NBSIR 85-3142

Laboratory Tests of A Gas Fueled Modulating Type Hot Water Boiler

E. R. Kweller

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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ABSTRACT

The objective of this study was to set up a modulating controlled hot water boiler in the laboratory and to simulate a variety of conditions that were cited by manufacturers of boilers as influencing and being distinct operating parameters for boilers. A further objective of these tests was to compare these responses to the fuel input rate with the mode of operation which was previously described for modulating controlled space heaters and furnaces. The variation of controlled fuel rate to the burner via the fuel modulating valve was measured under several controlled conditions. Effects of heating load, burner cycling rate and zone control, were investigated. The response of gas pressure modulation to the burner of a hot water boiler heating system was studied in several series of tests in the labortory. A boiler load simulator was set up and used for these tests to control the heating load (heat transfer rate at the radiators) and to simulate a variety of operating conditions that would be expected to exist with a boiler installed in the home. The effects of heat transfer rate and boiler water operating temperature on the modulated gas pressure are presented as a series of data in charts showing controlled gas pressure versus time. Cycling rate (burner on-off time) was also shown to have an effect on the operating gas pressure when operating in a cycling mode.

1.0 INTRODUCTION

1.1 Background

On June 16, 1982, NBS presented a summary of a test procedure developed for modulating controlled household heaters to the Gas Appliance Manufacturers Association Test Procedure Committee. At that meeting, a manufacturer of boilers using modulating controls contended that the NBS recommended test procedures addressing fuel modulating controls on warm air furnaces or household heaters [1]* did not adequately address the testing of modulating-controlled hot water boilers. The manufacturer contended that many variables specific to the installed system, control the firing rate of the burner other than the heating load as determined from the indoor to outdoor difference. For example, the amount of water in the system as well as oversize would be a determining factor on the percent of operating time at reduced input. In order to support the Department of Energy (DOE) proposed changes to test procedures to include modulating boilers, and to better quantify the effects of several variables, a modulating controlled boiler was set up and tested at NBS.

Proposed test procedures were subsequently published by DOE in June of 1983 [2]. Comments received responding to the proposed procedures were generally favorable with the exception of one commentor representing two manufacturers of boilers, stating their concern that the test procedure did not address zone control. In an analysis of comments by NBS, it was concluded that a separate test procedure for zone control applications was not practical "because of the many control schemes that can be employed, it would be impractical to devise a test procedure that would cover each one" [3].

* Numbers in brackets refer to references in Section 6.0.

1.2 Purpose of Fuel Modulation

The purpose of this control is to modulate (or throttle) the gas flow so that boiler output is matched to the heating load. The boiler is in effect resized to match the number of zones in operation.

This control is specifically recommended with systems having variable water-flow rates, such as zoned systems. One boiler manufacturer described the advantages of this type of controlled boiler [4] as follows:

> "We have found that it is fairly common for a heating boiler to have more output capacity than the heating radiation system installed in the home. When this occurs, the boiler may overdrive the heating system (that is add heat to the water faster than it is being removed via the radiation system) which will result in an ever increasing boiler water temperature until eventually the boiler will shut off on its high limit, even though the room thermostat is still calling for heat. This may result in several on/off cycles of the boiler during one sustained call for heat from the room thermostat. This phenomenon is especially true on a multi-zone system where only one zone may be calling for heat. On a field test of our boiler by one of the control manufacturers with the modulating system blocked open to act as an on/off boiler, there were as many as three complete on/off cycles per minute while delivering heat to a single zone. Modulation effectively eliminates these on/off cycles that would otherwise occur during a sustained call for heat."

Another advantage was described as "especially important when a hydronic boiler is used with an air handling fan and coil type of device. With a fan and coil unit, fluctuation in water temperature will result in fluctuations in delivered air temperature. Modulation achieves a more constant delivery of water temperature and results in a more comfortable stable delivery of heat to a room."

The advantages of reduced number of on-off cycles, as results with fuel modulation, is reduced cycling loss. If the burner cycles less, the off period cyclic loss is less. This has been recognized and has been applied in the current DOE test procedures [5] in terms of the adjusted burner on-off periods assigned for two stage and step-modulating controlled boilers (i.e. 15 minutes on and off versus 9.7 minutes on and 33.8 minutes off for single state thermostat). For those boilers which modulate between their maximum and reduced input condition, there is no cyclic loss assigned for the modulating mode of operation. (See 1.5.2 for further details.)

1.3 Objective

The objective of this study was to set up a modulating controlled hot water boiler in the laboratory and to simulate a variety of conditions that were cited by manufacturers of boilers as influencing and being distinct operating parameters for boilers. A further objective was to study the effects of these operating parameters under varying heating load conditions. In order to accomplish this task at minimal cost and time, it was necessary to run these tests under laboratory controlled conditions rather than in field tests. In order to simulate the varying load conditions that would be imposed on a boiler throughout the heating season (i.e. outdoor temperature variations), it was necessary to design a variable load simulator for these laboratory tests. A further objective of the study was to observe the response of the modulated fuel input (actually controlled gas pressure was monitored and converted to fuel input rate) with variation of imposed load and other parameters that would be expected to influence the controlled input of fuel.

A further objective of these tests was to compare these responses of the input energy with varying load to the mode of operation which was previously described for modulating controlled space heaters and furnaces in [1]. An overview of the previous study is included here in Appendix A.

2.0 Overview of DOE Test Procedures for Modulating Boilers

2.1 Effect of Heating Load on Burner Modulation

The effect of heating load on burner modulation was previously reported [1] (see figure 1) as a figure showing burner output versus outdoor temperature. In [1] and in this report, outdoor temperature below 65°F is considered as the only determinant of the heating load. And heating load is synonymous with the output energy delivered by the boiler. Burner response was shown (see figure 1) as a series of on-off burner cycles at the minimum input rate (cross sectioned blocks represent burner "on" condition in figure 1). At temperatures below the balance point temperature (Tc), burner cycling at the reduced input rate was no longer considered sufficient to satisfy heating required and the burner firing rate gradually increases in order to maintain the desired setting. For household heaters or furnaces, this setting is the room temperature thermostat setting, and for boilers, it is the boiler water temperature control setting as determined by the modulating control set point. Figure 1 is intended as a pictorial representation of the entire heating season, where the total heating load in the year is divided up into temperature bins and totaled for each 5°F bin. The objective being to obtain a weighting factor that applies to each mode of operation (i.e. cyclic mode and the modulating or non-cyclic mode). In actual operation during any day

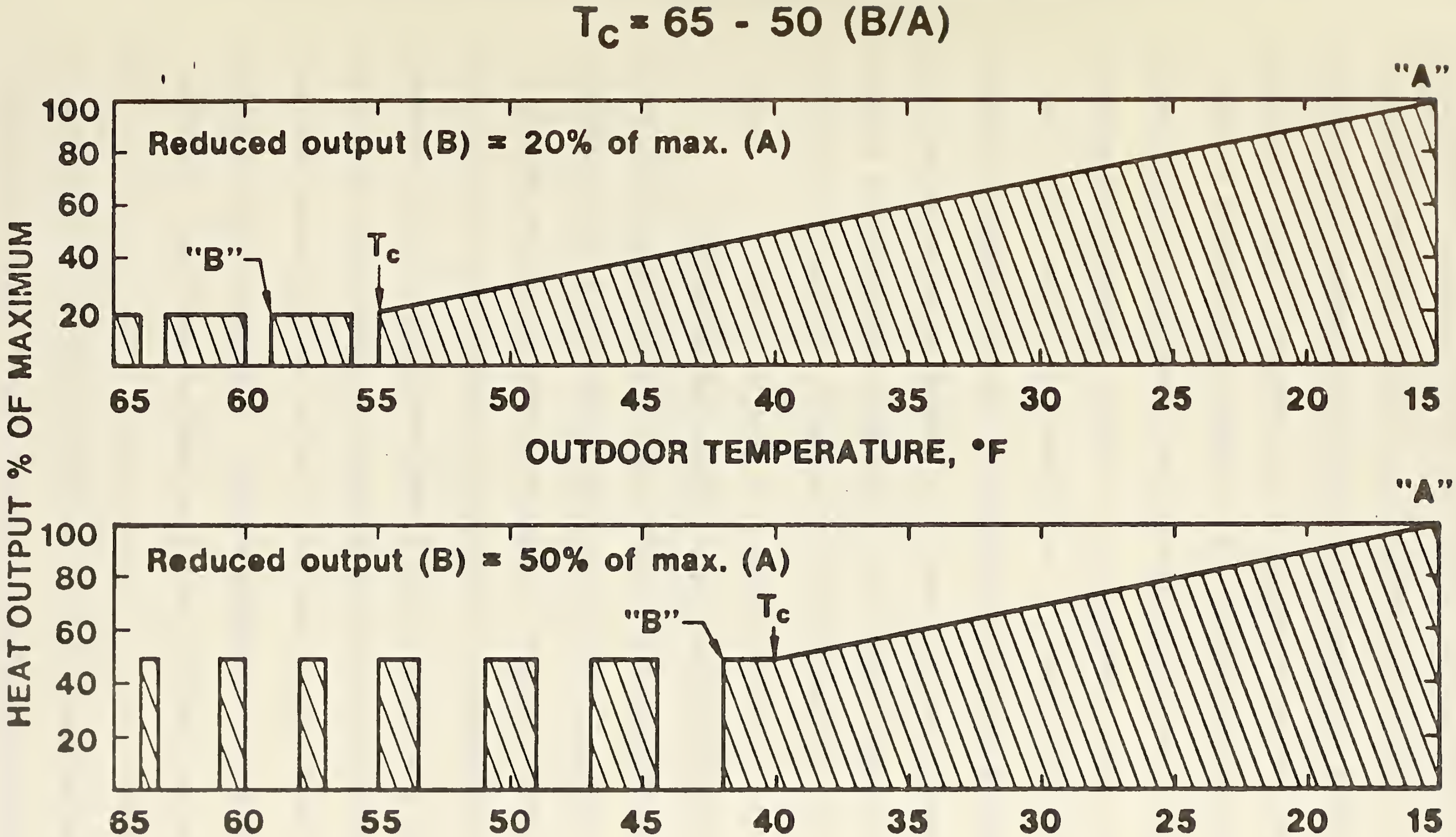


Figure 1. Burner response in cycling mode (between 65 and balance point T_c) and in non-cycling mode (between T_c and design temperature of 15 F) for modulating room heater

Note: The result of a change in reduced output rate (B) from 20% (upper figure) to 50% of maximum rate (A) in lower figure, is a shifting of the balance point from 55° to 40°. Respectively.

of the heating season either of these modes will be in effect. As the sun rises and sets, the solar heat gain affects the heating load; as windows or doors are opened cool drafts will affect the burner response, and as thermostat is set up or down the burner will respond independent of outdoor temperature. Internal heat gains or intermittent use of supplemental heaters, or a fireplace are other effects that cannot be quantified in this analysis. In reality, it is likely that burner on-off cycling occurs throughout the heating season irrespective of outdoor temperature because of these real-life effects and because a wall thermostat in the living area can override the modulation by cycling the burner off at any time. Other effects such as piping system volume, zone control, oversizing are considerations that have been identified. These were investigative tests and were run in an attempt to quantify their efforts, as reported in the following sections.

2.2 Effects of Cycling Rate or Oversizing on Part Load Efficiency

The test procedure prescribed by DOE [5] does not explicitly address the effects of oversize. However, there is implicit within the test procedure for modulating controlled furnaces or boilers an accounting of the oversize effects on part load efficiency. That test procedure assigns a zero oversize to the on-off cycling mode, which applies to the portion of the heating season between 65°F and the "balance point" temperature (i.e. the outdoor temperature where the minimum input rate setting is no longer sufficient to satisfy the heating requirements). A background report [6] that describes the effects of on/off times was reported in January of 1983.

As a result of that study [6], the typical burners on and off periods (ton, t off) for modulating controlled furnaces were assigned the values of 10 minutes on and ten minutes off, and boilers were assigned 15 minutes on and

15 minutes off. The conventional single stage thermostat on/off periods remains at 3.9 minutes and 13.3 minutes for furnaces; and 9.7 minutes and 33.3 minutes for boilers. The significance of this is an increase in the typical part load efficiency of approximately 6% for a modulating controlled boiler (see Ref. 6). The reason for this increase in efficiency is due to the increased proportion of burner on time to off time (i.e. reduced cyclic loss) and a total discounting of cyclic loss for a fraction of the heating season.

The non-cycling mode applies between the balance point and the coldest expected outdoor temperature (i.e. the design temperature which is 5°F as a national average). There are no cyclic losses assigned for that portion of the annual heating load because the modulating control is considered able to modulate the fuel and size the boiler output to just meet the load. In reality 100% modulation is unlikely to occur. Since there is a wall thermostat which is the primary control of burner on off operation, it is likely there will be some on/off cycling of the burner at even the coldest times of the year (i.e. due to night set back, internal heat gains, etc.). These effects have not been quantified and therefore the test procedure assumes no cyclic operation for that fraction of the total annual heating load when theoretically the burner should not be cycling off. That fraction is referred to as (X_2) in the DOE procedure [5] (see figure A-2 of Appendix). The fraction (X_2) is obtained from a relationship which identifies the balance point temperature (i.e. that outdoor temperature which divides the total heating season degree days between modulating mode and cycling mode. This balance point (Tc) is determined by a proportional relationship between the minimum (B) and maximum (A) output rates and the degree of oversize (α).

$$T_c = 65 - \Delta T_d \left[B/A\right]\left[1+\alpha\right] \qquad (1)$$

Where ΔTd is $60^{O}F$; (the difference between $65^{O}F$ and the design temperature of $5^{O}F$). In previous work published for vented space heaters [1] and [5], the outdoor design temperature was taken as $15^{O}F$ and there was no oversize factor considered. Therefore, the equation used previously to determine Tc (as shown in figure 1) was based on T = (65 - 15) = 50.

In the analysis used to develop this procedure, the range of outdoor temperatures were divided into temperature bins of $5^{O}F$ width. The numbers of hours within each bin was averaged from data from weather stations across the United States. The number of heating degree hours was thereby obtained for each site. The ratio of degree hours between $65^{O}F$ and any outdoor temperature (Toa) below $65^{O}F$ to the total annual heating degree hours is taken as the fraction of total annual heating load at Toa. This fraction between $65^{O}F$ and the balance point temperature (Tc) is applied to the minimum input rate, and is referred to as (X_1) in the DOE procedure. The corresponding fraction for the modulating mode is (1 - X_1) which is (X_2). See reference [1] and [6] for a further description of this procedure, and for examples of the test site weather data used to develop a national average for the values used for (X_1) and (X_2) as related to balance points.

From the above equation (1), it can be seen that as the oversize (α) of a boiler increases, the balance point (Tc) shifts to a lower outdoor temperature. Consequently, the fraction of the year in which the non-cycling mode applies (X_2) is reduced and the fraction applicable to the reduced input cycling mode (X_1) increases.

Another effect causing a shifting of the balance point is the ratio (B/A). This effect can be seen by returning to figure 1.

Given two boilers with different oversize conditions and thermal efficiencies and that otherwise are identical, the boiler that is more oversize would operate more of the season at the reduced input on-off cycling mode. This is because the oversized boilers reduced input rate is greater, therefore, it can satisfy a greater fraction of the heating season at its reduced input. Since the part load efficiency is generally less for the reduced input cycling mode, and that load fraction (X_1) is greater, this would reflect a lower weighted average annual part load efficiency for that boiler with the greater oversize condition.

