 | -9.6 |
| Average | | 4.6 | 1.8 |

* Not included in average

were typical of winter conditions, then the experimentally determined fuel savings based upon the before and after measured K - factors tend to provide a good approximation of seasonal fuel savings. This required that similar heating loads be experienced during the two test periods. In the NBS tests, however, outdoor temperature variations of 20°F or more occurred for the two test periods. Hence, the fuel savings predictions based on the measured K-factors may really reflect significant differences in seasonal efficiency of the furnaces or boilers under different heating loads and not the effect of installing a sealed combustion system.

In addition, the large variations shown between the experimental fuel savings and the NBS model predictions may be due to the off-cycle air flow rates. Tracer gas measurements on two sealed combustion systems showed flue and stack volumetric flow rates vastly different from those for units without sealed combustion. Thus, the validity of the air-flow rate factors used in the NBS prediction procedure may be questionable for sealed combustion systems. For these reasons, little confidence can be placed on the data in table 15 predicting fuel savings attributable to sealed combustion systems. Further field and laboratory testing of these types of systems should be carried out.

Table 16. Summary of Fuel Savings for Sealed Combustion Systems and Stack Dampers

| Unit | Preheat Unit | Fuel Savings Predicted for Test Period (%) | Experimentally Determined Fuel Savings (%) |
|---|---|---|---|
| 2 | Yes | 11.3 | -10.2 |
| 4 | No | 12.0 | 13.0 |
| 5 | Yes | 12.6 | 2.2 |
| 7 | Yes | 10.9 | 8.6 |
| 8 | Yes | 10.1 | 12.8 |
| 9 | No | 7.8 | 12.2 |
| 14 | No | 6.6 | 20.2 |
| 16 | Yes | 6.2 | 4.6 |
| 17 | Yes | 7.1 | 6.6 |
| Average | | 9.4 | 7.8 |

## 5.4 EFFECTIVENESS OF COMBINED STACK DAMPERS AND SEALED COMBUSTION SYSTEMS

As shown in table 16, the measured and predicted average fuel savings resulting from the use of sealed combustion systems and stack dampers were found to be 7.8 percent and 9.4 percent, respectively.

While these average savings are in fair agreement and appear reasonable, it is likely that this is due to the large savings resulting from the use of stack dampers. The same problems that arose with the determination of seasonal fuel savings attributable to sealed combustion systems alone also appeared to exist for the data on the combined effect of stack dampers and sealed combustion systems. The experimental data were obtained during test periods for which large differences in temperature occurred. Tracer gas measurements also indicated that the off-cycle flow factors for the type of system studied were not in agreement with the NBS factors. Again, it is concluded that there is considerable uncertainty regarding the applicability of the inverse K-factor comparison method of calculating seasonal fuel savings for this set of data because of the weather variations encountered during the test periods in question.

Table 17. Summary of Fuel Savings for Flue Gas Heat Reclaimers

| Unit | Flue Temperature Steady-State, °F | % Oversized | Relative Change in Seasonal Efficiency: Based on 6 bins | Based on Average Heating Season Temperature [3] |
|---|---|---|---|---|
| 3 | 690 | 213 | 10.5 | 10.3 |
| 5 | 620 | 85 | 6.5 | 6.6 |
| 7 | 740 | 275 | 6.7 | 6.6 |
| 17 | 455 | 5 | 2.7 | 3.4 |
| Average | | | 6.6 | 6.7 |

## 5.5 FLUE GAS HEAT RECLAIMERS

The estimated seasonal fuel savings from the installation of four flue gas heat reclaimers are shown in table 17. Unit 3 was the air-to-air heat exchanger, while the others used heat pipes to recover heat from the flue gases.

The calculated seasonal efficiency increase, resulting from the installation of the four heat recovery devices, averaged 6.6 percent, with a range of 2.7 to 10.5 percent. Using the average existing efficiency for units 3, 5, 7, and 17 of 69.2 percent, the efficiency increase would correspond to an average fuel savings of approximately 8.7 percent. The results reported in the table also indicate that minimal difference results from calculating the efficiency improvement by using six temperature bins as opposed to using the average heating season temperature.

It should be pointed out that the installation (unit 17) that yielded the lowest efficiency increase (only 2.7 percent) also had the lowest initial steady-state flue temperature. Since this unit was not wasting as much heat up the stack as the others, it would be expected that the heat recovered by the heat reclaimer would be less.

It appears that heat reclaimers can recover significant quantities of heat when the steady-state flue temperature significantly exceeds some minimum value (approximately 400°F). Heating systems that are running efficiently initially (i.e., with low flue temperatures) are not likely to incur significant fuel savings by the addition of such devices. On the other hand, inefficient units with high flue temperatures may benefit substantially.

