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EFFICIENCY OF WOOD-FIRED APPLIANCES

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by

A.C.S. Hayden*

ABSTRACT

This paper discusses the four techniques used to measure the efficiency of wood-fired appliances. The most accurate, reproducible method is the Instantaneous Heat Loss Method. Comparison with known systems in-situ gives a useful measure of the real efficiency of wood stoves in heating homes.

To properly complement existing heating systems, the stove should be placed in a major living area. If this is done, efficient air-tight wood stoves can indeed be an effective energy conservation device in home heating.

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1.0 INTRODUCTION

One of the most hazy areas in the subject of wood stoves is the term "efficiency." It is a word that is important to the buyer of the stove, and hence to the seller and the manufacturer, as well as to any group concerned with the optimum utilization of Canada's energy resources.

Claims have been made for many units that each is "The most efficient stove on the market," or that each operates at more than 75% efficiency. In general, the basis of these claims is tenuous, at best. Often the claimant has little or no idea of how to measure efficiency, or even what the term means. He is only partly at fault, however, because there is no truly valid precedure for measuring the absolute efficiency of solid fuel-fired heaters or even comparative performance of different units.

The Canadian Combustion Research Laboratory (CCRL), in cooperation with the Central Mortgage and Housing Corporation is developing such a standardized test for wood burning appliances over a complete burning cycle. The basis of this, as well as other less-general techniques, will be described in the following paper.

2.0 FUEL COMPOSITION AND BURNING

Most fuels have two prime constituents, carbon and hydrogen. Other components are varying amounts of sulphur, nitrogen, ash, oxygen and, for solid fuels such as wood and coal, significant amounts of water. The breakdown of these, called an ultimate analysis, is presented in Table 1 for a common Canadian hardwood, sugar maple.

It is the carbon and hydrogen, along with the water (moisture), which are most important as far as energy release is concerned. In the presence of air and heat, if the combustion is complete, the carbon is completely oxidized to carbon dioxide (CO_2) and the hydrogen to water vapour (H_2O). The nitrogen present in the air, along with the left-over oxygen and the water in the fuel, are heated to the temperature of the flue gases and go along for a ride up the chimney, carrying heat with them. If the combustion is incomplete, other intermediate products are formed, usually carbon monoxide (CO), some partially burned hydrocarbons (HC) and solid particles called soot, which are often pure carbon (C).

Unlike oil and gas, wood does not burn uniformly. In fact, there are three distinct phases in its combustion (see Table 2). The first phase, once the wood has been ignited, is the boiling off of the moisture. This can result in a significant heat loss.

The second is the vaporization of volatile hydrocarbons, which often pass directly into the flue gases as unburned or partially burned hydrocarbons, and form the bulk of the creosote deposits in the chimney.

The third is the combustion of the less volatile hydrocarbons in the wood and the remaining charcoal, often pure carbon.

In actual fact, the three phases do not occur distinctly in sequence, but rather simultaneously, moving gradually toward the third phase completely as combustion progresses in time. Nonetheless, the composition of the wood (i.e. the ultimate analysis) does not stay the same throughout the burning cycle, moving to continually increasing concentration of carbon.

3.0 COMBUSTION EFFICIENCY

In most oil and gas furnaces, combustion is effectively complete; i.e., only small amounts of carbon monoxide and hydrocarbons are formed, and combustion efficiency is nearly always greater than 99 per cent. For solid fuel-fired appliances, particularly those fired with wood, the combustion is not so complete, significant amounts of CO and HC can be formed, and combustion efficiency might sometimes be lower than 95%.

Hence, Combustion Efficiency is simply a measure of the completeness of combustion. To indicate how efficiently the energy in the fuel is transferred to the surroundings as heat, another concept, called appliance efficiency, is needed.

4.0 APPLIANCE (WOOD STOVE) EFFICIENCY

The elusive term which we were searching for at the beginning of the paper is thus best termed Appliance Efficiency. It is a measure of the ability of the wood stove to extract heat from the wood and supply it to the house. Figure 1 shows the heat from the wood going in two directions: into the house, and up the chimney in the form of a heat loss. Appliance Efficiency is thus the ratio of the heat supplied to the house to the heat in the wood, multiplied by 100; or, looking at it from the other side, 100% minus all the heat losses up the chimney. The following discussions are concerned with the measurement of this efficiency.

4.1 Techniques for Measuring Appliance Efficiency

There are four basic methods which can, to varying degrees of success, be used to measure appliance efficiency (Table 3). The first method, Simplified Heat Loss, is an indirect method which estimates the losses up the chimney assuming constant wood composition. It is not totally accurate, because of the previous assumption, but does give a fair appreciation of stove performance and potential problems. The second technique, Heat Output, is a direct measure of the heat supplied by the stove to its surroundings; there are significant problems in its application.

The third technique, Continuous Instantaneous Heat Loss, is the method we are adopting and developing at CCRL. It is a highly accurate complex method for measuring efficiency indirectly, by knowing in detail all the heat losses going up the stack. The fourth, Comparison In-situ with Known System, involves installation of the stove in a house of known thermal performance with a conventional heating system, and measuring the effect of the stove on the operation of the conventional system. A discussion of the four techniques follows.

4.1.1 Simplified Heat Loss (Indirect Method) (Reference 1)

This method makes some simplifying assumptions as to how wood burns. In particular, it assumes that the composition of the wood does not vary through the burning cycle. As we have already seen, this is not the case. However, it does give a very good insight into the various aspects of wood stove efficiency with quite simple measurements, where the major heat losses occur, and why.

Figures 2, 3, 4 and 5 are graphs showing the various heat losses: Dry Flue Gas Loss; Hydrogen Loss; Heat Loss due to Moisture in the Wood; and Heat Loss due to Carbon Monoxide.