Applying the test procedure to the test boiler used here with its minimum and maximum output rates of 15,880 Btu/h and 56,375 Btu/h, the balance point would be calculated as follows using the average assigned 70% oversize condition for ( ),

$$TC = (65) - 60 \cdot [15,880 \div 56,375] \cdot (1.7) = 36^{o}F.$$

From the test procedure (6), the fraction of total annual heating load applied to the modulating (or non-cycling mode) would be (X_2) = 48%. See Appendix fig. A-2. The weighted part load efficiency would be based on 52% of the part load cycling efficiency calculated at reduced input rate plus 48% of the non-cycling (modulating) mode efficiency. Efficiency in the modulating mode is determined based on the steady state efficiency at maximum input and at minimum input, and is proportioned using a calculation that takes oversize into consideration (see Appendix A Figure A-3 for a further description of that calculation procedure).

3.0 TEST EQUIPMENT AND PROCEDURES USED

3.1 Scope

The response of gas pressure modulation to the burner of a hot water boiler heating system was studied in several series of tests in the laboratory. A boiler load simulator was set up and used for these tests to control the heating load (heat transfer rate at the radiators) and to simulate a variety of operating conditions that would be expected to exist with a boiler installed in the home. The effects of heat transfer rate and boiler water operating temperature on the modulated gas pressure are presented as a series of data in charts showing controlled gas pressure versus time. Cycling rate (burner on-off time) was also shown to have an effect on the operating gas pressure when operating in a cycling mode.

The variation of controlled fuel rate to the burner via the modulating controller was measured under several controlled conditions. Effects of heating load, burner oversizing, zone control, and system volume, were investigated.

As a result of these tests, recommended modification of the DOE test procedure is being made for fuel modulating boilers equipped with manually adjusted boiler water control valves. (See Section 6.0 for Recommendations.)

3.2 Test Boiler

The prepackaged hydronic boiler used in these tests is shown installed in Figure 2. Figure 2 shows a cross section through this boiler. This is a low mass type of design using copper coils and a finned tube to absorb radiant and convective heat from the gas fueled burner. The copper tubing

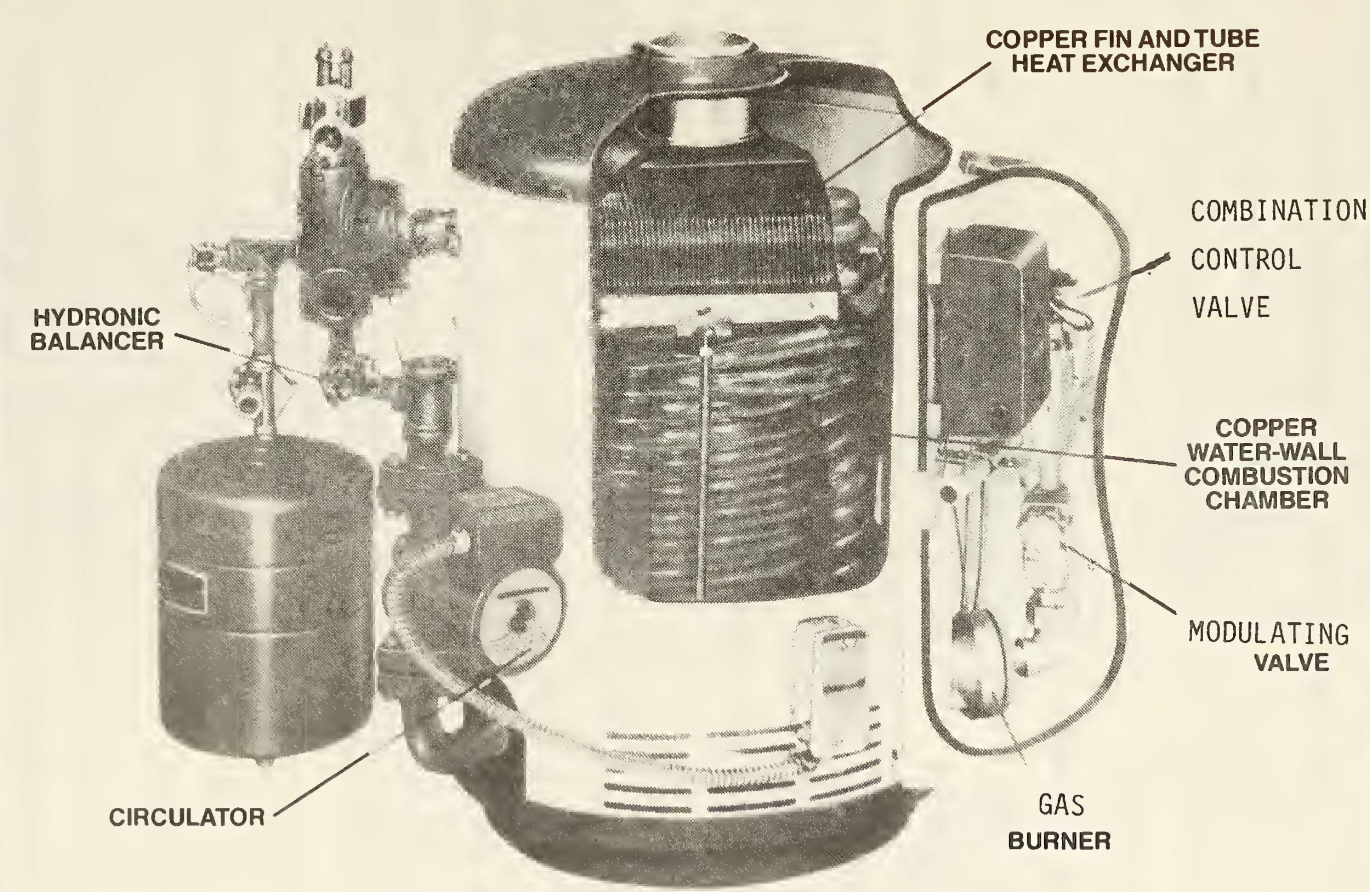


Figure 2. Modulating Hot Water Boiler Used for Testing

is coiled around the burner to form a "water wall combustion chamber." Hot combustion products rise upward and heat water flowing through the finned tube tube heat exchanger. Rated input of this boiler was 80,000 Btu/h, and maximum rated output was 64,000 Btu/h. Maximum fuel input as received was measured at 74,205 Btu/h and minimum input measured 21,456 Btu/h. Maximum output including jacket loss based on a measured flue loss of 24% with the as received maximum input was 56,395 Btu/h. Minimum output based on flue loss was 15,880 Btu/h.

3.3 Boiler Load Simulator

Figure 3 shows a flow schematic of the boiler system, meters, controllers, and the data recording instrumentation used. Figure 4 is a photograph of this equipment. In Figure 4, the modulating boiler is shown in the center, data recording equipment to the right and the boiler load simulator (100 gallon water holding tank at the left).

As shown in figure 3, there is a closed flow of water from the boiler to four groups of five ft long fin tube radiators (four per group) immersed (vertically) in the holding tank. The top of these fin tube radiators can be seen in the open top of the holding tank in figure 4. Energy picked up by the boiler water is circulated from the boiler through the fin tube radiators. Some of this energy is removed from the hot boiler water through heat transfer to the cooler water in the holding tank. Boiler water is then returned to the boiler through a pump, and the cycle is repeated. Metered water flow through this closed loop along with the temperature rise across the boiler allows for measuring the output energy (Q out) of the boiler water. If the amount of energy removed from the circulating boiler water is less than energy added by the burner, the fuel gas flow to the burner will eventually be reduced (or modulated) by actions

MODULATING BOILER TEST SETUP

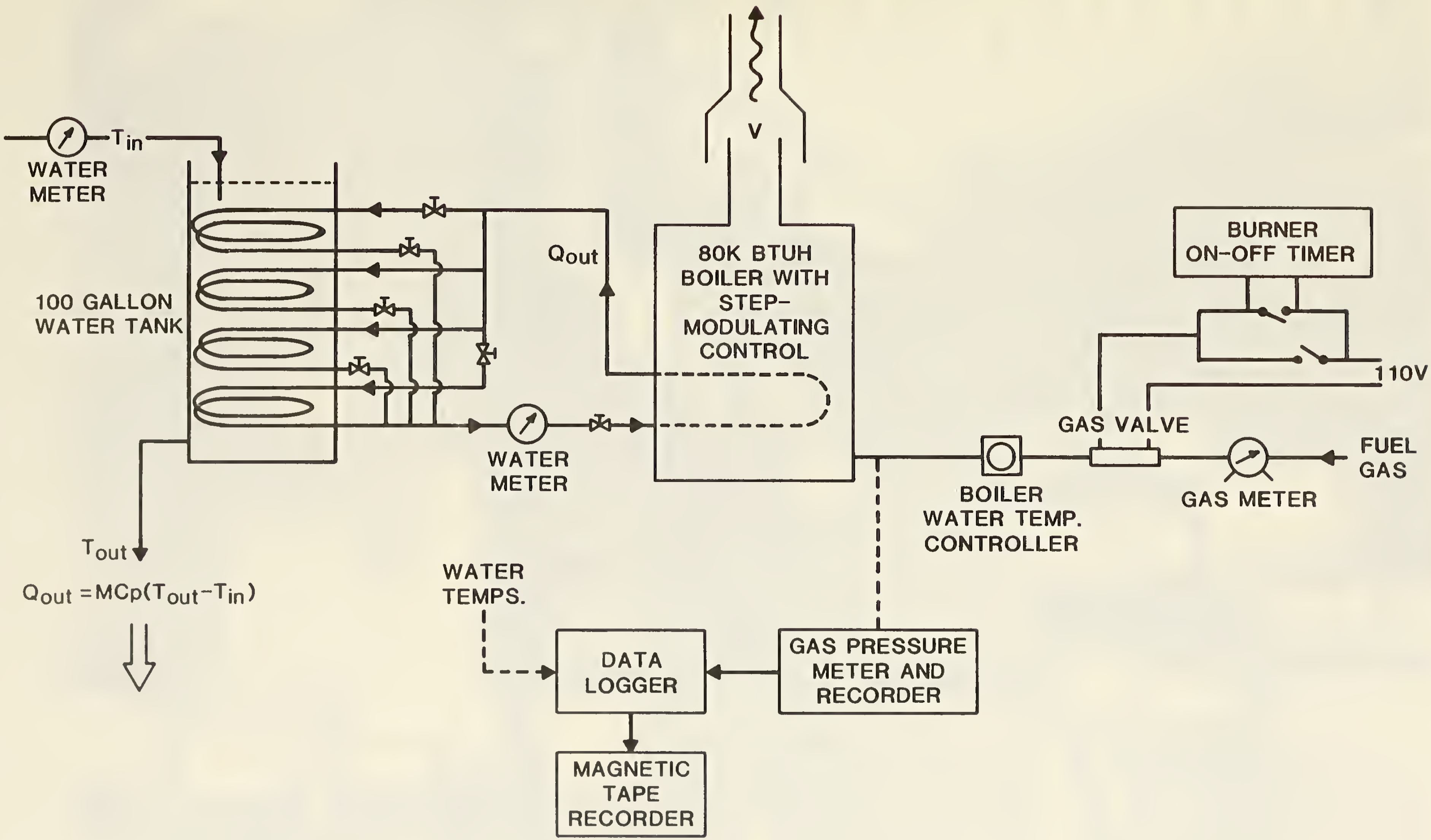


Figure 3. Flow diagram of laboratory test equipment and instrumentation used in boiler testing.

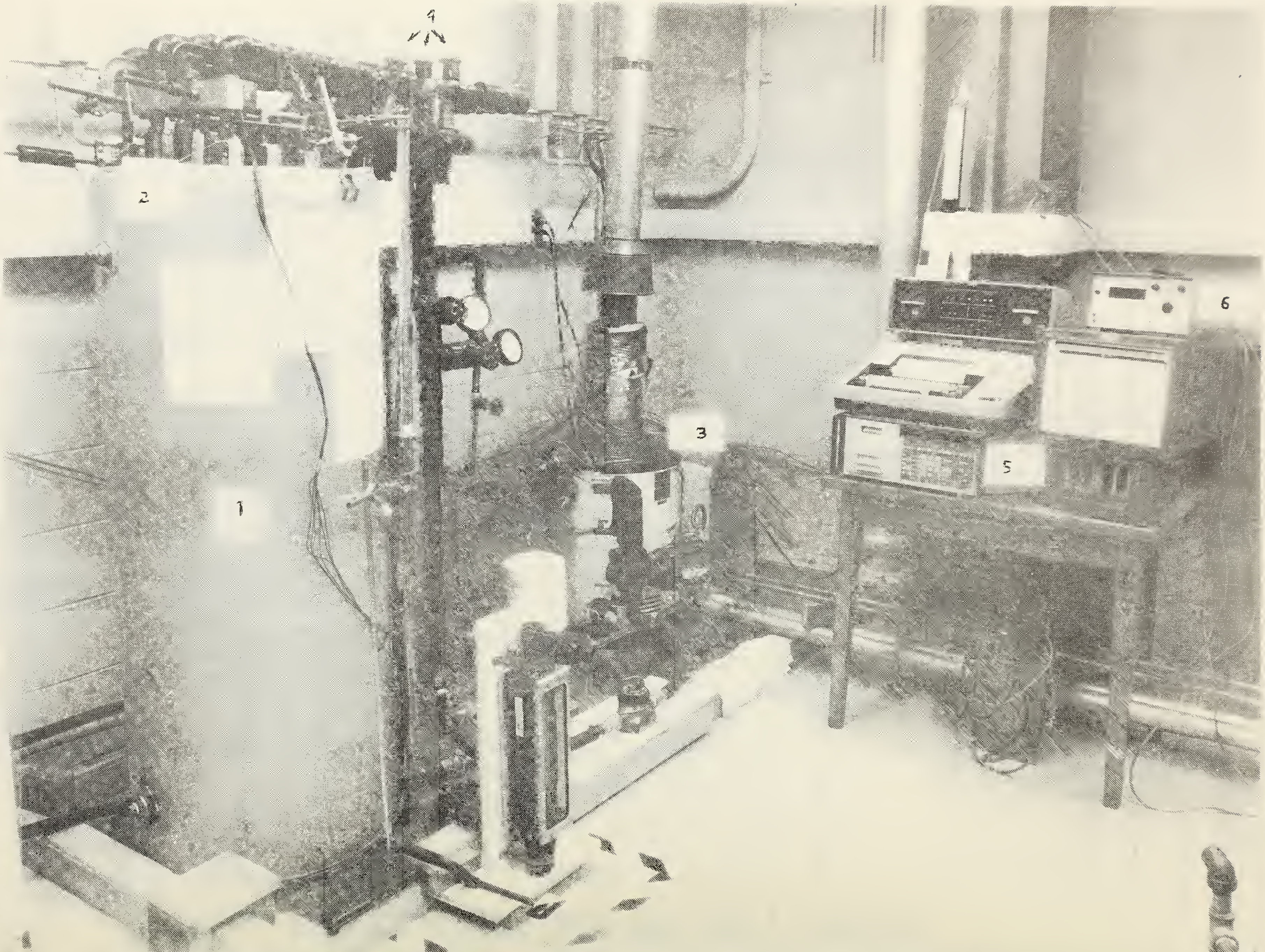


Figure 4. Laboratory test equipment showing: (1) Boiler load simulator-holding tank, (2) Finned tube radiators (3) Test Boiler (4) Zone control valves, (5) Data logger and recorder (6) electronic

of the boiler water temperature controller, (i.e. the fuel modulating control). Conversely, if the amount of energy being removed is greater than energy being supplied by the burner, the boiler water temperature will drop and the modulating control will respond by increasing the flow of gas to the burner. This process continues in order to maintain boiler water temperature to a predetermined temperature. In operation, the modulating control is set to any of nine settings from "1" to "9" on the control which corresponds to a water temperature from 120°F at No. 1 to 240°F at No. 9 (i.e. 15°F increase per each setting). See section 3.3 for further details of modulating controller. By controlling the flow of cooling water through the holding tank, it was possible to control the temperature of the holding tank water and the degree of heat transfer from the boiler water flowing through the fin tube heat exchangers. Rate of heat transfer is synonymous with the heating load and is measured by the rate of heat picked up and removed from the holding tank. Heating load was there-by adjusted by flow of cold water through the holding tank. Metered water flow and water temperature rise from (T in) to (T out) of the tank was calculated as (Q out) or the load imposed on the radiators (i.e. Q out is the product of mass flow of water (M), specific heat (Cp) of water, and the temperature rise (T out - T in)).