# 6. CONCLUSIONS

## 6.1 SUMMARY

Field studies of the performance of oil-fired residential heating equipment during New England winters demonstrated the feasibility of equipment modifications for reducing fuel consumption. A number of different types of modifications were made and the resulting improvement in both equipment efficiency and fuel use was determined.

Annual tune-ups were shown to increase steady-state efficiency of oil-fired heating systems (measured by determining the amount of $CO_2$ and the net stack gas temperature) by about 2 percent. Although improvements in efficiency levels were demonstrated to last for at least three months, other data indicated general deterioration in performance over longer periods of time.

A more serious problem, in terms of the amount of fuel used, is that of oversizing. Measurements of heating systems taken during the winter of 1975-1976 indicated that at least 97 percent of the units were oversized by an average of 168 percent. To reduce the problem of oversized units, procedures for optimizing (reducing) nozzle size were developed and implemented. In a second phase, reductions in firing rate were combined with modification of the air handling equipment of the burners. This change resulted in a 14 percent average reduction in fuel use, depending on the type of burner modified. In some cases the burner was in such poor shape that it was replaced, resulting in an average fuel savings of 29 percent when combined with the reduction in firing rate. Use of reserve storage tanks on hot water systems using tankless coils also resulted in fuel savings when combined with reduced firing rate. The observed improvements in fuel consumption for the different modifications were in good agreement with the computer model calculations, thus providing some predictive validity for the simulation.

Finally, the fuel savings potential of several innovative heating equipment modifications was examined during the 1976-1977 heating season. These included stack dampers, sealed combustion systems, and heat recovery devices. Of the three, the stack damper offered the best potential fuel savings of about 6 to 8 percent, although some problems of electrical failure and noxious odors developed. Data from the sealed combustion systems were inconclusive, while the heat recovery devices appeared to be most effective for heating systems which were not running efficiently.

The data obtained in the course of field tests on residential oil-fired heating equipment over three New England winters indicated that modifications to this equipment can result in substantial improvements in equipment efficiency and reductions in fuel use. In addition to regular tune-ups and maintenance, reduction of firing rate through optimizing nozzle size and modifying the burner offers the greatest likelihood of reducing energy consumption. Furthermore, these equipment modifications can be made by local oil-company service personnel. Data obtained in these tests were also verified by computer simulation of equipment performance, demonstrating the value of simulations for predicting fuel savings nationally for a variety of equipment modifications.

## 6.2 ADDITIONAL RESEARCH

An obvious omission from the studies reported here is the type of furnace or boiler that is designed to cool the flue gas below its condensation temperature before leaving the heat exchanger to reclaim the latent and sensible heat. Although such equipment was not available at the time these studies were conducted, prototype models for gas-fired furnaces have since been evaluated by NBS [16]. The test procedures developed for DOE have been revised to include condensing units [17]. Because such units have seasonal efficiencies which are very similar to their steady-state efficiency, and which are on the order of 90 percent or more, the modifications and devices reported herein would not result in the same savings and might not even be mechanically feasible.

The cost-effectiveness of the various modifications was deliberately omitted because of the rapidly changing nature of fuel and equipment costs. A case study by NBS provides some calculations of the effects of equipment modifications on life-cycle operating costs [18], however.

In addition, since these field studies were done, NBS has conducted additional research on the effect of various design options on the performance of heating equipment through a mixture of laboratory, field, and computer modeling research. Nevertheless, the data presented in the present report clearly demonstrate the effectiveness of annual maintenance and firing rate reductions, relatively simple modifications which can be made by local oil-service personnel, in reducing annual fuel consumption.

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## Appendix - Procedures for Optimizing Nozzle Sizes

The following procedures for reducing nozzle sizes in oversized forced warm air or forced hot water heating systems were developed from the test results and experience gained in the New England field test program. (These procedures are not recommended for use on steam heating systems).

Step 1

### Repair and Tune-Up the Heating System

The heating system should be thoroughly checked and repaired before optimizing the nozzle size. All air leaks into the combustion chamber should be sealed and the oil burner given a regular tune-up. Optimizing the nozzle size should be done in addition to regular servicing, not as a substitute for regular servicing.

Step 2

### Measure the Steady-State Efficiency and Smoke Concentration

Steady-state efficiency should be determined by measuring flue gas temperature, the percentage of $CO_2$ in the flue gas, and the smoke concentration (smoke number on a Bacharach Smoke Scale of 0 through 9). It is usually necessary to wait at least 15 minutes after start-up for a unit to reach a steady-state operating condition. Units should operate with steady-state efficiencies at or above 75 percent. If the steady-state efficiency is less, or the smoke number is greater than #2, Step #1 has not been satisfactorily carried out, or the burner or heat exchanger needs replacement.