To use these graphs, the following must be measured: flue gas temperature; combustion air (room) temperature; amount of excess combustion air, derived from either the carbon dioxide or oxygen content of the flue gas; and the carbon monoxide content of the flue gas as a measure of incomplete combustion.

Detailed explanation of these graphs follows:

4.1.1.1 Dry Flue Gas Loss (Figure 2). This graph shows the heat loss, in per cent of fuel input energy, represented by the sensible heat in the dry flue gas leaving the stove. It is dependent on the excess air level and the temperature of the flue gas above the combustion air temperature. Heat loss is plotted against total combustion air for a range of temperature differentials. The CO_2 and O_2 curves conveniently relate flue gas analysis to combustion air.

4.1.1.2 Hydrogen Loss (Figure 3). This graph shows the heat loss in per cent of fuel input energy, due to the water vapour in the flue gas formed from the combustion of hydrogen in the wood. It comprises the heat necessary to evaporate the water thus formed and to superheat it to the flue gas temperature. It is a function solely of stack temperature and combustion air (room) temperature.

4.1.1.3 Heat Loss due to Water (Moisture) in the Wood (Figure 4). This graph shows the heat loss, in per cent of fuel input energy, due to the heat required to raise the water in the wood to the boiling temperature, eavporate it, and superheat the water vapour to the final flue gas temperature. For wood at room temperature, as assumed in Figure 4, the loss depends on the water content of the wood and the stack temperature. For wood stored at cold outside temperatures and then immediately fired, a more complex graph is required.

4.1.1.4 Heat Loss due to Incomplete Combustion (Carbon Monoxide) (Figure 5). This graph shows the heat loss, in per cent of fuel input energy, due to carbon monoxide in the flue gas. If combustion were complete, all the carbon in the fuel would be oxidized to CO_2. The presence of CO indicates incomplete combustion and is a good indicator of hydrocarbons and soot in the flue gas as well, all of which mean that all the energy in the fuel has not been converted into heat.

4.1.1.5 The use of these charts is illustrated by the following example. Sugar maple, represented by the ultimate analysis in Table 1, was burned in an airtight wood stove. The measured operating conditions were:

Room temperature - 70°F
Wood temperature - 70°F
Wood moisture - 20% (air dried)
Stack temperature - 600°F
CO_2 in flue gas - 7%
CO in flue gas - 1%

The Simplified Heat Loss method gave the following results:

Total combustion air (from Figure 2) -	300%
Excess air -	200%
Dry flue gas loss (from Figure 2) -	21.0%
Hydrogen loss (from Figure 3) -	7.5%
Moisture loss (from Figure 4) -	4.0%
Loss due to CO (from Figure 5) -	2.8%
TOTAL HEAT LOSS	35.8%

The estimated appliance efficiency of this stove is thus

100.0 - 35.8 = 64.2%

How do the parameters of stack temperature, combustion (or excess) air, wood moisture content and incomplete combustion affect efficiency?

Stack Temperature: The greater the stack temperature, the lower the appliance efficiency, due to increased Dry Flue Gas Loss, Hydrogen Loss, and Wood Moisture Heat Loss

Combustion (Excess) Air: The greater the amount of air required for relatively complete combustion, the poorer the appliance efficiency, due to increased Dry Flue Gas Loss.

Wood Water (moisture) Content: The greater the amount of water in the wood, usually due to inadequate air drying, the poorer the appliance efficiency.

Incomplete Combustion: The greater the amount of carbon monoxide and other partially burned fuel components, the poorer the efficiency.

These dependencies are summarized in Table 5.

The Simplified Heat Loss Technique is the accepted and most accurate method for measuring the efficiency of constant-firing-rate furnaces and boilers, fuelled with oil, gas or even powdered coal, from huge electrical utility boilers to small domestic furnaces. However, for a bulk-fired appliance, such as a wood stove, it does have a major problem associated with it - that the composition of the wood does not remain constant throughout the burning cycle.

4.1.2 Heat Output Method

For a furnace or boiler, where the heat output passes through narrow confined ducts or pipes, this method is relatively straightforward. However, for a wood stove, where radiative heat transfer occurs in all directions to some degree at the same time, and even slight natural or fan-induced air currents can increase convective heat transfer, it is extremely difficult to obtain a realistic number for the true heat output.

One of the most widely publicized applications of this technique has been by J. Shelton (2). Shelton has set up what is called a calorimetric room - an extremely well-insulated structure housing the test stove. There are two openings into the room. Air at a known temperature is blown in through one and withdrawn through the other, where its heat gain is measured. Because the room is so well insulated, all the heat gained by the air is from the stove. Efficiency can thus be determined from a knowledge of the input energy of the wood. One of the major drawbacks of this technique is that it sets up a large air movement around the stove which would not be there in practice. Since it is well known that increased air velocity over a hot surface significantly increases the amount of convective heat transfer (just think of your warm air furnace when the circulating fan is running and when it isn't), the measure of heat output is not a valid one.

A second, more exotic calorimetric room is being used in Europe. Here the room is totally enclosed and insulated. Lining the interior is a water jacket casing through which water is pumped at a specific flow rate. The temperature gain of the water is measured, and taken as the stove output. Because there is not any greater than normal air movement over the stove, this technique is far superior to Shelton's. It does, however, confine the stove to only one extremely well insulated, completely enclosed room, making it unrepresentative of most homes.

In fact, all direct Heat Output methods for measuring efficiency suffer from this same drawback; also, the translation of results from one testing agency to another is almost impossible, unless exactly the same construction is followed in all cases. These procedures might lead to even worse comparison to real-life performance than is seen from the well-known EPA mileage figures for automobiles.

Another serious drawback to any direct method for measuring efficiency such as those just described is that it tells little of why the stove is performing well or poorly, or whether or why there might be problems with such things as creosote formation and temperature levels.