The tank water level was maintained constant throughout the test by the use of a liquid level control of the water supplied to the tank. Drain rate was controlled using a manual value at the base of the tank.

Flow rate of water through the boiler was initially adjusted to obtain approximately a 20°F temperature rise at maximum input rate of the burner.

3.4 Modulating Control Valve

The DOE test procedure [5] applies to either of two types of modulating controls defined as either two stage or step modulating. This test boiler uses the step modulating type of control. The step modulating type is believed to be the most prevalent type used for boilers.

The mode of operation of a step modulating control was previously described in reference [1] for space heaters. In most cases, thermostatic space heater controls use a closed hydraulic sensing and actuating devices consisting of a bulb, capillary and bellows or diastat. One manufacturer [7] describes the operation of the hydraulic control as follows:

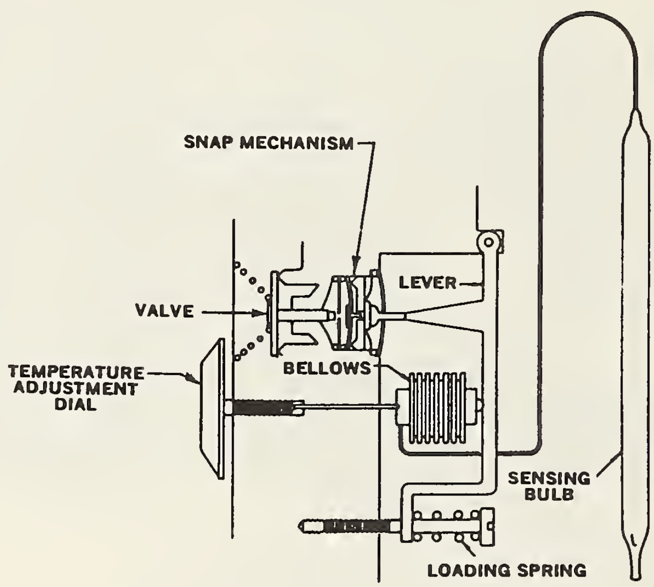


Figure 5. Hydraulic Sensing and Actuating Mechanism

The interior of the system is filled with a liquid which has a high coefficient of expansion. A rise in temperature sensed by the bulb causes an expansion or increase in volume of the liquid which is transferred through the capillary to expand the bellows. The amount of movement of the bellows depends on the temperature being sensed which provides for temperature calibration. The bellows is normally spring loaded in compression and the resulting movement under variable temperature conditions utilized for operating snap mechanisms for valve opening and closing. The movement is also used in some cases for securing varying pressure regulator settings for modulating valves. A schematic of a hydraulic sensor and actuating system used for snap action control is shown in figure 5.

Operation of the modulating control used with this boiler is described by the control manufacturer [8] as follows: "The valve snaps open to a minimum flame condition and modulates between minimum and maximum flame in proportion to the demand for heat". As the temperature approaches the set point of the control, the flame diminishes and the valve either snaps off or optionally (depending on the model) will operate at the minimum flame condition. A second valve installed upstream in the burner manifold is used for burner on-off operation under control of the room thermostat. See Figure 2 which shows this burner manifold where the upstream valve is referred to as the combination control valve.

The same type of hydraulic operated control valve used with room heaters is used with the modulating burner on boilers with the exception that the sensing bulb, instead of sensing air temperature, is installed to sense the boiler water temperature and control it to a preselected temperature. The control used for this boiler had a control knob with settings of one "1" to nine "9".

The valve is factory set at the number six "6" position but can be reset to produce the approximate boiler operating temperature desired. A table of boiler water temperature versus control knob setting as listed in the installation and operation manual for this test boiler is as follows:

KNOB SETTING - TEMPERATURE EQUIVALENTS (^{o}F)

Knob Setting	1	2	3	4	5	6	7	8	9
Operating Temperature	120	135	150	165	180	195	210	225	240

Temperature adjustment is described in the operating instructions as follows: "The control knob should be set to the desired operating temperature at the time of installation." An interview with a local plumbing company familiar with the installation of boilers of this type revealed that the control knob is unlikely to be changed to any other setting after being set by the installer.

3.5 Instrumentation

In addition to water flow and water temperatures described above, the gas fuel input rate was metered through a wet test meter, and fuel input flow rate in terms of Btu/h was determined using an on-site continuously recording calorimeter to measure the heating value of fuel. Gas pressure out of the modulating control was monitored using an electronic manometer. All temperatures and the modulated gas pressure were scanned at a fixed interval rate by a data logger and these data were recorded on magnetic tape. Data tapes were read into a data file at the NBS central computer. Stack flue loss readings were also measured using a non-dispersive infrared analyzer to measure carbon dioxide. Flue gas temperatures were measured using nine parallel connected thermocouples located in the flue pipe cross section. Six thermocouples were also located on the center line of the holding tank and positioned vertically at equal distances from top to bottom of the tank.

3.6 Test Procedures

3.6.1 Heating Load

Two methods were used to adjust the heating load. The first method of using cold water flow into the holding tank and out to the drain line was described in section 3.3. In addition to energy flow to drain, the change in energy content of the holding tank was determined. The difference between initial and final average tank temperatures was used together with the holding tank water volume and density to calculate energy stored in the tank during the test. Six thermocouples positioned in the holding tank water are used to determine the average tank temperature changes. Water temperatures during these tests were held as close as possible to room temperature. Therefore, it was not necessary to determine the jacket loss of the tank for this test method. This method of test was used in obtaining the data reported in sections 4.3 and 4.4.

A second method used to measure heating load involved using the holding tank without the flow of water to drain. The temperature rise of holding tank water was used to determine the average heating load during the burner on period. This is the same procedure as in the first method when correcting for the difference between energy content of the tank over the test period. In addition, the standby loss of this uninsulated tank was predetermined in order to correct for jacket loss of the tank. An adjustment for standby loss was needed during this second test method because the tank water temperature was above room temperature for all tests. This second method of test was used in obtaining the data reported in Section 4.2.

The second method was found to be more useful for adjusting the load. In order to adjust to a very low load with a normal controller setting of the modulating control, it became necessary to reduce the temperature difference between water in the radiators and the tank water in order to operate at a reduced input rate. Operation at minimum input rates using the tank drain method of load adjustment was only possible at the lowest controller settings.

3.6.2 Cycling Rate

An oversized installed heating system in the home will result in reduced burner on-time. Since the boiler heating system used in this study was not controlling a room temperature, the study of cycling rate was limited to controlling burner on/off operation by either manual switching of the electric power to the gas valve or by on/off timer as shown in figure 1. The effects of cycling rate also overlap with the study of zone control and heating load. For further detailed description of the effect of cycling rate on part-load efficiency see 4.4.

3.6.3 Boiler Water Temperature Contol Setting

Several series of tests were run with various control settings of the modulating control. In order to operate at the minimum input rate as prescribed in the test procedure, it was necessary to set the control to the No. 3 or lower position. Also, the study of heating load effects was limited at both extremes by the control setting. In order to operate at the simulated higher heating loads, the control had to be set up to a higher water temperature setting. Test results are reported in Section 4.2.

3.6.4 Piping System Volume

Initial testing was run with a minimum amount of insulated piping. The insulated piping runs between the boiler and water holding tank can be seen in figure 2. In order to study the effect of additional water volume as would be found in the field, two 10 ft lengths of 2 inch diameter steel pipe were installed in the piping system. These lengths can be seen at the lower right background of figure 2 (beneath the instrument table). Internal volume of these two pipes (3.4 gallons) is approximately equivalent to 75 ft of the one inch pipe size or 140 ft of 3/4 inch copper tubing (type L). Internal volume of this pipe contains 3.4 gallos of water.

3.6.5 Zone Control

In order to simulate zone control up to three of the four sets of radiators were by-passed using shut-off control valves. These four valves are shown schematically in figure 2, and can be seen in figure 3 at the top of the manifold headers in the piping system which is installed above the holding tank. These test results are reported in Section 4.3.

4. TEST RESULTS AND DISCUSSION

4.1 Introduction

The overall objectives of the study (previously described in Section 1.3) were carried out by showing how the fuel gas modulating control of a boiler would respond to the various test parameters. In order to show this, all test results in this report are presented in graphical form as curves of the modulated gas pressure measured at the outlet of the modulating control valve (or inlet to the burner) versus elapsed time after burner start-up. An example of one set of data obtained is shown in Figure 6. The equivalent fuel gas input rate corresponding to the fuel gas pressure is also plotted in Figure 6. Since fuel input rate Btu/h varies as the square root of gas pressure drop the effect of a change in gas pressure is not as great expressed in terms of fuel input. Boiler output rate with this boiler varies practically directly as boiler input rate. Boiler output (including jacket loss) was 76% of the boiler input at steady state operation at maximum input rate, and 74% of the input at the minimum input rate.

In most tests with this boiler, the response curve for on-off cycling was similar to the curve shown in Figure 6. Tests were run with on-off times of 15 minutes for the test runs shown in Section 4.2 because the DOE procedure [5] uses 15 minutes as the assigned burner on and off periods in the calculation of the part-load cyclic efficiency. Other burner on-off times were investigated and those results are reported in Section 4.3.

4.2 Variable Heating Loads and Control Settings

Table 1 summarizes the results obtained in seven tests of varying heating loads varying from 18,500 Btu/h to 33,400 Btu/h. Figure 7 shows the data obtained in four of these tests (tests 1, 2, 4 and 7 from Table 1).

This series of tests was run using the second method of test described in Section 3.3 (i.e. the temperature rise of water in the holding tank over the test period to calculate the load). Boiler water temperature in the piping system leaving the boiler and entering radiators in the holding tank is labeled "Water In" in Figure 7. Boiler water out of the holding tank at the entrance side to the boiler is labeled "Water Out."

The effect of the cold water in the line on start-up is apparent in Figure 7. At the start of the first test (A), water temperature in the piping system is shown to be near 80°F. As this water heats up to approximately 157°F leaving the boiler (water into holding tank radiators), the gas pressure drops to approximately 2 inches W.C. after 8 minutes. Temperature

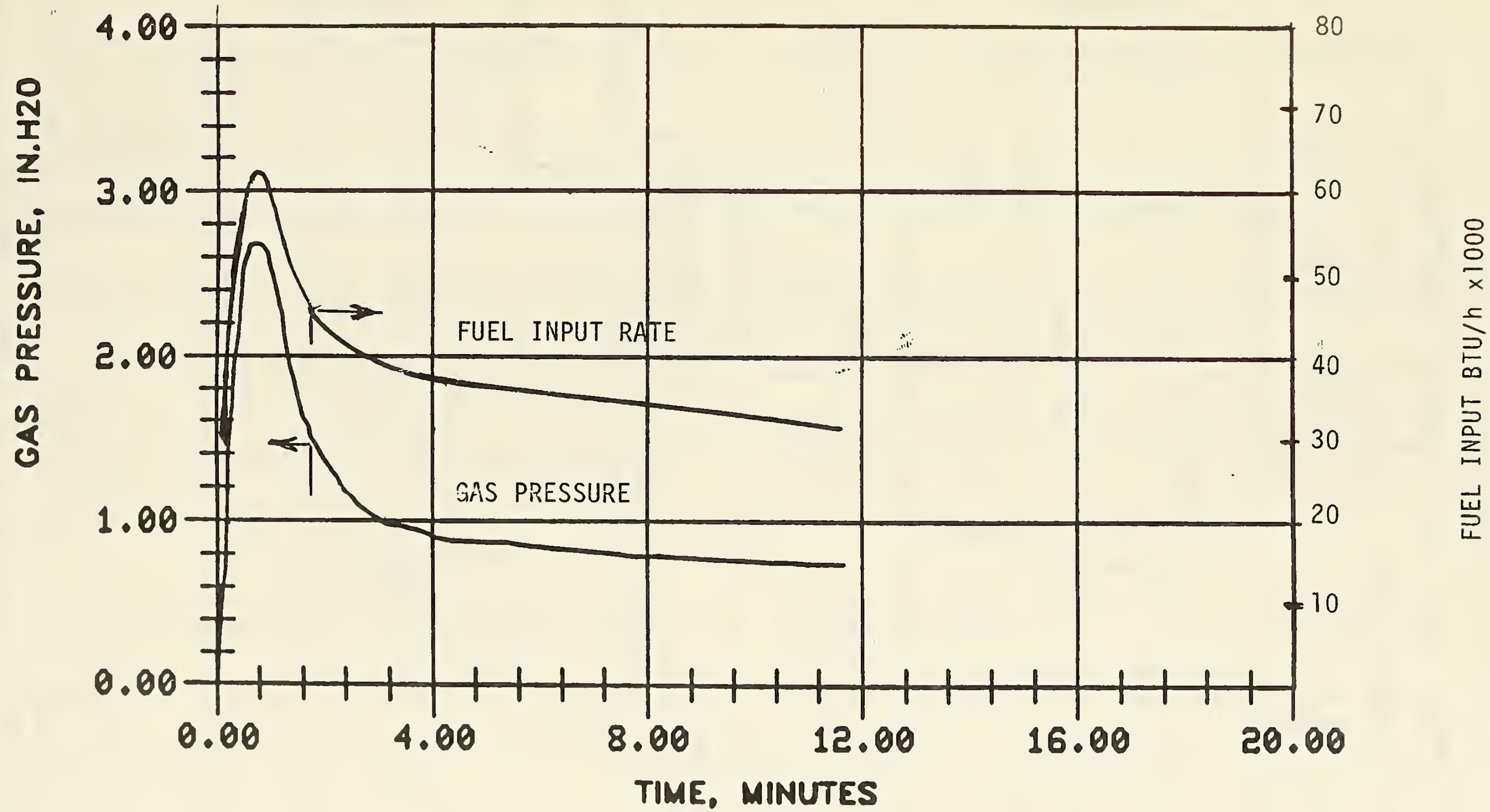
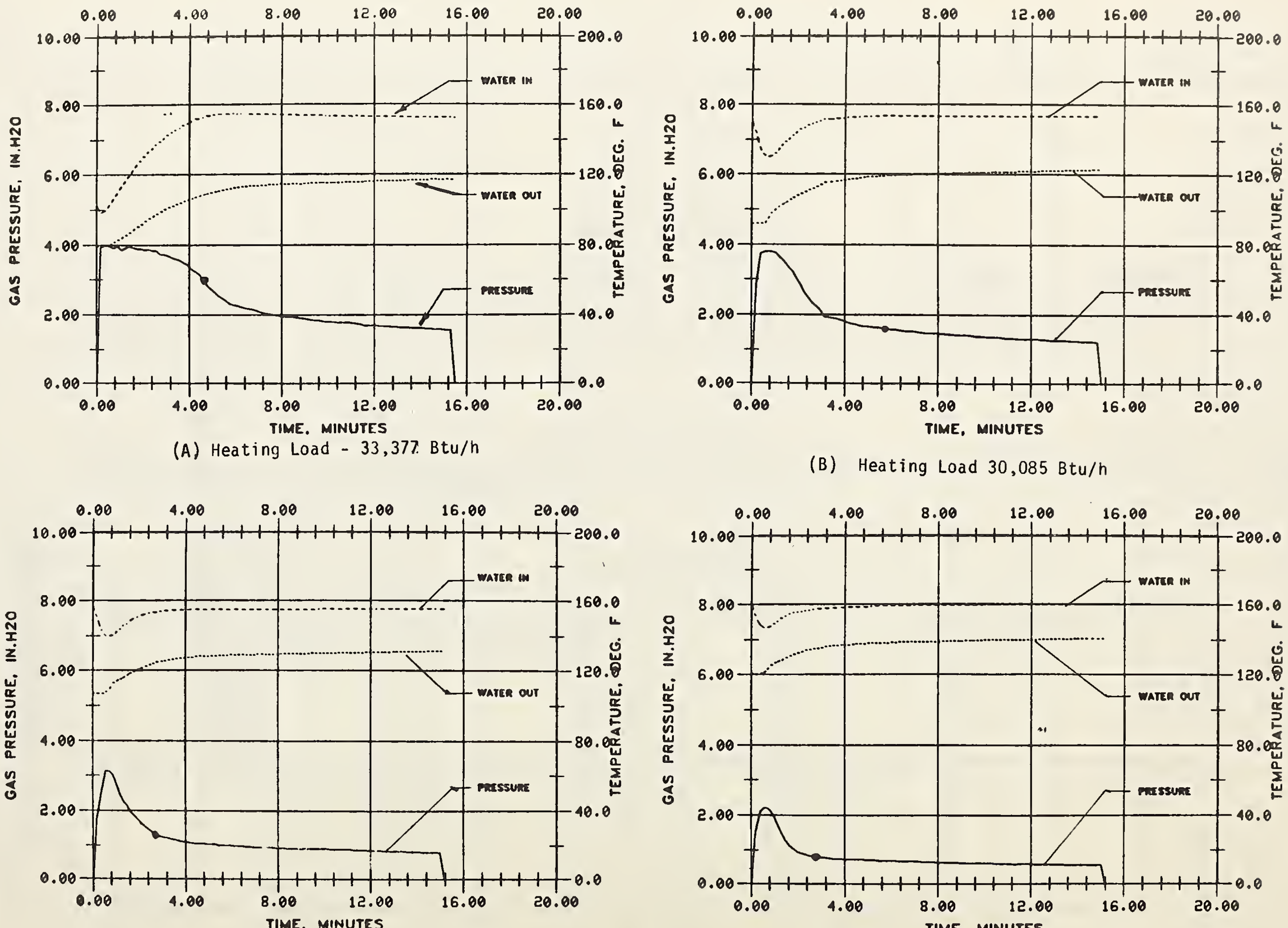