Step 3

### Determine First Trial Nozzle Size

Using the local outdoor design temperature for the area[1] and the winter K-factor for the residence[2] (degree days per gallon), determine the "minimum nozzle size" by using either:

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1/ If this is not known, refer to chapter 33 of the ASHRAE Handbook of Fundamentals [19]. Use the 97.5 percent values for the nearest weather station listed.

2/ The winter K-factor should be the average value derived over one or more complete heating seasons. The K-factor for a residence is defined as the number of degree days occurring in a time period divided by the total number of gallons of oil used during the same period to maintain a house at its normal thermostat setting.

(1) the graph displayed in figure 7

(2) a calculator such as in [20] or

(3) the formula:

$$\text{minimum nozzle size} = \frac{(65 - T_D)}{(\text{K-factor})(24)}$$

where $T_D$ is the local outdoor design temperature in °F and the K-factor is in degree days per gallon of oil. Thermostat setback is encouraged as an additional energy conservation measure. If the owner plans to practice thermostat setback, insure adequate indoor temperature recovery after setback by increasing the minimum nozzle size found above by adding a value in gallons per hour equal to the product of the heated house floor area in square feet and the pickup capacity factor (PCF) divided by 105,000 Btu/gallon[1], where PCF is given by the following table [21]:

| Outdoor Design Temperature, °F | Pickup Capacity Factor[2] Btu/hour-sq-foot floor area |
|---|---|
| 40 | 9.5 |
| 30 | 13.0 |
| 20 | 14.9 |
| 10 | 15.8 |
| 0 | 17.0 |
| -10 | 17.7 |
| -20° | 18.8 |

The minimum nozzle size selected should be at least:

0.5 gph for warm air systems;
0.65 gph for hot water systems not supplying domestic hot water;
0.85 gph for hot water systems with aquaboosters; or
1.20 gph for hot water systems using tankless coils without a storage tank.

The first trial nozzle should be selected to give the same spray pattern and angle as the nozzle presently installed in the unit and should never be larger than the present nozzle.

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1/ Based upon approximatey 140,000 Btu's per gallon of fuel oil and on assumed steady state efficiency of 75 percent.

2/ Based upon 10°F thermostat setback and 2 hour pickup time as given in [21].