4.1.3 Continuous Instantaneous Heat Loss

The method adopted by the Canadian Combustion Research Laboratory, the Continuous Instantaneous Heat Loss, has none of the drawbacks of the preceding techniques in terms of the accuracy of efficiency measurement, and allows for much more complete understanding of the performance of each unit. As for the Simplified Heat Loss method previously described, it is based on the indirect measurement of efficiency by determining all the heat losses, shown in Table 4.

Those losses resulting from complete combustion - the Dry Flue Gas Loss, the Hydrogen Loss and the Moisture Loss - are instantaneously determined for fuel analyses modified continously throughout the burning cycle, in a manner similar to that for the Simplified Heat Loss Method. As well, the products of incomplete combustion - carbon monoxide, unburned carbon in the form of soot, and partially burned "creosotic" hydrocarbons - are all considered for their heat loss effects.

Flue gas components measured and the technique used are listed in Table 6. All the components in the exhaust stream, as well as the weight change of the wood, are measured and recorded simultaneously on magnetic tape throughout the burning cycle. Afterwards, on the computer, the wood composition is modified throughout the cycle and the instantaneous heat loss calculated, based on the modified analysis for that instant in the cycle. Efficiency profiles through the burning cycle are thus generated;these are integrated to obtain average efficiency and heat output over the cycle.

Having a complete record of all the operating characteristics enables us to look at the performance of a wide number of generic types of stoves under different control conditions and burning different woods, and to better assess safe operating procedures to reduce the potential for creosote formation and possible chimney fires.

A breakdown of the volatile hydrocarbons (creosote) from one test run is shown in Table 7. Phenols are the prime components, along with acetic acid and some benzenes. This result was obtained by putting condensed flue gases through an automated mass spectrograph.

Figure 6 , a sample output from one of the test runs over a burning cycle, shows how stack temperature, carbon dioxide, carbon monoxide and fuel weight can vary.

4.1.4 Comparison In-situ with Known System

As previously discussed, there are three basic ways to measure the efficiency of a wood stove in a test bed or laboratory, with the Continuous Instantaneous Heat Loss by far the superior method. However, "the proof of the pudding is in the eating," as the saying goes, so the final assessment of how a unit performs and what potential wood stoves have as energy conservation devices is the effect they have on a conventional heating system when placed in a home.

The determination is not so simple as merely saying "I used 200 gallons fuel oil less than last year." The effect of other conservation measures, either hard mechanical modifications to the house,such as greater insulation or storm windows, or soft changes to lifestyle, such as lower thermostat settings are important. Climatic effects, particularly outside temperature, must also be considered. The technique for carrying out such tests is outlined in references 3 and 4.

The heating profile of the house under normal operating conditions is established over the range of seasonal temperatures. Then a new profile is established using the conservation device under consideration, in this case, wood stoves. Sample profiles for a house heated with an electric boiler and with a wood stove are shown in Figure 7. Both profiles are then integrated over the temperature profile of a real heating season to give yearly energy consumptions. In this case, the wood stove showed a seasonal efficiency of about 65% relative to the electric system.

The technique has also been used to evaluate the"heating" effect of built-in fireplaces inthe test homes.In instances where the fireplace did not radiate on the thermostat, conventional fuel consumption was found to actually increase during fireplace use, indicating a negative efficiency. Where the fireplace actually radiated directly on the thermostat, conventional fuel consumption dropped by up to 20%, with the rest of the house becoming distinctly cold. This fuel saving could have been equally realized by merely turning down the thermostat, which is what in effect happened.

It is planned to carry out similar field evaluations for most of the generic wood stove types now being tested at CCRL under the Continuous Instantaneous Heat Loss Method, to give an appreciation of what results from the lab test method mean in real life.

5.0 THE WOOD STOVE AS AN INSTRUMENT OF ENERGY CONSERVATION

For any wood stove to be an effective energy conservation device, it obviously must be efficient, as well as safe. The more efficient the unit, the less wood is required for the same heat output.

Beyond that, placement of the stove becomes very important. If the stove is to be anything more than a decoration, or another energy consumer in a house already more than amply filled with other consumers, it should be located in a <u>major living area</u> of the house. Often this would be the living or family room located on the main floor. This room ideally has large open connections to the rest of the house, allowing heat from the stove to pass freely to other rooms. Often in a two-storey house, the stairs to the second floor also pass in or near to this room, providing a convenient "warm air duct" for heat to flow upstairs, as well as a good"cold air return."

With an attractive, comfortable airtight stove, the family would tend to gather in an area around this efficient heat source, and the house thermostat could be lowered again, saving further energy.

An attractive yet efficient alternative to the inefficient fireplace is a "combi-fire" airtight stove, where the doors may be opened to allow viewing of the flame, the only aesthetically desireable feature of a fireplace, or shut where the stove is a highly efficient airtight.

One of the main drawbacks to locating the stove in a basement recreation room, other than the fact that many of the family may not wish to spend their evenings there, is the fact that it is often quite difficult to get the heat generated from the stove to the rest of the house. Basement walls are often not insulated and provide a rapid path for heat loss to the outside. Thick wall-to-wall carpets and underpads on the main floor act as an insulating layer to prevent heat from passing up into the major living areas. A stove in a "rec" room often becomes merely an additional energy consumer, rather than an effective complement to an existing heating system.

6.0 RATINGS

Because most wood stoves are radiant or radiant/convective heaters, as opposed to central furnace systems, saying that a stove can heat 1000 or 2000 or even 3000 square feet of living area is almost meaningless, for location of the stove is essential to its ability to provide real heat to a house. Also, the heat requirement is widely different for houses with different levels of insulation in the same city, or for houses in different cities,like Toronto and Winnipeg.

Rating a stove for particular energy (Btu) outputs for different wood types, especially for hardwoods and softwoods, might help.

The rating itself is derived from the measurement of efficiency and the amount of heat in the fuel wood.

Often, a small stove, firing at a fairly high rate, is a more efficient and safe unit than a larger stove which must be drastically underfired in order that the inhabitants of the house may not feel they are under a hot mid-day desert sun.