Figure 6. Modulating fuel response curve of gas pressure and fuel input rate vs. time after burner start-up.



(A) Heating Load - 33,377 Btu/h

(B) Heating Load 30,085 Btu/h

(C) Heating Load - [illegible],749 Btu/h

(D) Heating Load - 18,445 Btu/h

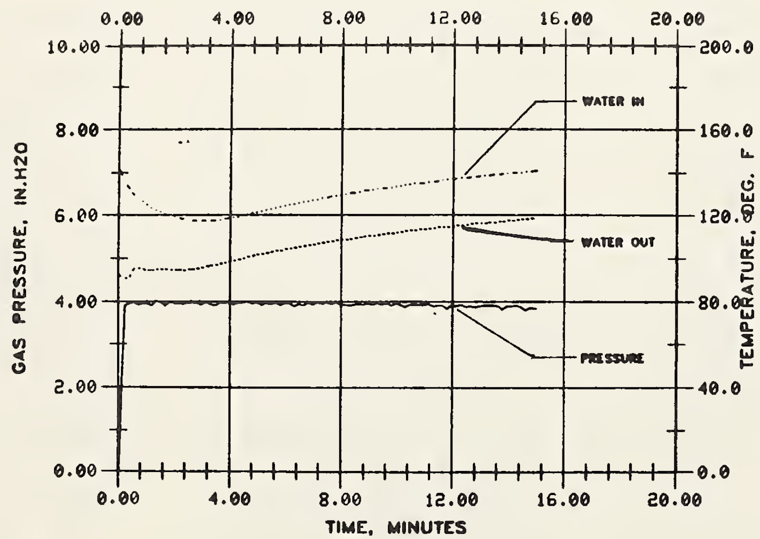
Figure 7. Modulated gas pressure and boiler water temperature in and out of holding tank vs. elapsed time after burner start-up under four heating load conditions, using control setting No. 6

rise across the boiler was then approximately 40^{o}F (i.e. 157^{o}F less 117^{o}F). The average gas pressure, equivalent fuel input rate, and holding tank water starting and ending temperatures data are shown in Table 1. The change in energy content of the tank plus the tank surface heat loss is taken as the tank imposed load in this series of tests. Boiler output rate was also determined by continuous measurement of boiler water temperature rise and boiler water flow rate. Boiler output rate is, therefore, practically the same as the heating load measured at the holding tank. Part load efficiency from the data of the boiler input and output rates may also be determined. For the data shown in Table 1, the part load efficiency based on output to input ratio varies from 60% for Run No. 1 to 56% for No. 7. In this test, the boiler loop water flow rate was 1.8 gallons per minute. Results of three additional series of tests at control settings No. 8, No. 2, and No. 4, are shown in Figure 8, 9, and 10. Figure 11 summarizes these test results for control settings No. 6 and 8, with gas pressure versus time for the various heating loads tested.

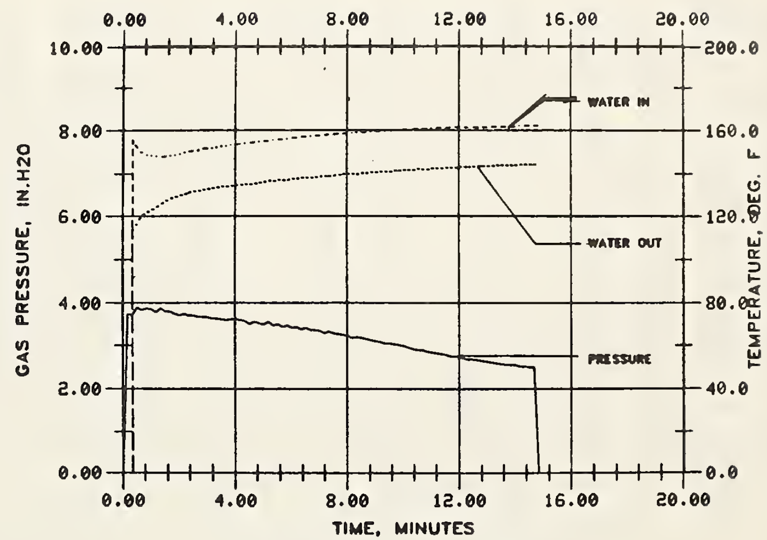
4.3 Zone Control

The procedure used for simulation of zone control for these laboratory tests was described in Section 3.6.5. During these tests, the pump was cycled off with the burner. The method of the load control for these tests was by a measure of the flow of water through the holding tank and temperature rise of the water from the water supply line to the drain line (See 3.3 for details).

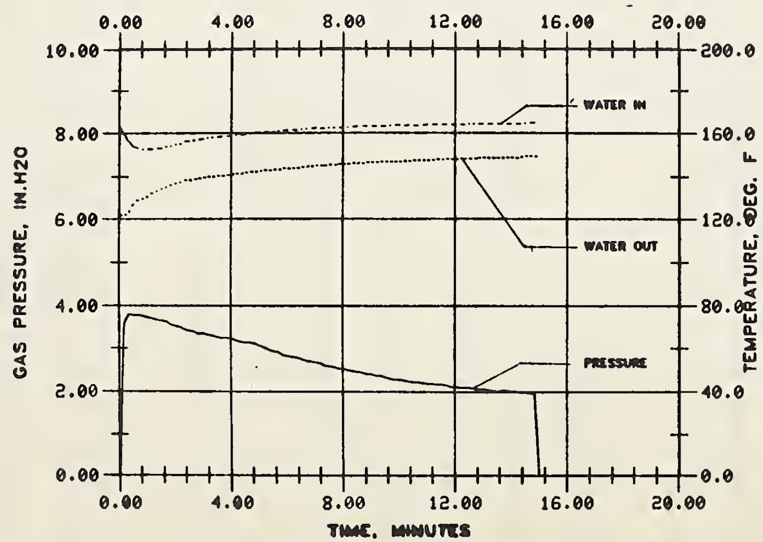
Results of these tests do not impact on the existing DOE test procedure [5] because zone control is not considered in the calculation of part-load or annual efficiency. The objective of these tests as with previous tests with load control was to observe the effect of modulated fuel gas pressure



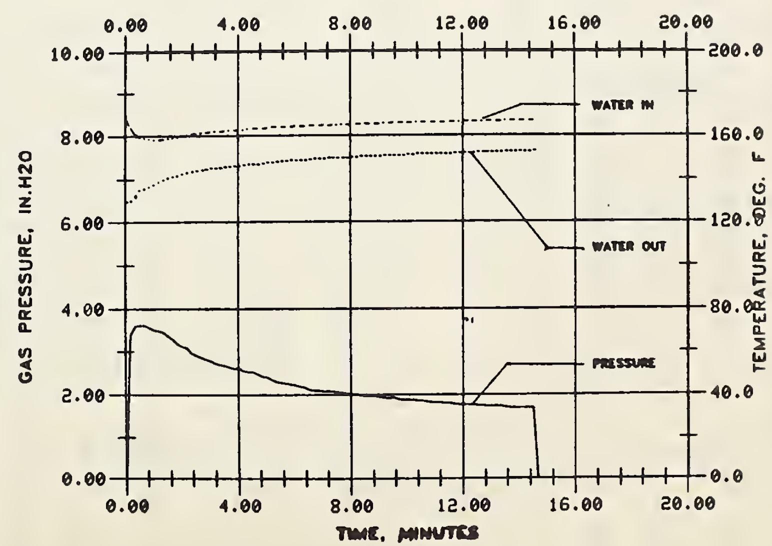
(A) Heating Load -58,618 Btu/h



(B) Heating Load -54031 Btu/h



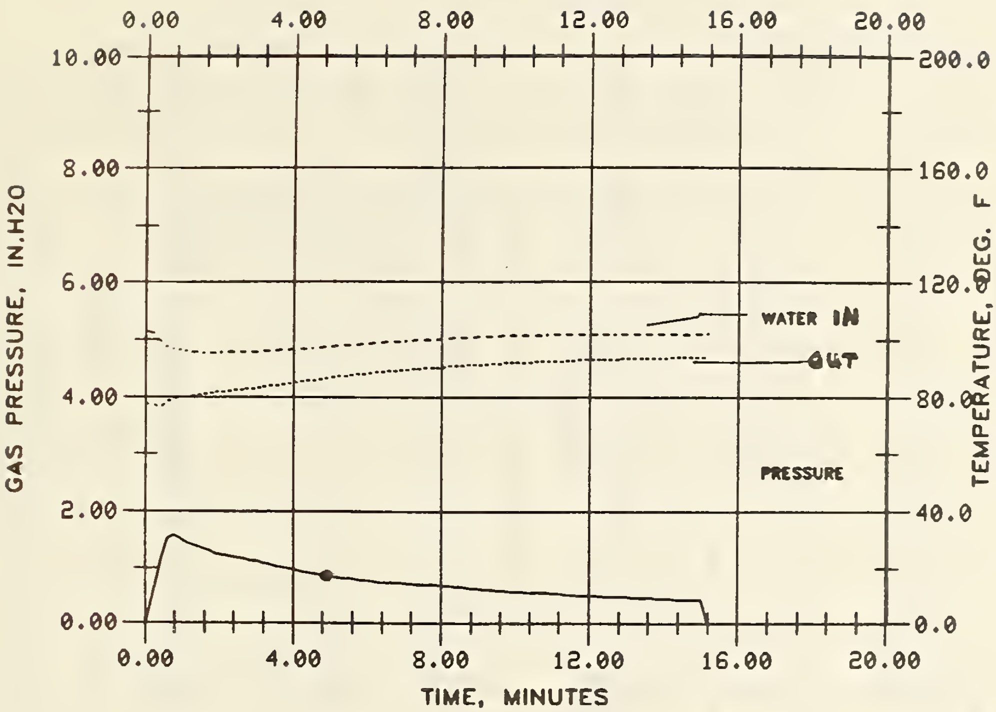
(C) Heating Load - 45,954 Btu/h



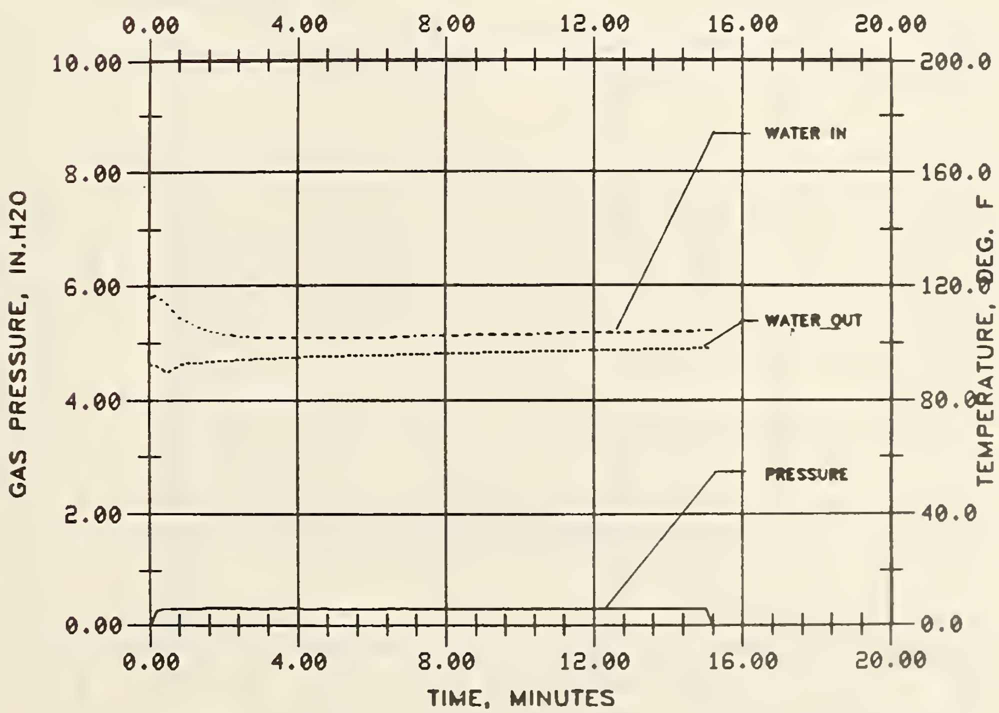
(D) Heating Load 41,961 Btu/h

Figure 8. Controlled gas pressure and boiler water temperatures vs. elapsed time after burner start-up under four heating load conditions using control setting No. 8.

