

Masonry Heater Performance Evaluation: Efficiency,  
Emissions, and Thermal Modeling

by

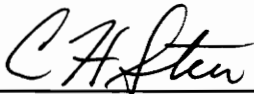
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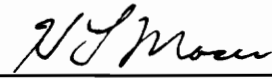
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by

Mauricio F. Gutierrez

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(ABSTRACT)

Two stack loss efficiency measurement methods, the Total Combustible Carbon (TCC) and Combustibles Meter (CM) methods, have been modified for use on masonry heaters. The applicability of the two methods has been verified with 6 tests on two masonry heaters.

Each test starts with a cold heater and requires five firings to achieve two different burn rates. The efficiencies calculated for each firing are weighted according to burn rate following EPA Method 28 for wood heaters.

The TCC Method uses carbon balances to calculate the chemical energy loss and the dry stack gas mass for calculation of sensible energy loss. The sensible loss that occurs during the off-period, when combustion of wood has stopped, is measured directly by injecting carbon dioxide in the stack and using it as a tracer gas to measure stack flow

rate. In both methods the latent energy loss is calculated from wood moisture content and hydrogen content.

The CM Method measures losses more directly and is considered the reference method in this work. The chemical energy loss is measured using a flame combustibles meter. The stack flow rate, which is used for the calculation of sensible loss, is measured directly using carbon dioxide tracer gas during both the on and off periods of the appliance.

The overall average efficiencies measured by the two methods, in 5 tests on two different appliances, differed by a maximum of 1.7 percentage points of the fuel energy input. On the average they differed by about 1 percentage point.

The results of a one-dimensional finite-difference model of the heat exchanger of one of the tested masonry heaters is compared against thermocouple-measured temperatures.

For the 3 tests performed the model predicts the measured temperatures to within 12% during the first half of a firing cycle when the burn rate is high, and to within 5% during the second half of the cycle when the burn rate is low.

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## NOMENCLATURE

$\alpha$	Thermal diffusivity ( $\text{m}^2/\text{s}$ )
B	Thermal expansion coefficient for air ( $1/\text{K}$ )
Bi	Biot number (dimensionless)
C	Mass fraction of carbon in dry (zero moisture content) fuel (0.508 for Douglas fir)
CATCH	Filter catch (kg)
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CO <sub>2A</sub>	Ambient carbon dioxide concentration (wet mol%)
CO <sub>2B</sub>	Concentration of CO <sub>2</sub> tracer gas in the bottle (mol%)
CO <sub>2S</sub>	Stack carbon dioxide concentration (dry mol%)
CO <sub>2T</sub>	Tunnel carbon dioxide concentration (wet mol%)
CO <sub>2TI</sub>	Incinerated tunnel carbon dioxide concentration (wet mol%)
CM	Combustibles Meter
C <sub>ds</sub>	Constant pressure specific heat of the dry stack gas ( $\text{kJ}/\text{kg K}$ )
C <sub>H2O</sub>	Constant pressure specific heat of water ( $1.9 \text{ kJ}/\text{kg K}$ )
Dh	Hydraulic diameter of a channel, equal to four times the area of the channel divided by its perimeter (m)

$\Delta t$	Time increment or interval (s)
$\Delta x$	Space increment or distance between nodes (m)
FCM	Flame Combustibles Meter
$Fo$	Fourier number (dimensionless)
$g$	Gravitational acceleration ( $9.8 \text{ m/s}^2$ )
$H_m$	Mean Heat transfer coefficient ( $\text{W/m}^2 \text{ K}$ )
$h_{fg}$	The latent heat of vaporization of water (2442 kJ/kg at room temperature)
$H_w$	The mass fraction of hydrogen in dry wood (0.0583 for Douglas fir)
$k$	Thermal conductivity ( $\text{W/m K}$ )
$L$	Length (m)
$LHV_{CE}$	Assumed lower heating value of the combustible emissions (400,000 kJ/kg-mole)
$LHV_S$	Assumed lower heating value of smoke (30 MJ/kg)
$LHV_G$	Lower heating value of the filtered tunnel sample (gas) (kJ/kg)
$MC_d$	Dry basis moisture content of the wood (%)
$M_{ds}$	Average molecular weight of the dry stack gas (g/(g-mole))
$m_{ds}$	Mass of dry stack gas (kg)
$m_{dw}$	Mass of dry wood (kg)
$m_{H_2O}$	Theoretical water emission (kg)
$\dot{m}_S$	Stack mass flow rate (g/s)