7.0 SUMMARY

1. Wood stove efficiency is a complicated term which is best measured by the Continuous Instantaneous Heat Loss Method.
2. The Simplified Heat Loss Method enables rapid analysis of the merits of stove design and performance, but suffers in final accuracy.
3. Direct measurement of the heat output of wood stoves can be unrepresentative and do not give any indication of the reasons for a stove's performance or lack of same.
4. Wood stoves should be located in a major living area of a house.
5. A smaller stove, firing a a high relative output rate is usually more efficient and safe than a large stove firing at a low rate.
6. Combi-fire stoves give efficient operation and allow viewing of the flame when desired, providing an efficient alternative to a fireplace.
7. If the above recommendations are followed, an efficient wood stove can be an effective energy conservation complement to an existing heating system.

8.0 REFERENCES

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2. Shelton, J.W., "Wood Stove Testing Methods," ASHRAE preprint, Atlanta, January, 1978.
3. Hayden, A.C.S., Braaten, R.W., Brown, T.D., "Oil Conservation in Home Heating," American Society of Mechanical Engineers Paper ASME 76WA/Fu8, December, 1976.
4. Hayden, A.C.S. et al, "Emissions and Energy Conservation in Residential Oil Heating," Journal of the Air Pollution Control Association, Vol. 28, No. 7, July 1978.

TABLE 1

SUGAR MAPLE

ULTIMATE ANALYSIS

(DRY BASIS)

CARBON	49.6%
HYDROGEN	5.2%
SULPHUR	0.1%
NITROGEN	0.2%
ASH	2.0%
OXYGEN	43.0%

GROSS CALORIFIC VALUE (HIGHER HEATING VALUE) : 8300 BTU/LB

TYPICAL MOISTURE CONTENT : 10-20%

TABLE 2

SIMPLISTIC PHASES IN THE BURNING OF WOOD

1. BOILING OFF OF THE WATER AS STEAM.

2. VAPORIZATION OF THE VOLATILE HYDROCARBONS.

3. COMBUSTION OF THE WOOD PROPER.

TABLE 3

METHODS FOR MEASURING WOOD-FIRED APPLIANCE EFFICIENCY

1. Continuous Instantaneous Heat Loss (CCRL)	Indirect
2. Simplified Heat Loss (Combustion Curves)	
3. Heat Output (Calorimetric Room)	Direct
4. Comparison In-situ With Known System	

TABLE 4

STACK HEAT LOSSES

COMPLETE COMBUSTION	DRY FLUE GAS LOSS
	HYDROGEN LOSS
	MOISTURE LOSS
INCOMPLETE COMBUSTION	CARBON MONOXIDE
	CARBON (SOOT)
	HYDROCARBONS (CREOSOTE)

Table 5

GOVERNING FACTORS IN WOOD STOVE EFFICIENCY

1. Excess Air : The More The Excess Air, The Poorer The Efficiency
2. Stack Temperature : The Higher It Is, The Poorer The Efficiency
3. Fuel Moisture : The Greater The Moisture, The Poorer The Efficienc
4. Incomplete Combustion : The More, The Poorer The Efficiency

TABLE

MEASUREMENTS FOR INSTANTANEOUS HEAT LOSS METHOD

COMPONENT MEASURED	TECHNIQUE
CARBON DIOXIDE IN FLUE GAS	INFRARED ANALYZER
CARBON MONOXIDE "	INFRARED ANALYZER
OXYGEN "	PARAMAGNETIC ANALYZER
AMBIENT HYDROCARBONS "	INFRARED ANALYZER
350°F HYDROCARBONS "	FLAME IONIZATION DETECTOR
WATER-CONDENSED HYDROCARBONS "	MASS SPECTROMETER
WATER "	DEW CELL
EQUIVALENT OXYGEN "	FUEL CELL
TEMPERATURES	THERMOCOUPLES
SOOT	DUST SAMPLING TRAIN
FUEL WEIGHT	CONTINUOUS DIGITAL SCALE
NITROGEN OXIDES	CHEMILUMINESCENT ANALYZER