F

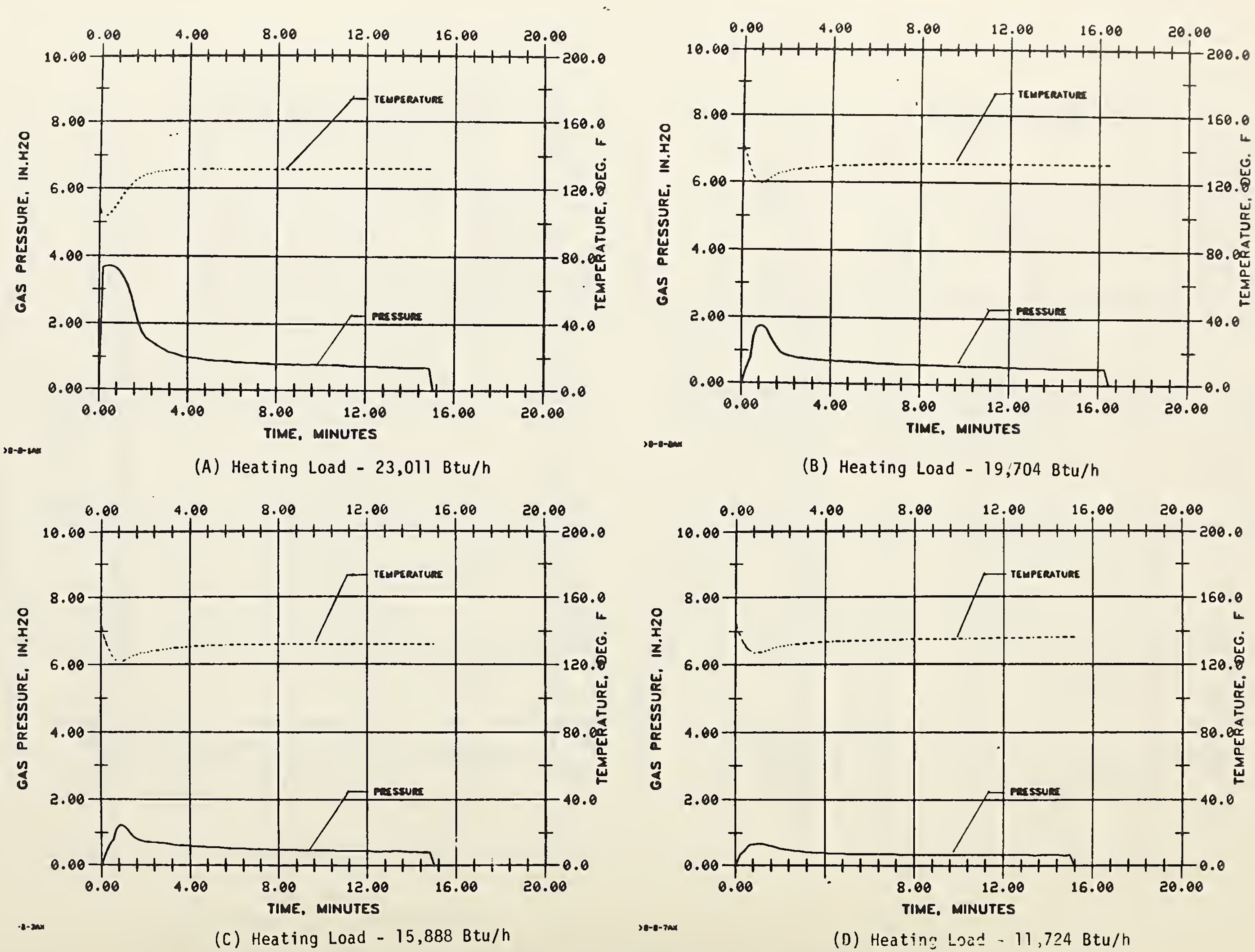


(A) Heating Load -15390 Btu/h



(B) Heating Load -12109 Btu/h

Figure 9. Modulated Gas Pressure and boiler water temperature in and out of holding tank vs elapsed time after burner start-up using control setting No. 12



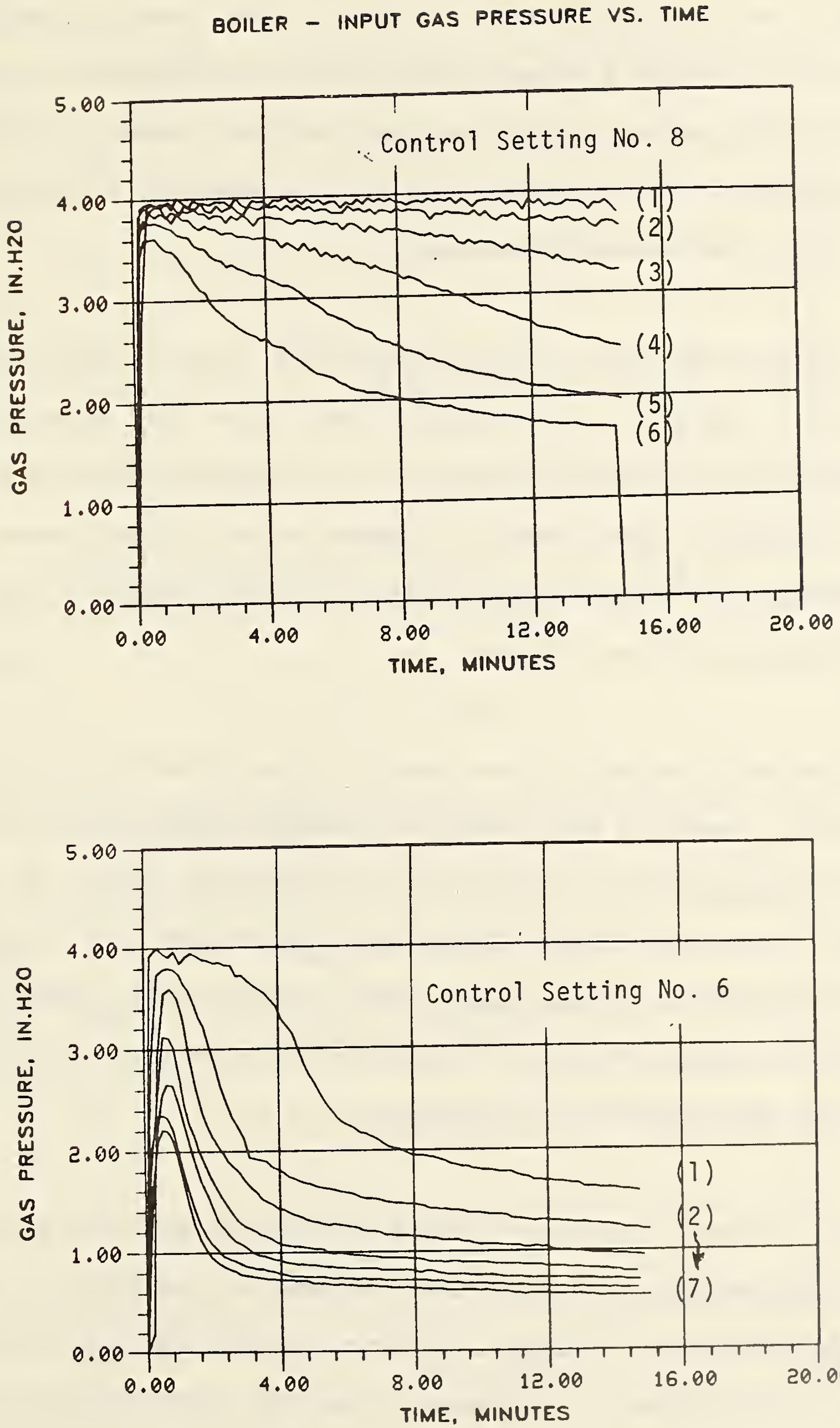
(A) Heating Load - 23,011 Btu/h

(B) Heating Load - 19,704 Btu/h

(C) Heating Load - 15,888 Btu/h

(D) Heating Load - 11,724 Btu/h

Figure 10. Modluated Gas pressure and water temperature entering boiler (out of holding tank) vs. elapsed time after start-up using control setting No. 4



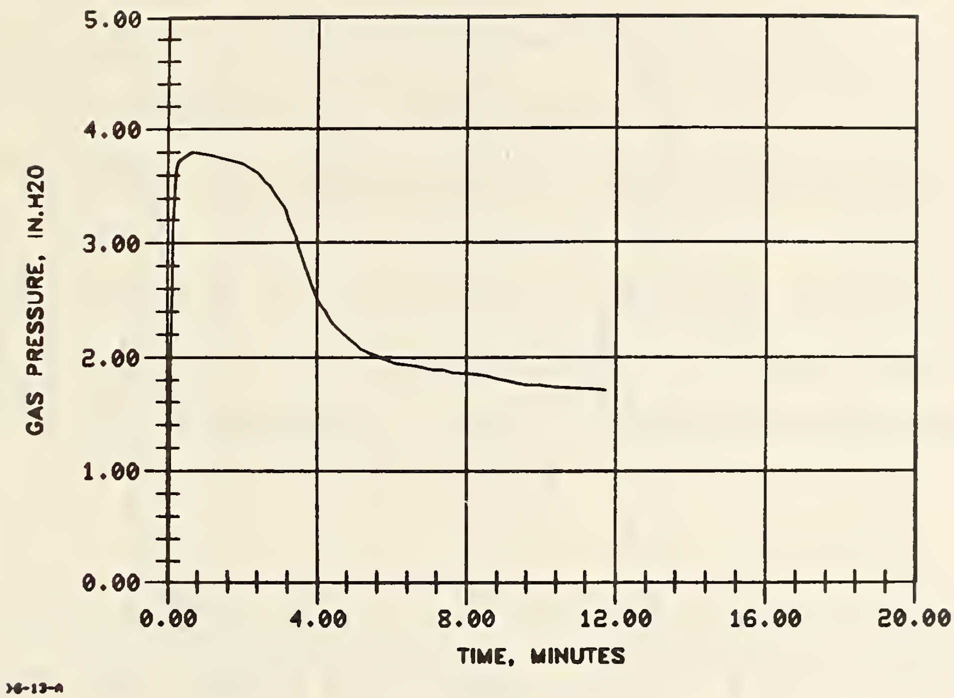
ıre 11. Modulated gas pressures for various heating loads vs. elapsed time after start-up

during the burner operation period. In these tests, results reported are from the third cycle of a three cycles test and represent a repeatable condition. Tests were run with one, two and four zones in operation. Results with one zone in operation was almost identical to the two zone results and are therefore not reported.

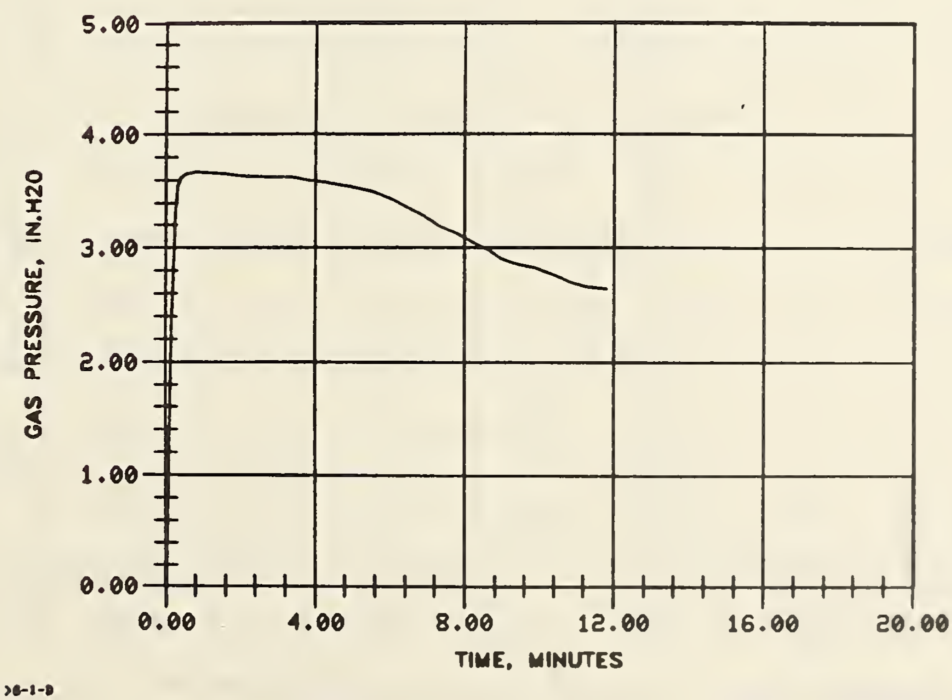
Figure 12 shows the results obtained with two zones in operation (two sections of 4 radiators per section in use) versus four zones (sixteen total radiators) using control setting no. 6 . These test results are also reported in Table 2. These tests are compared using the same burner on-off periods because the length of burner on-off periods (cycling rate) also affects the modulated gas pressure.

Figure 13 shows the effect of zone control using the modulating control setting No. 3. Figure 13 also shows the secondary effect of burner on-off times. The comparisons in Figure 13 are between (A) versus (B) and (C) versus (D) for the zone control effect, while (A) versus (C) and (B) versus (D) shows the effect of cycling rate. Test results are also shown in Table 3 for the test runs of Figure 13. (Section 4.4 discusses the effect of burner cycle rate results in more detail.)

The effect of these zone control tests could be considered as simply a change in the heating load due to the increase in heat transfer surface area of the radiators in operation. An increase from two zone to four zone operation was in effect an increase in heating load by 50% at control setting No. 6 (see Figure 12 and Table 3), and 25% increases for control setting No. 3 (Figure 13).