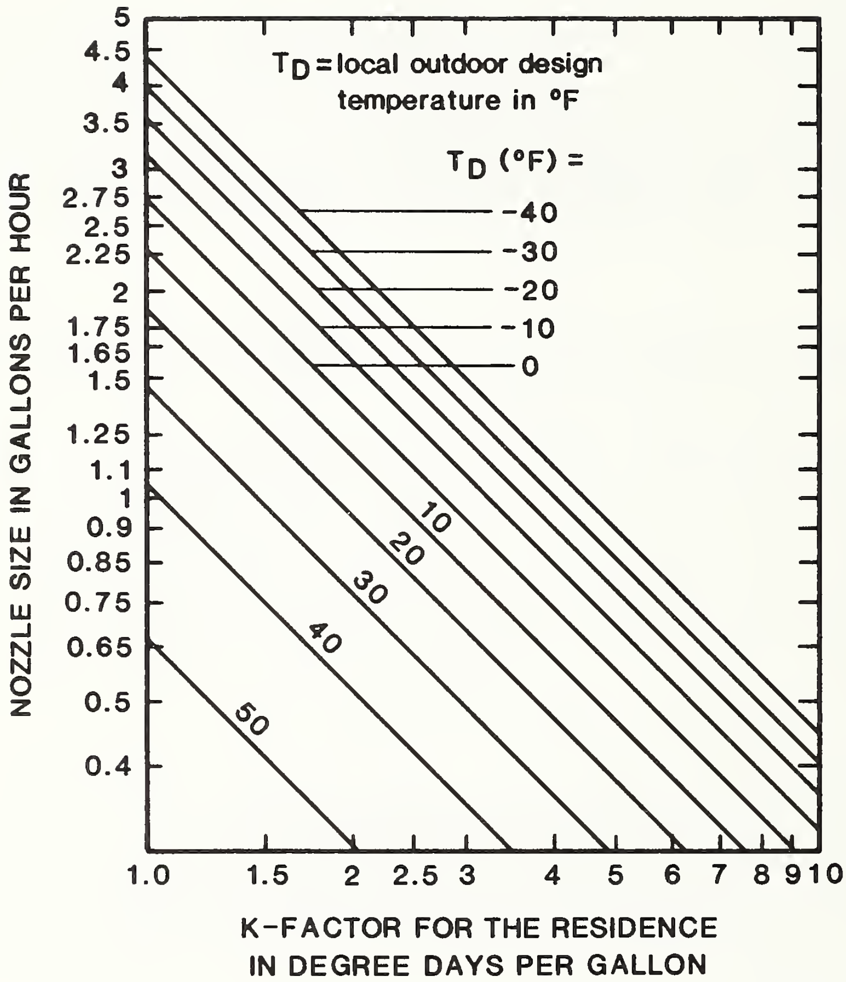


Figure 7. Minimum nozzle size

Step 4

## Install Trial Nozzle and Make Required Adjustments

Install the trial nozzle and see if the flame fits the combustion chamber. If it does not, a nozzle with a different spray pattern and angle may be needed. Using a smoke measuring device, adjust the oil burner to the "best" operating condition using either the "eyeball" inspection approach or the procedure outlined in reference [22]. This "best" condition will generally correspond to the smallest opening in the air shutter (least amount of excess air) which will allow the burner to operate with an oil-free (non-yellowed) smoke spot having a smoke number of #1 or less on the Bacharach Smoke Scale. Check the draft and readjust the draft regulator if necessary. The fire should be uniformly distributed in the combustion chamber and must not touch any metal surfaces. There should be no delayed ignition, visible flame instability or pulsation noise.

Step 5

## Remeasure the Percentage of $CO_2$ and the Flue Gas Temperature

The percentage of $CO_2$ and the flue gas temperature should be remeasured. The percentage of $CO_2$ in the flue gas should be equal to or higher than the reading obtained with the original nozzle. As a general rule, the final $CO_2$ reading should not be allowed to fall below the reading obtained with the original nozzle by more than 0.2 percentage points for each 10 percent reduction in firing rate.

In addition, the smoke number must be less than or equal to #1 on the Bacharach Smoke Scale. The temperature of the combustion gases before entering the draft regulator should be above 370°F in order to avoid the possibility of corrosion.

Satisfying the above conditions should result in a steady-state efficiency not significantly lower than with the original nozzle. As a check, recalculate the new steady-state efficiency and compare it with the original. If the new efficiency is not below the original efficiency by more than 2 or 3 percentage points, the new nozzle is the proper one and you may skip step #6. If this is not the case, one or more additional nozzles should be tried. This is discussed in step #6.

Step 6

## Trying Additional Nozzles

If the conditions discussed in step #5 have not been meet, repeat steps #4 and #5 using other nozzle sizes. It is not possible to give a hard and fast rule for selecting the successive nozzles. It may be desirable to try one or more additional nozzles of the same size but with different spray patterns or angles or it may be necessary to go to a larger size nozzle. The only generalization which can be made is that if after installing a trial nozzle, the flame pattern looks good but the excess air has to be increased considerably in order to keep the smoke equal to or below #1 on the Bacharach Smoke Scale, the next nozzle size should probably be halfway between the newly installed size and the original nozzle size. Experience will be the best guide in selecting the successive trial nozzles.

Step 7

Record Results

Carefully record the following information and leave a copy with the owner or place a tag on the equipment:

- date of servicing
- the original nozzle size and type
- the final nozzle size, type, and spray angle
- the number and size of each nozzle tried (include the final nozzle in this count)
- the initial and final $CO_2$, stack temperature, and smoke readings.

This information will be helpful for future servicing of the unit and could be invaluable in trouble-shooting any problems which might arise immediately after a reduction in firing rate.

Step 8

Repeat Nozzle Optimization Procedure

If the procedure in step #3 resulted in the proper nozzle size in step #5, the nozzle size should be re-evaluated after one heating season. The reason for this is that the K-factor used in step #3 to calculate the minimum nozzle size is dependent upon the seasonal efficiency of the heating system. Reducing the firing rate should increase the seasonal efficiency, leading to a larger K-factor. This new K-factor should then be used to find a new minimum nozzle size.

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**5. AUTHOR(S)**

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**11. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Recent studies of the performance of residential oil-fired heating systems in the New England area from 1974-1977 demonstrated that significant energy savings are achievable through better maintenance and simple system modifications. These studies showed that annual tune-up of the furnace or boiler would improve the seasonal efficiency of most units, while considerable energy savings are possible by reducing the firing rate of the burner. Reduction in nozzle size with burner modification or with the installation of a new flame retention burner was found to reduce oil consumption substantially. In addition, more innovative equipment modifications such as the use of stack dampers, sealed combustion systems, and heat recovery devices also resulted in fuel savings, although to a lesser extent. Both experimental field data and results from computer simulations of furnace performance are presented.

**12. KEY WORDS** *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

boiler; energy savings; firing rate; fuel efficiency; furnace; nozzle size; oil-fired; residential heating; sealed combustion; stack damper.

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