TABLE 7

TYPICAL CREOSOTE COMPONENTS

ACETIC ACID	22%
PHENOL	7%
OTHER PHENOLS	40%
BENZENES	16%
OTHER	15%

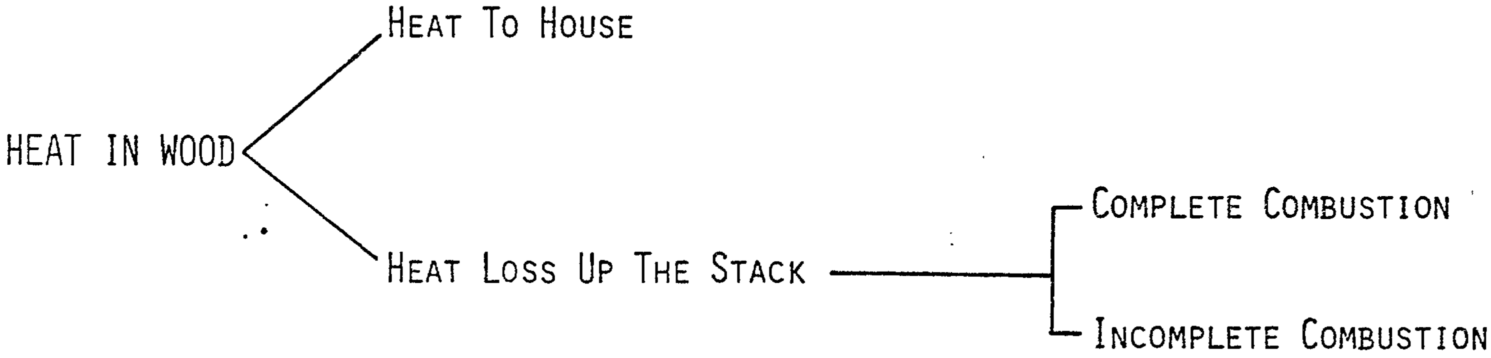

Figure 1. Heat Flow From Wood Stove