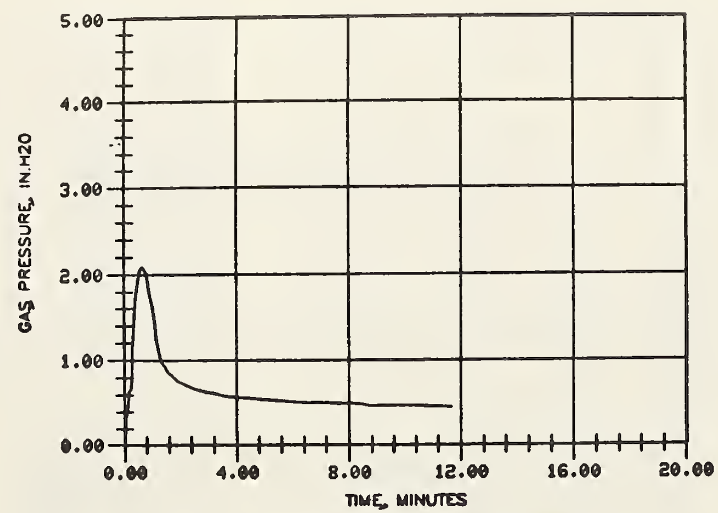


(A) Two Zones

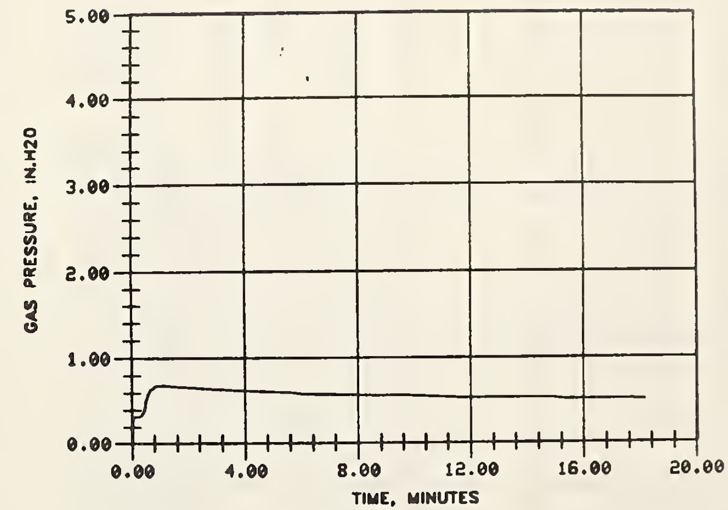


(B) Four Zones

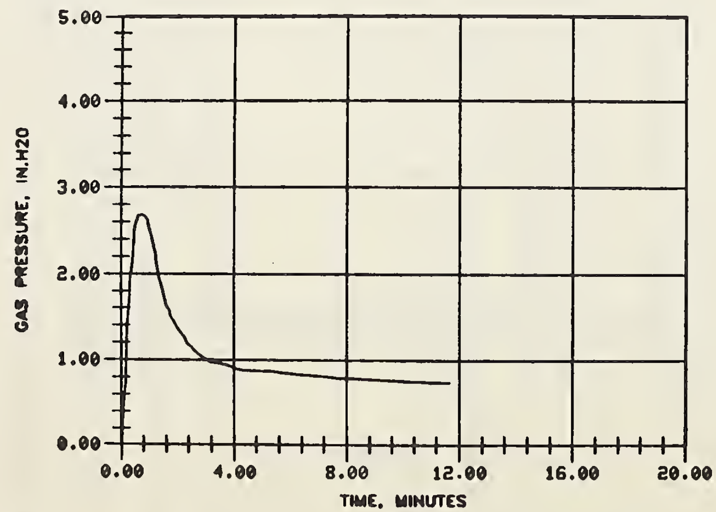
Figure 12. Modulated gas pressure vs. elapsed time after start-up at control setting No. 6 showing effect of two zone vs. four zone operation



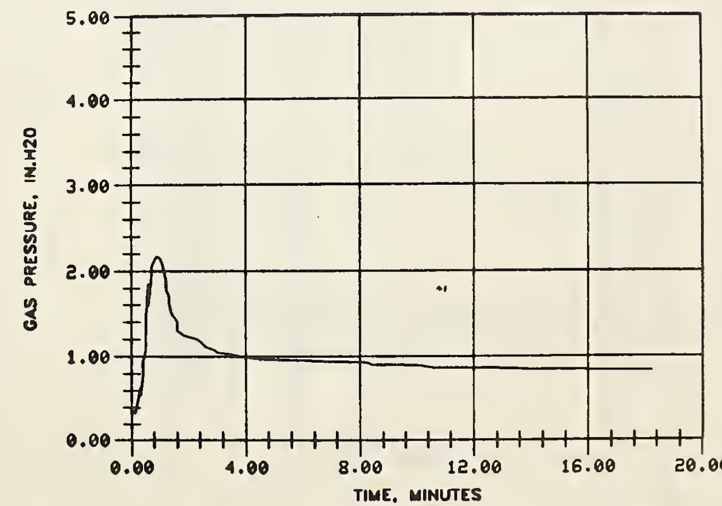
(A) Two Zone -11.7 min.on,20.8min. off



(C) Two Zone - 18.3 min. on 12.7 min. off



(3) Four Zone - 11.7 min. on,20.8 min.off



(D) Four Zone 18.3 min. on,12.7 min. off

Figure 13. Modulated gas pressure vs. time after start-up at control setting No. 3 showing effects of two zone vs. four zone operation for two cycling rates

4.4 Burner Cycling Rate

Effects of burner on-off times on the modulated gas pressure was shown in Figure 13 in combination with zone control. Another set of test data is shown in Figure 14 for three on-off periods. Test results for Figure 14 are also summarized in Table 4. The results of these tests all show that the shorter off-period decreases the peak gas pressure on start-up. This is due to the fact that water temperature drop in the piping system is less on start-up and the subsequent response of the modulating control gas valve.

The colder the boiler water is at start-up the more pronounced the peak and the longer is the duration of elevated pressure on start-up. This can be seen by comparing the boiler water temperature data on start-up or at 25 seconds after start-up in Table 4 with the curves of Figure 14. (See Section 5.1 for more discussion of the modulating control response to varying water temperature in the lines.) Higher control settings accentuate this effect. The effect is more apparent in the data of Figure 14 at control setting No. 6 then in Figure 13 with a No. 3 setting. This is due to the faster rate of cooling of water in the piping system at the higher control settings. Rate of cooling in the lines in this test with radiators immersed in water was considerably faster than it would be if the test had been operated with natural convective heat transfer with room air. However, these data are still considered to reflect field conditions. The lower heat transfer with natural convectors would be offset by increased loss through the piping system because the heat transfer surface area of the total piping system in the home would be very much (perhaps ten to 100 times, depending on the installed condition) greater than in this laboratory test. These tests were run with a very short run of piping

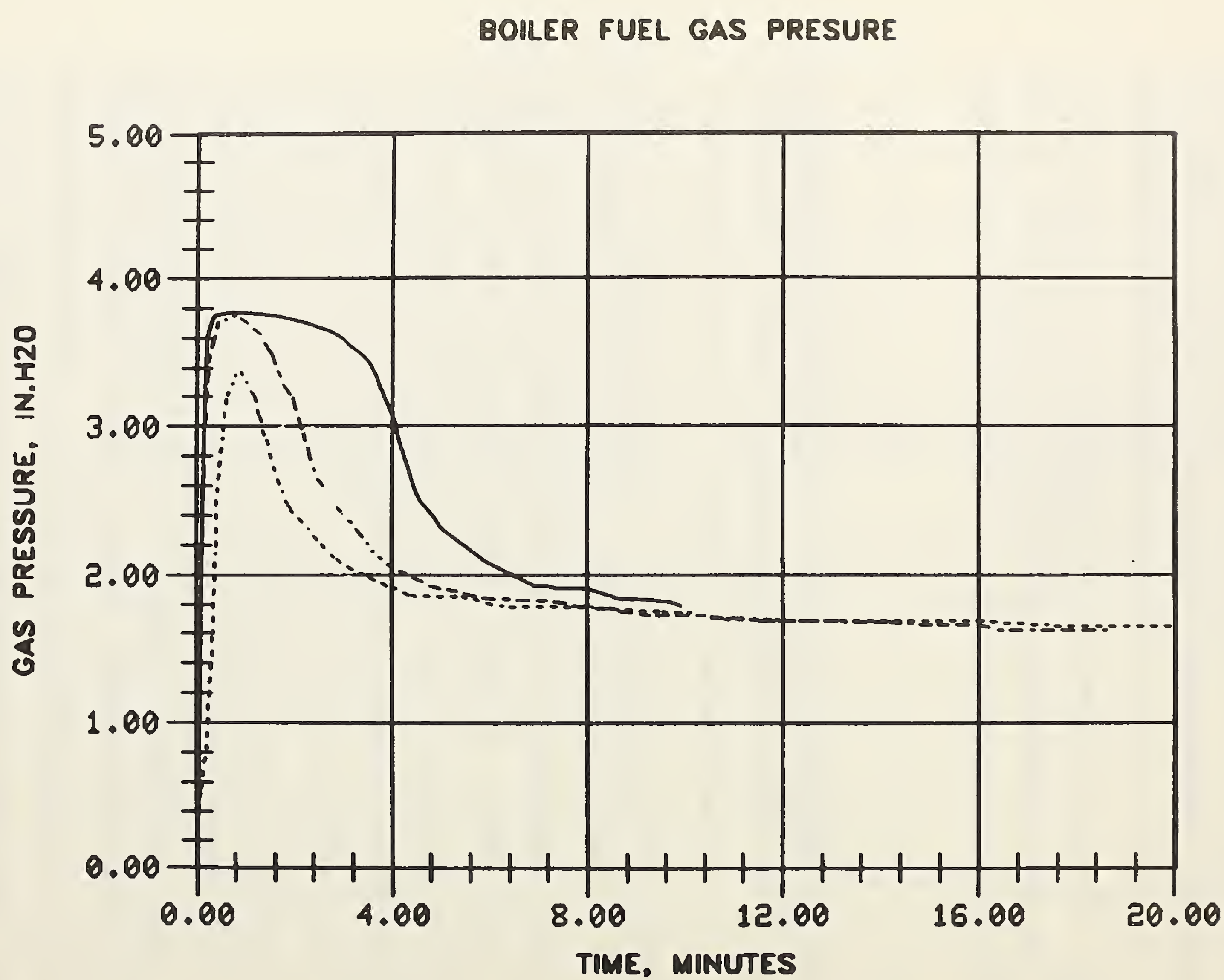


Figure 14. Modulated gas pressure vs. time after start-up showing effect of burner cycling rate

(A) - 10 min on,30 min off ; (B) 18.7 min on,12.5 min off ; (C) 75 min on,8.3 min off between the boiler and the tank. It should be expected that a decrease in this peak effect would result with a large volume of circulating boiler water.

In order to account for the effect of this peaking of gas pressure on start up under cycling conditions, the reduced output rate would need to be adjusted. The effect of adjusting this output would be to reduce the calculated balance point (TC) with a subsequent increase in effect of efficiency at the reduced input because of an increase in the value of (X-1). The time weighted average gas pressure during the 15 minute on-period would need to be calculated. The difference between this average pressure and the steady state pressure as now used in the procedure can be seen in figure 7 by comparing gas pressures corresponding to the average (see dot marked on curve) with the steady value (after 15 minutes). This difference would not be as noticeable if it were shown in terms of fuel input rate because input varies as the square root of pressure drop. See figure 6 for that comparison. No changes are being recommended for this effect because the difference is small in comparison to the greater effect described below in Section 5.1.

4.5 System Volume

Test results were not conclusive in any of the data comparing results with and without the added piping volume. Therefore, no data is presented on this aspect of the testing. An expected effect that may have resulted with more extensive system volume variation was discussed in Section 4.4.

5.0 Discussion

The purpose of this section is to point out the similarities or differences between the assumed modes of operation used in development of the DOE procedures for modulating furnaces and vented heaters and the results found here with a fuel modulating controlled boiler.

5.1 Operation in the Cyclic Mode

Previously, representations of burner cycling were described schematically as shown in Figure 1. Figure 1 shows shaded areas of cyclic burner on periods up to the balance point (Tc). These are shown as distinct step changes from the off condition of the burner to the minimum input rate. The burner is then shown to operate at constant rate until the thermostat caused the gas value to step to the off condition. The representation of burner response in Figure 1 applied when the sensing element was sensing room air temperature near the heater. (The sensing bulb with a room heater is located near floor level behind the heater.) In most tests of this modulating controlled boiler, the response of the modulating control at burner start-up was similar to the response shown in Figure 6. This response differs in appearance from that previously used to describe the space heaters cyclic operation. The initial peak of the curve (as shown in Figure 6) is followed by a drop in pressure to a practically continuous and steady pressure. This response was characteristic of all test results obtained. The only variation in results was in the accentuation of the peak condition at start-up with the various tests. The reason for the peak on start-up is due to a drop in temperature of boiler water in the piping system to a temperature below the set point temperature of the control. The first water sensed by the control when the pump starts up is this relatively cold water in the lines. The controller senses this temperature and compares it to the control set point. With this water temperature lower than the equivalent control setting, the burner increases fuel input above the minimum fuel input rate. After all boiler water in the piping system loop has passed through the boiler, the cold water has been purged from the system and is replaced by hot water. Immediately after the cold water is purged, the control senses the water temperature to be above the set point and responds by reducing gas pressure. This condition results at approximately one minute after the initial start-up as shown in Figure 6 by the drop in gas pressure at that time. In all test results, a time weighted average gas pressure during the burner on-period was calculated. The average pressure for the curve shown in Figure 6 was 1.04 inches of water.

The DOE Test Procedure [5] calls for operation at the minimum input rate for determining a part load cyclic efficiency. In reality, operation with the minimum boiler water temperature conditions is questionable for this boiler which would require manually resetting to a lower setting after the boiler control is adjusted at the time of installation. Discussions with a boiler installer has revealed that it is unlikely the control would be reset by the homeowner after installation and unlikely he would be told to reset it by the installer, since that could lead to complaints of insufficient heat output during coldest weather. In the absence of an automatic reset control that would control to minimum input, it is not likely that operations at any time would exist with the minimum boiler water setting. It is, therefore, probable that part load efficiency of manually adjusted modulating boilers in the field will be somewhat inconsistent with that predicted by DOE procedures in laboratory testing. This is because off-period loss would be greater (with conventional atmospheric burner) since the boiler water temperature would be at a higher temperature, (i.e. 160 F in Figure 7 at No. 6 setting compared to approximately 100 F with control setting No. 2). The operating temperatures specified for these two settings in the manufacturers instructions shown in Section 3.4 are as follows:

195 F at Control Setting No. 6

135 F at Control Setting No. 2

Tests were not run with this boiler to quantify what effects this change in water temperature would have on the part load efficiency. However, tests were run previously at NBS (but not previously published) using a hot water boiler of the same rated input as this unit (80K Btu/h) at a variety of supply water temperatures. The following results were obtained for that boiler:

Boiler Water Temperature		Steady State	Part Load Sensible Loss		Part Load Efficiency %
Inlet	Outlet	Efficiency %	Ls on (%)	Ls off (%)	(Nu)
123°F	146°F	80.1	8.4	7.4	71.4
149°F	171°F	80.2	9.5	8.5	69.2
165°F	185°F	79.5	10.2	9.1	67.9

In addition to the lower efficiency that would result at the higher boiler water temperature, annual efficiency would be less in the field because the boiler would operate more of the time in a cycling mode. That is, the fraction of operation in the cycling mode would be greater since the higher boiler water temperature could satisfy a greater fraction of the total annual heating load. Therefore, the weighting factors calculated by the DOE procedure would use less weighting at the reduced input cycling mode than would result in the field.

With this test boiler adjusted to the manufacturers recommended control setting (No. 6) the data shown in figure 7-D applies. With a supply water temperature of 140 F and a 20 F rise, the burner output rate after 15 minutes was 22,200 Btu/h. This output rate results in a calculated balance point temperature of 25 F (vs. 36 F with the current test procedure) and corresponds to annual heating load fraction for reduced input (X-1) of 81% (vs. 51% under the current method method of test).