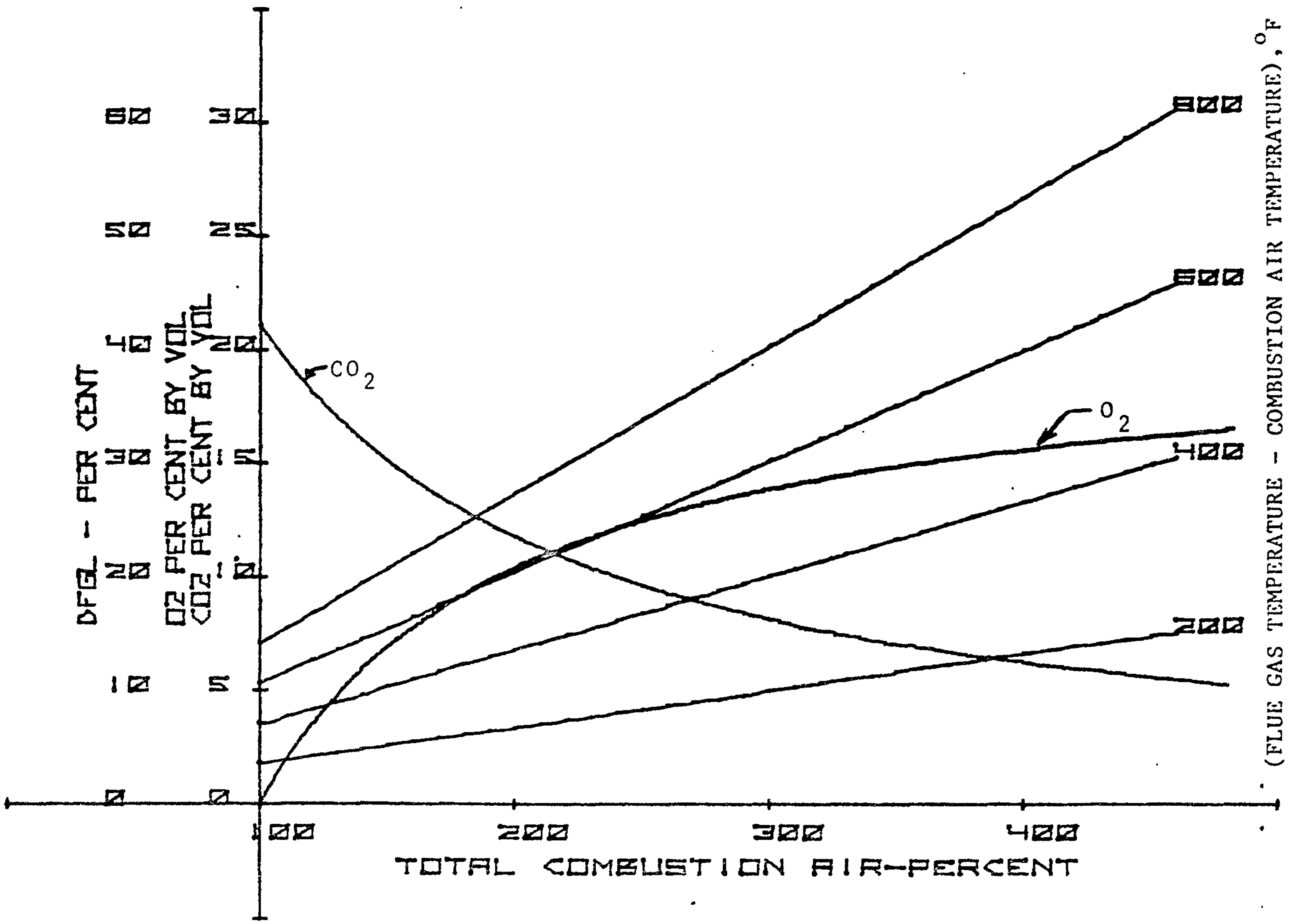

FIGURE 2. DRY FLUE GAS LOSS (DFGL) - SUGAR MAPLE

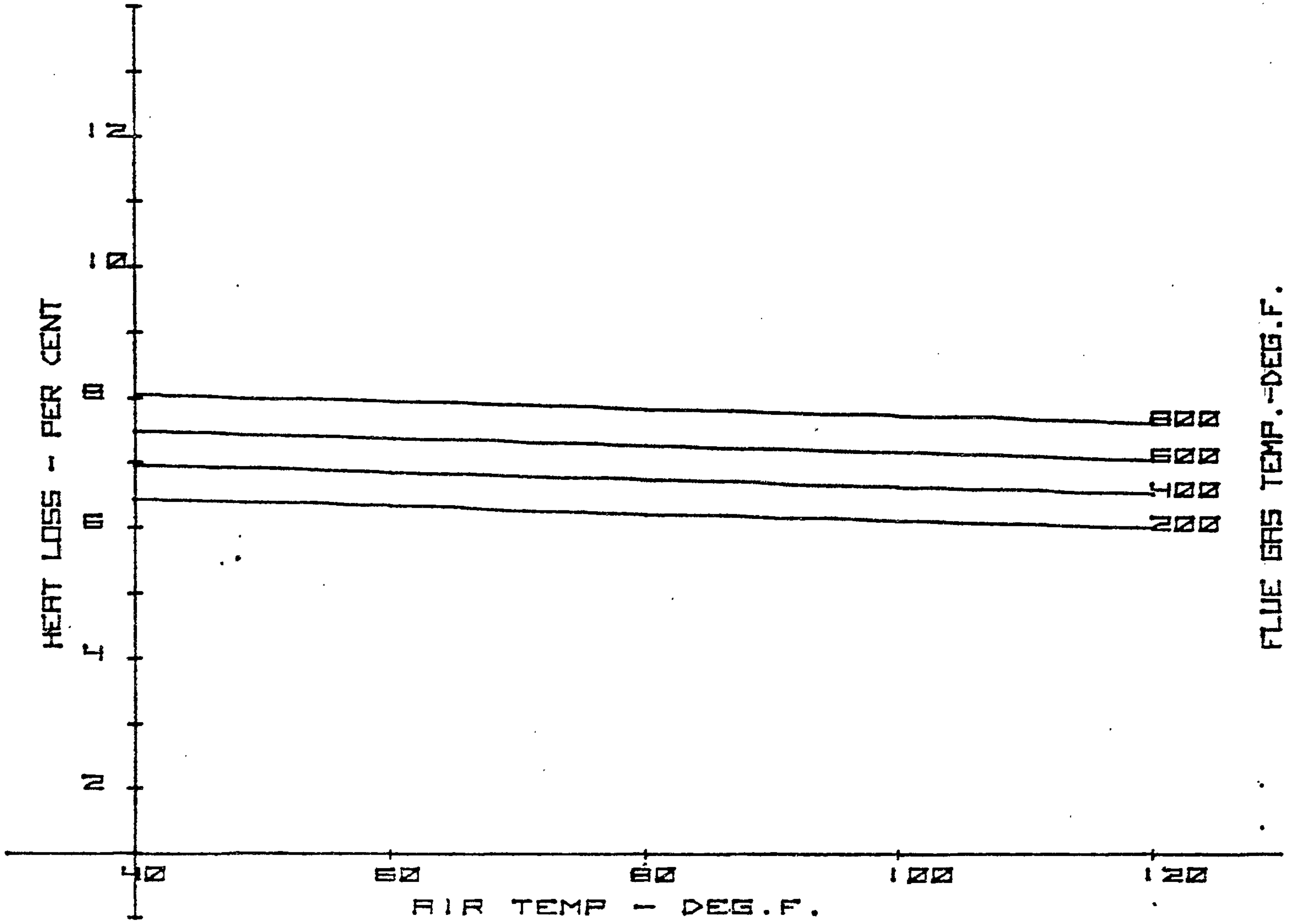

Figure 3. Hydrogen Loss - Sugar Maple

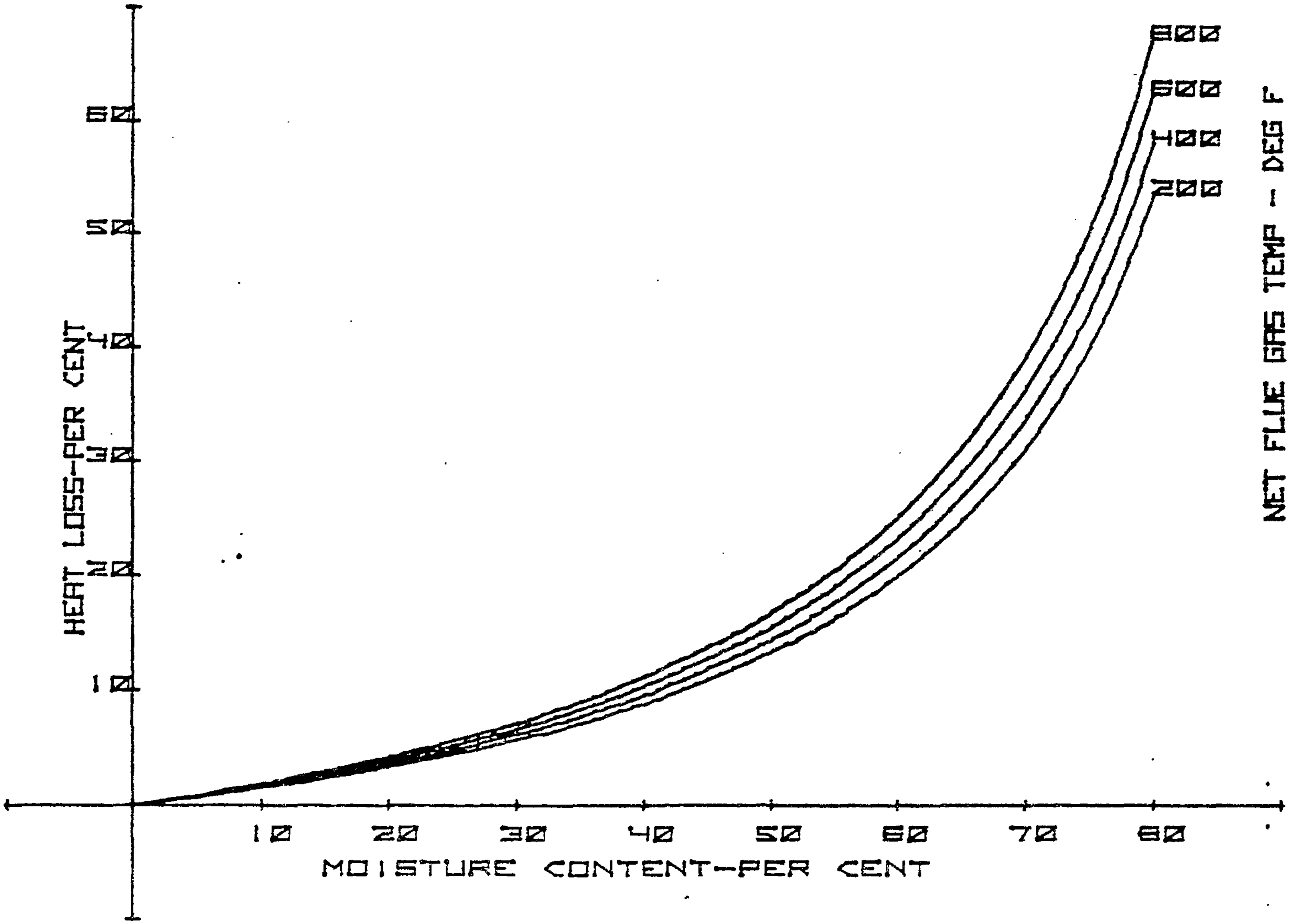

FIGURE 4. HEAT LOSS DUE TO MOISTURE IN WOOD - SUGAR MAPLE

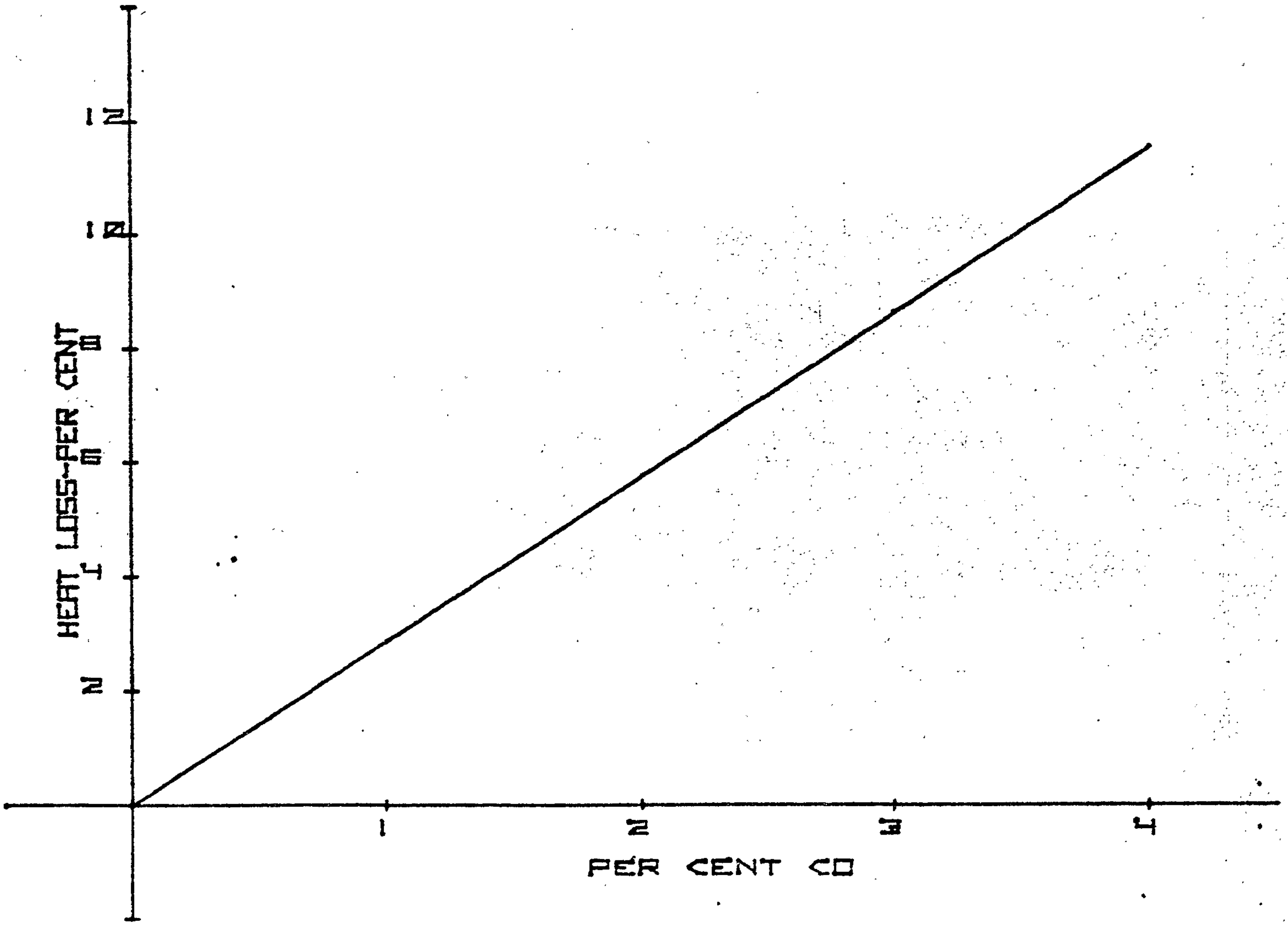

Figure 5. Heat Loss Due To Carbon Monoxide (CO) - Sugar Maple

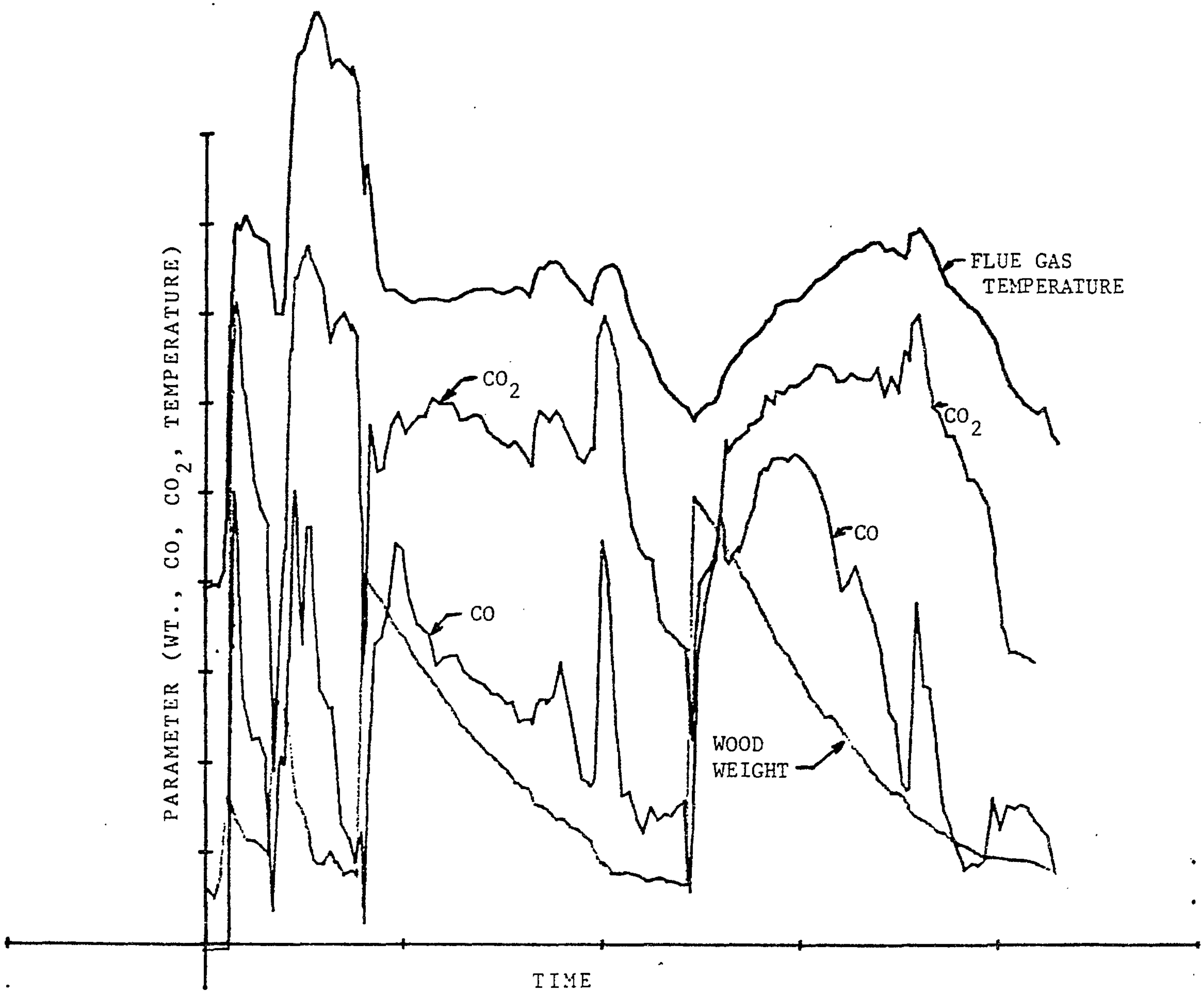