Another inconsistency with the current DOE procedure exists between the supply water temperature to the boiler in laboratory testing (i.e. constant 120°F) and the changing supply water temperature found in these simulated use tests. In all tests run as shown by Figures 7 through 10, the supply water temperature to the boiler at burner start-up was continuously increasing after burner start-up. In other words, it can be seen that supply water temperature to the boiler is not a straight line. In Figure 7, system return water out of the radiators at start-up compared to four minutes after start-up was 12°F lower. One result of this change in supply water temperature is the peaking of fuel input rate after start-up. No changes are recommended to correct for this in the DOE procedures for the following reasons:

The DOE procedures [5] calls for collecting data of the flue temperature during a heat-up test to steady state conditions at the minimum input, followed by measurement of flue temperatures during a cool down test from the minimum input steady state condition. Flue gas temperatures on heat-up are measured at 1.0 minute and 5.5 minutes after start-up. The calculation of an on-period time constant (τ on) requires that the steady state flue gas temperature be greater than flue gas temperature measured one minute after start-up. If it is not greater, the on-period time constant (τon) would be impossible to calculate and be undefined. It follows from the curves of modulated gas pressure versus time that fuel input rate may be greater one minute after start-up than after operating 15 minutes or at steady state operation, particularly for the higher control settings, No. 6 (see Figure 7) and No. 8 (Figure 8). If a water supply temperature profile was to be used in laboratory tests to reflect actual use profile as shown by these figures, this could result in the temperatures being greater at one minute after the start-up than at steady state, due to the drop in fuel input rate. For this reason and the need to calculate the on time constant as described above, a constant supply water temperature is necessary for laboratory testing.

5.2 <u>Operation In The Non-cycling Mode</u>

The response curves of Figure 7 and 8 are at heating loads which would all be considered to be above the balance point used in the DOE test procedures. The balance point equivalent load for this boiler is considered to be 15,000 Btu/h which is the minimum adjusted output rate of the boiler. Therefore, the cycling mode of this boiler would apply to the heating load conditions shown in Figures 10(C) and (D) with control setting No. 4, and to the two loads shown in Figure 8 with control setting No. 2. The DOE procedure specifies on and off times of 15 minutes for boilers. All the tests were run with burner on periods of 15 minutes followed by a 15 minute off-period. Above the balance point the DOE test procedure does not consider on/off cycling in the calculation procedures with the step modulating type control. However, if the control were the two stage type, on/off cycling would apply.

The average gas pressure condition that would exist with burner on/off cycling can be seen on the pressure curves of Figure 7 where the solid circle on each curve shows this average pressure. Without cycling and with continuous modulation (assuming no cycling operation below 36^{o}F), the average pressures would be similar to those steady pressure conditions for the heating loads shown at 15 minutes in Figure 7. The design heating load that would be applicable with this boiler installed assuming it was 70% oversized would be: (maximum output - 1.7) = 33.173 Btu/h (i.e. maximum output measured was 56,395 Btu/h). This would apply at a design temperature of 5^{o}F. Therefore, the heating loads shown for control setting No. 8 in Figure 8 would apply only when the boiler were less than 70% oversize. For example referring to Figure 8(D), the oversize fraction at designs conditions for a 41,961 Btu/h heating load would be: 1 - [56395 - 41,961] = 0.34, or 34% oversize. This is not to say that burner fuel input rate would never exceed this rate. Since the boiler water is cold on start-up, particularly after an extended off-period, such as after night setback, the maximum fuel input condition as shown by Figure 8-A could well exist even with 70% oversized boiler. When adjusted at the manufacturers recommended modulating control setting for this boiler (i.e. No. 6 setting), the operating gas pressure that would be expected to apply in the modulating modes are those shown in Figure 7. Figure 15-a shows a representation of the gas pressures versus time for three heating load conditions simulating Figure 7 data. Figure 15-b shows these average gas pressure (solid dots) versus equivalent outdoor temperature. By plotting these as average loads, versus outdoor temperature as shown in 15-b a curve results that would be similar to that part of Figure 1 from the balance point Tc to the design temperature of 5^{o}F. Figure 15-c shows this curve more specifically by using data from columns (6) of Table 1.

6.0 RECOMMENDATIONS

It is recommended that the DOE test procedures be revised to specify that when a manufacturers installation instructions include a recommended setting of the modulating control (i.e. boiler water temperature setting) that testing at reduced input rate be carried out with a boiler water temperature consistent with that recommended setting. It is recommended that a supply water temperature be specified that is 20°F less than the resulting boiler water temperature found when the boiler is operated with the manufacturers recommended control setting. If there is no recommended control setting supplied by the manufacturers installation instructions, the supply water temperature used should be 20°F less than the resulting outlet water temperature found when the control is set at the mid-point setting of the control valve.

It is also recommended that the average output rate measured at the manufacturers recommended setting (or mid-point setting) be specified as the minimum output rate to be used in calculation of the balance point (T_c).

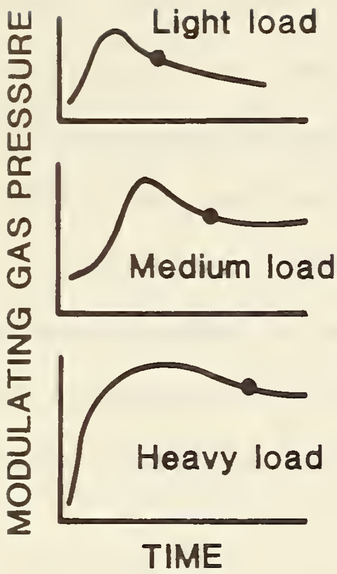


Figure 15 (A)

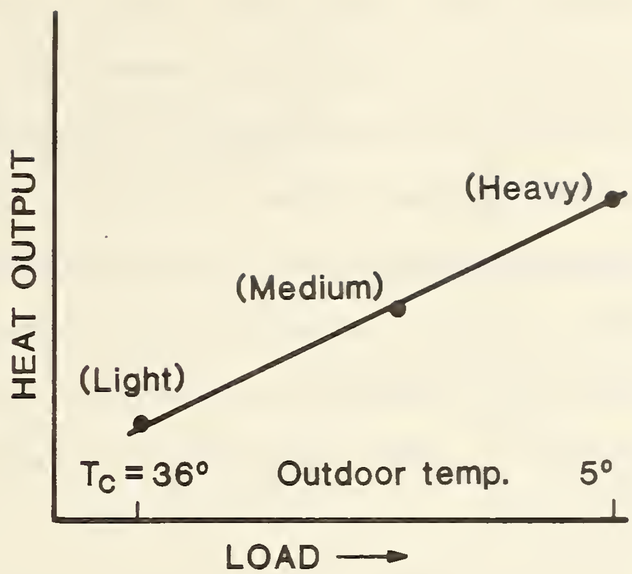


Figure 15 (B)

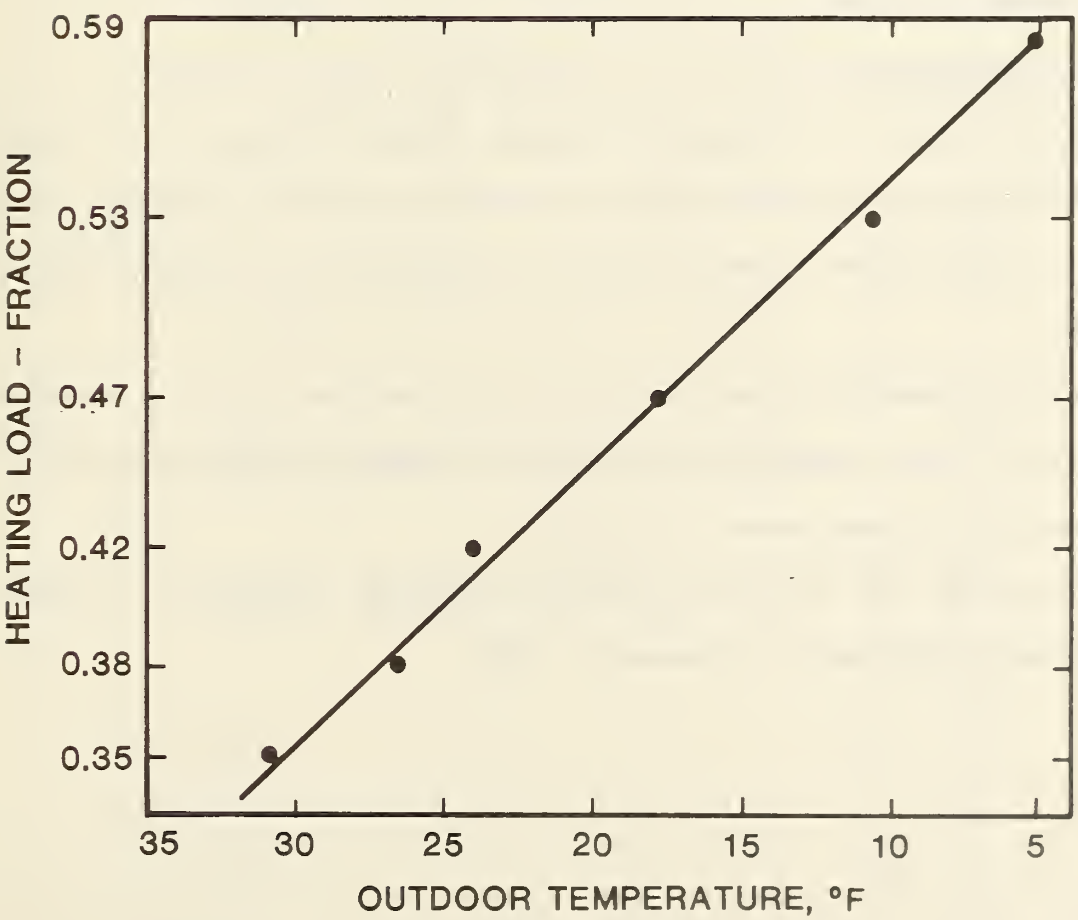


Figure 15 (C)

Figure 15. Upper left (A) Representation of data obtained. Upper right (B) Representation of data expressed as it relates to outdoor temperature. Lower figure (C) - Example of actual test data obtained at No. 6 Setting.

References

(1) Kweller, E.R. and Palla, R.L., "A Test Method and Calculation Procedure for Determining Annual Efficiency for Vented Household Heaters and Furnaces Equipped with Modulating Type Controls," NBSIR 82-2497, National Bureau of Standards, Gaithersburg, MD 20899.

(2) Federal Register 48, No. 118, pp. 28014-28046, June 17, 1983.

(3) Kweller, E.R., "Analysis of Public Response to Proposed Department of Energy Test Procedures for Furnaces, Boilers, and Household Heaters," February 7, 1984, Letter Report to Department of Energy, Washington, DC 20585.

(4) Letter from Mr. L. J. Ashton Raypak Inc. to Esher Kweller, September 24, 1982.

(5) Federal Register 49, No. 61, pp. 12148-12178, March 28, 1984.

(6) Kweller, E.R., "An Analysis of Burner On and Off Periods and Their Effect on Part-Load Efficiency for Furnaces and Boilers Equipped With Modulating Control," Letter Report to Department of Energy, January 1983.

(7) Scharer, Edward B., "Gas Heating Appliances and Controls Training Manual," Robert Shaw Grayson Controls Company, Form 28-181-0075D, January 1969, Long Beach, California.

(8) "Thermostat Gas Valves, V5155A,B," Honeywell Form No. 71-92082, Honeywell, Minneapolis, Minnesota 55408.

Table 1.

Test Data for Measured Heating Load for Control Setting No. 6.

(1)	(2)	(3)		(4)		(5)		(6)	(7)	(8)
Test No.	Average Fuel	Boiler		Tank Water		Tank Energy		Output	Load	Outdoor
	Gas Pressure inches w.c.	Input Rate Btu/h	Output Rate Btu/h	Start of Test (°F)	End of Test (°F)	Change of Water Btu/h	Jacket-Loss Btu/h	Load % of Max	Btu/h	Temperature Equivalent (°F)
1	2.40	56000	33531	80.4	90.7	33028	349	59 (1)	33377	5° (2)
2	1.76	50000	29944	91.8	100.4	28685	1400	53	30085	10
3	1.38	44500	26643	100.9	108.3	24147	1944	47	26092	18
4	1.13	40500	23599	108.5	114.6	20007	2672	42	22749	24
5	0.96	37000	21648	114.6	120.2	18198	3100	38	21298	27
6	0.84	35000	19941	119.8	124.3	14920	3915	35	18835	31
7	0.76	33500	18704	124.3	128.7	14172	4272	33	18445	32

(1) Boiler Output ÷ Max Boiler Output = 33531 ÷ 56395

(2) Calculated from relationship of proportions of Temperatures & Heating Load, adn based on Maximum Heating Load of Maximum Boiler Output ÷ $(1+\alpha)$ where α = oversize fraction or 70%

$$\frac{(65 - 5)}{(65 - T)} = \frac{(56395 \div 1.7)}{33377} \quad \therefore \; T = 5^{\circ}$$

Table 2. Zone Control with Modulating Control Setting #6 (See Fig 12)

	Zones in Use	Boiler Load * Btu/h	Cycle On time	Cycle Off time	Average Gas Press in. w.c.	Input Equivalent Btu/h
(A)	2	27,593	11.7	20.0	2.4	58000
(B)	4	41,126	11.7	20.8	3.3	68000

* Using Water flow thru holding tank to control heating load and hold tank water at approximately room temperatures.

Table 3. Zone Control with Modulating Control Setting #3 (See Fig 13)

Run	No. of Zones in use	Boiler Load	Cycle Times On	Cycle Times Off	Average Press	Average Fu Input Rate Btu/h
(A)	2	23,000	11.7	20.8	0.65	31,000
(B)	2	24,000	18.3	12.7	0.59	30,000
(C)	4	29,520	11.7	20.8	1.04	38,500
(D)	4	28,899	18.3	12.7	0.96	37,500

Table 4. Results obtained with variable burner on-off times (See figure 14)
Modulating control setting No.6

	time on (minutes)	time off (minutes)	imposed load load (Btu/h)	$t_{on} / (t_{on} + t_{off})$	Average Gas Pressure (inches) w.c.	Tank Temperature (F) Start	End	Boiler Water temperature @Start	+25 Sec.	End
(A)	10	30	37000	0.25	2.7	76.6	76.3	118.8	105	159
(B)	18.7	12.5	38600	0.60	2.0	75.4	73.9	163	124	155
(C)	75	8.3	40990	0.90	1.7	77.5	75.9	166	145	153

Table 5

UNITS CONVERSION TABLE: SI/INCH-POUND/SI

TO CONVERT	MULTIPLY BY	TO OBTAIN
Lb (Pounds)	0.454	Kg (Kilograms)
Kg (Kilograms)	2.2046	Lb (Pounds)
Cu. Ft. (Cubic Feet)	28.3	L (Liters)
L (Liters)	0.03531	Cu. Ft. (Cubic Feet)
in (Inches)	2.54	cm (Centimeters)
cm (Centimeters)	0.3937	in (inches)
ft (Feet)	0.3048	m (meter)
m (Meters)	3.281	ft (feet)
BTU (British Thermal Units)	1.055	K J (Kilojoules)
kJ (kilojoules)	0.9479	Btu (British Thermal Units)

TEMPERATURES (T), CONVERSION EQUATIONS:

FOR TEMPERATURE USE:

°F to °C: $[(T)^{\circ}F - 32^{\circ}F]\ (5/9) = (T)^{\circ}C$
°C to °F: $[(T)^{\circ}C]\ (9/5) + 32^{\circ}F = (T)^{\circ}F$

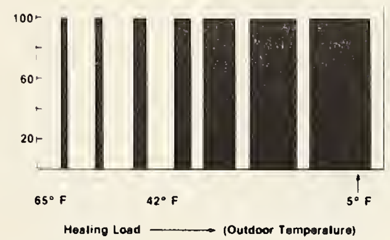
FOR TEMPERATURE DIFFERENTIALS OR TOLERANCE USE:

°F to °C: $(T)\ ^{\circ}F\ (5/9) = (T)^{\circ}C$
°C to °F: $(T)\ ^{\circ}C\ (9/5) = (T)^{\circ}F$

APPENDIX _- OVERVIEW OF TEST PROCEDURE FOR MODULATING FURNACES

Figure A-1. Over view of test procedure for modulating controlled vented heaters and furnaces (Read down)

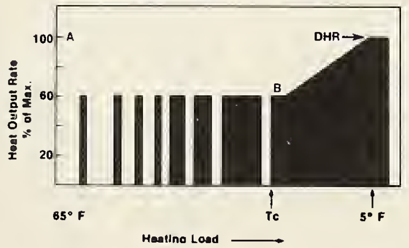
Single Stage Thermostat Control



The conventional furnace or boiler operates in an on-off cycling mode at the maximum fuel input rate in response to the thermostat control. (shaded area shows burner on)

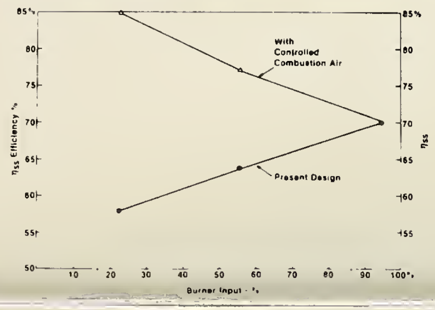
Many gas fueled room heaters and some hot water boilers use a modulating control which cycles the burner on and off at a reduced firing rate when heating loads are light, and modulates fuel firing rate between reduced and maximum rates as heating load changes. The modulating mode begins at a balance point equivalent to outdoor temperature T_C.