FIGURE [illegible]. SAMPLE OUTPUT FROM INSTANTANEOUS HEAT LOSS MEASUREMENTS

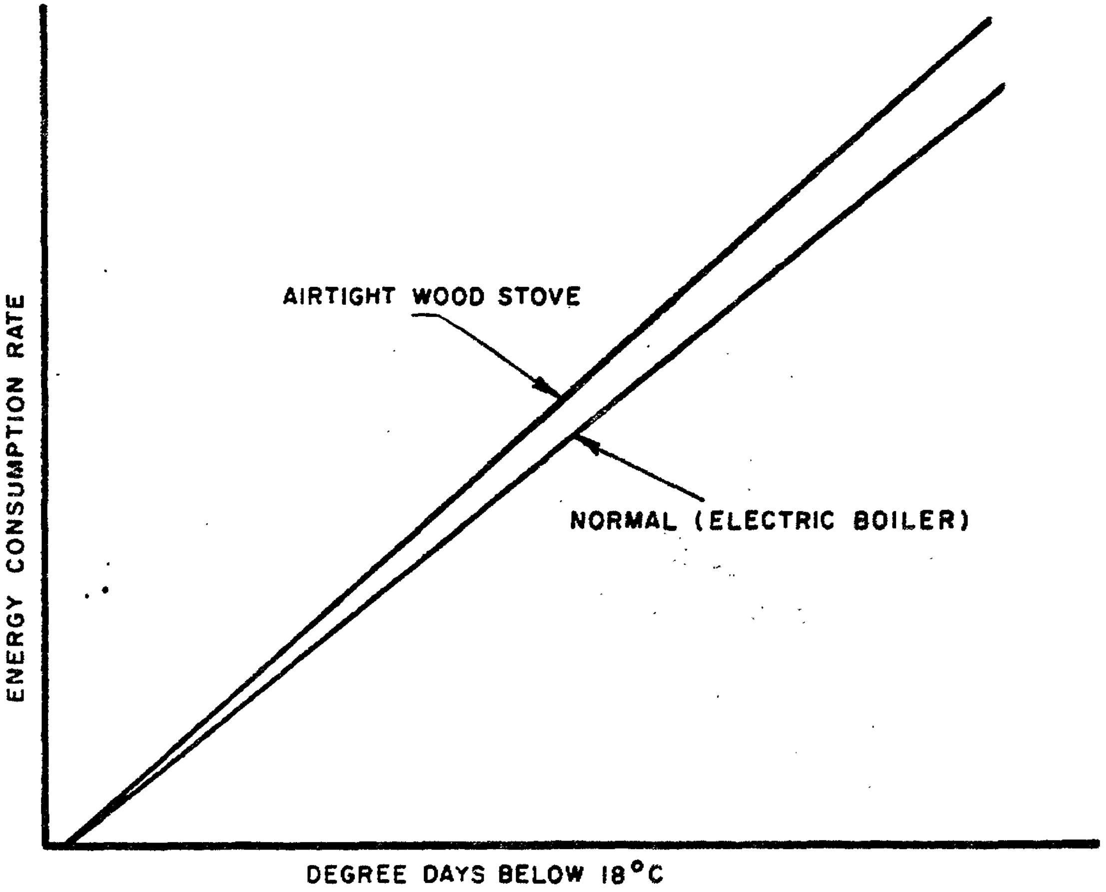

FIGURE 7. HEATING PROFILES FOR IN-SITU TEST IN HOUSE, FOR AIRTIGHT WOOD STOVE AND ELECTRIC BOILER