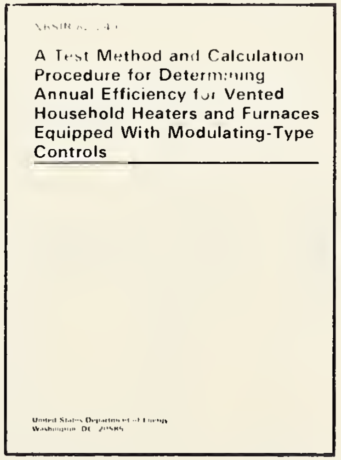
Step-Modulating Control



Since thermal efficiency can change with firing rate and since current test procedures only measure efficiency at maximum rated input, a procedure was needed for modulating controlled equipment to reflect in-use conditions and to credit improved controls. Significant efficiency improvement can be obtained with fuel modulation by controlling the combustion air supply.

These results were found using a 35 K Btu/h room heater.




A Test Method and Calculation Procedure for Determining Annual Efficiency for Vented Household Heaters and Furnaces Equipped With Modulating-Type Controls

United States Department of Energy
Washington, DC 20585

OBJECTIVES:

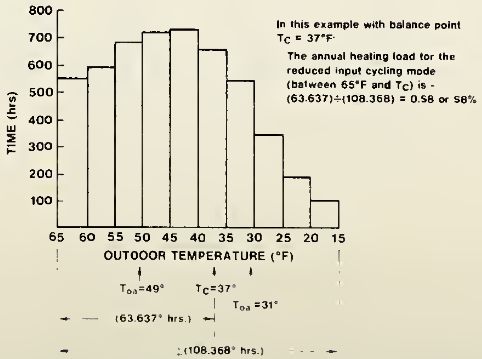
- Minimize testing involved
- Part load efficiency that reflects both operating modes
- Annual efficiency which credits improved controls

APPROACH:

Determine the weighted part load efficiency over the heating seasons

An average of the number of hours in 5°F Bins from weather data of cities across the USA can be used to determine annual heating degree hours between 65°F and a national average design temperature, T_D (15°F for space heaters; 5°F for boilers & furnaces) and between 65°F and any balance point temperature (T_C).

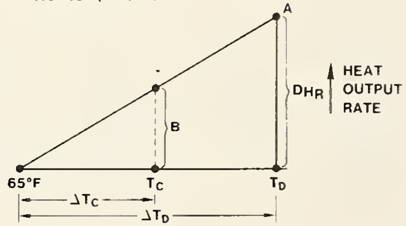
From these data a generalized table of values applicable to all furnaces and boilers and to all house hold heaters were developed. The figure below shows these generalized values for household heaters.



Example of bin method used to determine percentage of time in cycling mode

PROCEDURE FOR
LOCATING THE BALANCE POINT

Given a heater with maximum and reduced input rates, the corresponding output rates "A" and "B" are obtained by applying their measured thermal efficiency to each of the measured input rates.



From these similar triangles the ratio of heater output rate "B" (which is at the balance point T_C) to the heater output rate at the design heating requirement (which for heaters corresponds to the maximum output rate "A") is equivalent to the corresponding ratio ΔT_C to ΔT_D.

$$\frac{\Delta T_C}{\Delta T_D} = \frac{B}{DHR}$$

$$\therefore T_C = 65 - \Delta T_D\left(\frac{B}{A}\right)$$

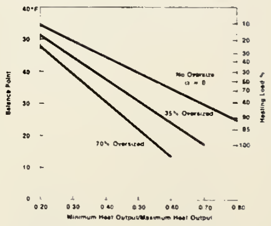
For heaters $\Delta T_D = 65°-15°$; for boilers $\Delta T_D = 65°-5°$.

When oversizing is applicable (i.e., for furnaces & boilers) the DHR < A and $T_C = 65 - \Delta T_D\left(\frac{B}{A}\right)(1+\alpha)$

For a known design heating requirement the oversize percentage α for a given heater is determined: $\alpha = \left(\frac{A}{DHR} - 1\right)100$

With balance point and oversize percentage known, the figure below shows generalized values developed for all household heaters.

Annual heating load % applicable to reduced input cycling mode



With annual heating load fraction applicable to reduced input rate (X) known, a weighted efficiency $(\eta u)wt$ follows:

WEIGHTED PART LOAD EFFICIENCY $(\eta u.\ wt)$

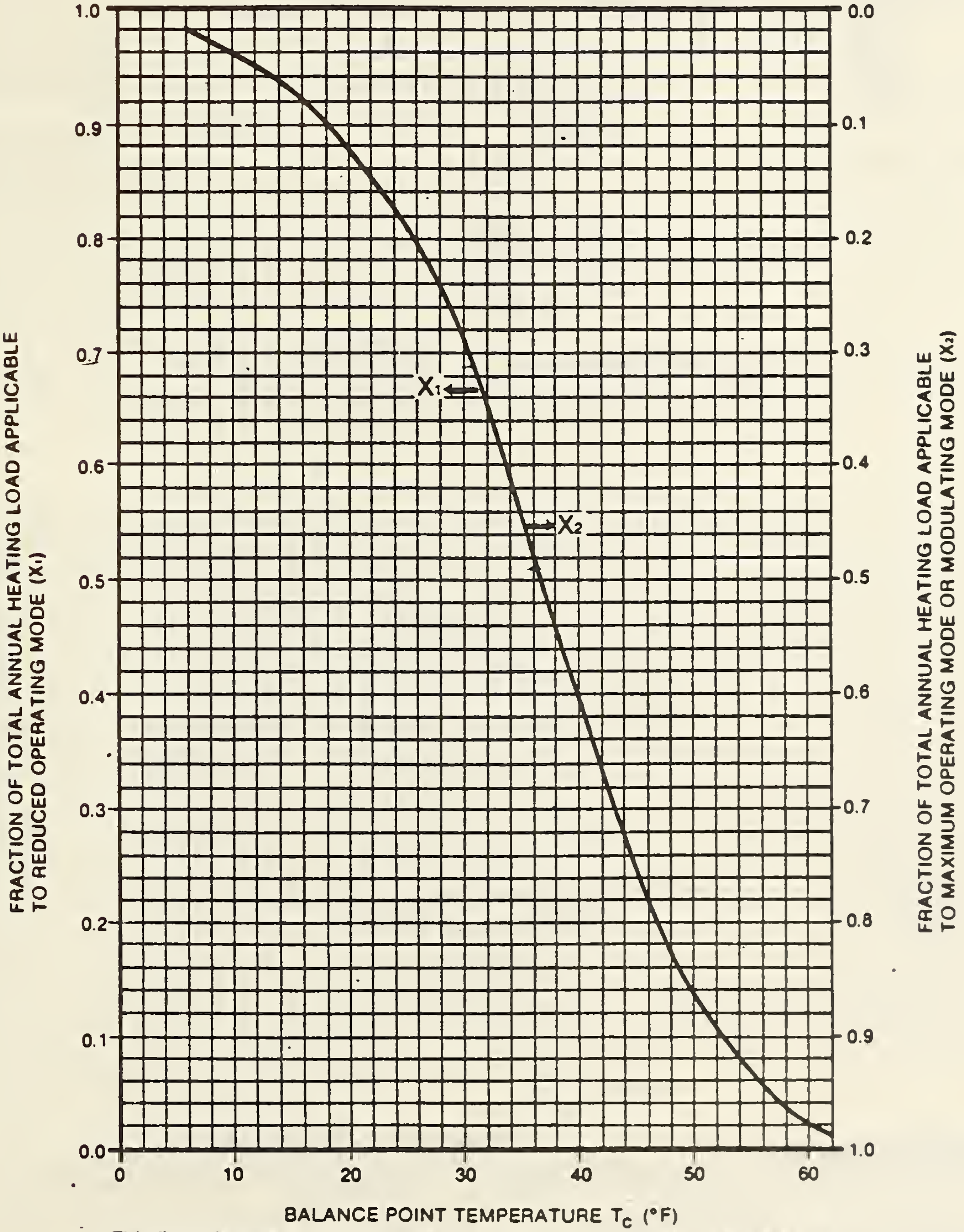
$$\eta u.\ wt = \eta u_{\text{Reduced Input}}(X) + \eta u_{\text{Modulating Input}}(y)$$

where x = Fraction of annual heating load at reduced input rate

y = Fraction of annual heating load in modulating mode = (1−X)

See NBSIR 82-2497 for further information

Fraction of Total Annual Heating Load Applicable to Reduced Operating Mode (X_1) and to Maximum Operating Mode or Modulating Mode (X_2) vs. Balance Point Temperature for Modulating Furnaces and Boilers.



This figure is based on 5200 degree-days and 5°F outdoor design temperature.

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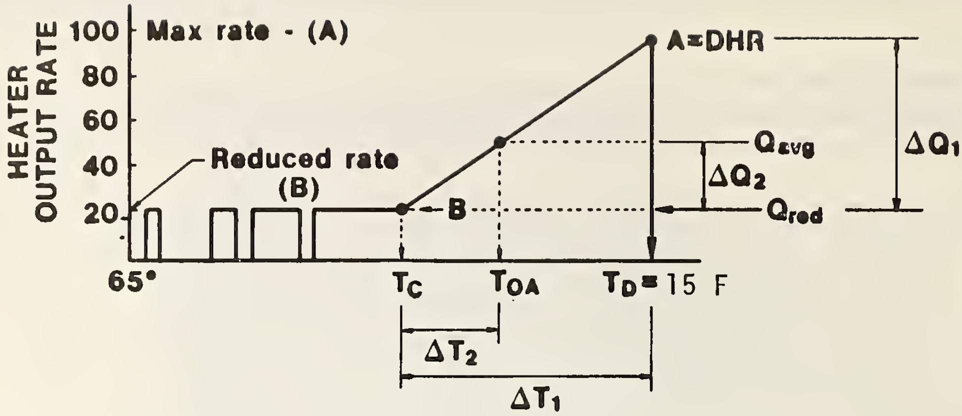
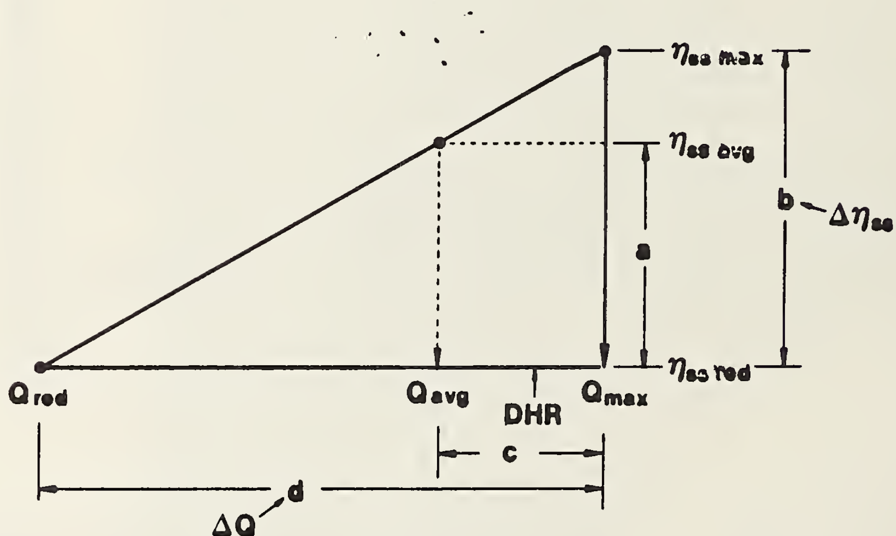
Figure A-2 Load fractions assigned to reduced input cycling mode and to modulating mode vs. balance point temperature.



$$\frac{\Delta Q_1}{\Delta T_1} = \frac{\Delta Q_2}{\Delta T_2}$$

$$Q_{avg} = \left[DHR - Q_{red}\right]\left[\frac{\Delta T_2}{\Delta T_1}\right] + Q_{red}$$



$$\frac{a}{d-c} = \frac{b}{d}$$

Substituting for Q_{avg}: $\eta_{ss\,avg} = \Delta\eta_{ss}\left[\frac{(DHR)(\Delta T_2) - (Q_{red})(\Delta T_2)}{(\Delta T_1)(\Delta Q)}\right] + \eta_{ss\,red}$

for DHR = Q_{max}: $\eta_{ss\,avg} = \frac{\Delta T_2}{\Delta T_1}\cdot\Delta\eta_{ss} + \eta_{ss\,red} = \left[\frac{T_C - T_{OA}}{T_C - 5}\right](\eta_{ss\,max} - \eta_{ss\,red}) + \eta_{ss\,red}$

Figure A3. Calculation procedure used to derive average output rate (Q_{avg})-upper figure and average steady state efficiency ($\eta_{ss\,avg}$) - lower figure for step-modulating controlled furnaces and boilers

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Esher R. Kweller

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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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)*

The objective of this study was to set up a modulating controlled hot water boiler in the laboratory and to simulate a variety of conditions that were cited by manufacturers of boilers as influencing and being distinct operating parameters for boilers. A further objective of these tests was to compare these responses of the fuel input rate with the mode of operation which was previously described for modulating controlled space heaters and furnaces. The variation of controlled fuel rate to the burner via the fuel modulating valve was measured under several controlled conditions. Effects of heating load, burner cycling rate and zone control, were investigated. The response of gas pressure modulation to the burner of a hot water boiler heating system was studied in several series of tests in the laboratory. A boiler load simulator was set up and used for these tests to control the heating load (heat transfer rate at the radiators) and to simulate a variety of operating conditions that would be expected to exist with a boiler installed in the home. The effects of heat transfer rate and boiler water operating temperature on the modulated gas pressure are presented as a series of data in charts showing controlled gas pressure versus time. Cycling rate (burner on-off time) was also shown to have an effect on the operating gas pressure when operating in a cycling mode.

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

Annual efficiency; boiler; gas fueled; heating; modulating; part load efficiency; hot water.

13. AVAILABILITY

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