$m_{\text{samp}}$	Total sample mass flow (g)
$\dot{m}_T$	Tunnel mass flow rate (g/s)
$\dot{N}_{\text{CO}_2}$	Flow rate of introduced tracer gas (mole/s)
$\dot{N}_S$	Molar stack flow rate (mole/s)
$\dot{N}_T$	Molar tunnel flow rate (mole/s)
Nu	Nusselt number for fully developed flow (dimensionless)
$Nu_m$	Mean Nusselt number (dimensionless)
PM	Particulate Matter
Pr	Prandtl number (dimensionless)
$\dot{Q}_{\text{CO}_2}$	Volume flow rate of introduced carbon dioxide tracer gas (l/min)
Ra	Rayleigh number (dimensionless)
$Re_{Dh}$	Reynolds number based on hydraulic diameter (dimensionless)
	Density ( $\text{kg}/\text{m}^3$ )
$T_j^p$	Temperature at node j at time p (K)
TCC	Total Combustible Carbon
TL	Test length (min)
Tr	Room air temperature (K)
Ts	Surface temperature of the wall (K)
Tg	Stack gas temperature (K)
V	Kinematic viscosity for air ( $\text{m}^2/\text{s}$ )
W	Average water content in the stack sample (mole percent)



$W_m$  Average water content in the stack sample  
(mass percent)

**Subscripts**

$j$  Node  $j$   
 $j+1$  Node after  $j$   
 $j-1$  Node before  $j$

**Superscripts**

$p$  Previous time; the time right before the  
temperature calculation takes place  
 $p+1$  Next time; the time for which temperatures are  
calculated

## Chapter 1

### INTRODUCTION

Masonry heaters are wood-burning home heating appliances made of brick, clay, tile, or stone. Although they are more common than iron stoves in the colder areas of Europe and Asia, they are relatively new in North America.

Their potential for cleaner and more efficient burning stems from the fact that combustion and heat transfer occur in separate places. Rapid combustion takes place in the firebox from which there is minimal heat loss and the resulting high temperatures can translate into good combustion efficiency and low emission of pollutants. Heat transfer to the room takes place in the walls of the heater where the large surface area provides for good heat transfer efficiency.

Masonry heaters have the potential for reducing both wood consumption and pollutant emissions from wood heating in the United States. To hasten the acceptance and improve the design of masonry heaters, manufacturers need an efficiency testing method which they can use to evaluate, compare, and improve the performance of their appliances.

The objective of this work was to develop methods that could be used to measure the efficiency of masonry heaters.

In addition it was required that the efficiency testing methods developed be compatible with emissions testing for carbon monoxide and particulate matter.

A computer model of the contraflow heat exchanger of one of the tested masonry heaters was developed. The model addresses questions concerning the issues of design, materials, and geometry: What are the effects of these variables? how do high burn rates and stack flow turbulence affect heat transfer efficiency? what is the key mechanism for good masonry heater performance? This simple model represents an initial step into the computer modeling of the thermal performance of these heating appliances.

## Chapter 2

### LITERATURE REVIEW

#### 2.1 MASONRY HEATER DEFINITION

The proposed ASTM standard for construction of masonry heaters which comes out of a task group created in 1985 for the promulgating of standards for masonry heaters proposes the following definition of a masonry heater:

"Masonry Heater - a vented heating system of predominantly masonry construction having a mass of at least 1764 lbs (800 kg) excluding chimney and heater base. In particular, a unit designed to (1) enable a charge of solid fuel mixed with an adequate amount of air to burn rapidly and more completely at high temperature in order to reduce emission of unburned hydrocarbons, and (2) to capture and store a substantial portion of the resulting heat energy in the mass of the appliance through internal heat exchange flue channels, and (3) to gradually release the stored energy to the space to be heated".<sup>1</sup>

This definition of masonry heaters covers the aspects that make masonry heaters different from other residential wood-burning appliances such as stoves and fireplaces.

In a masonry heater most of the combustion takes place in the firebox where there is little heat transfer and enough air for rapid combustion. This can translate into high combustion temperatures, good combustion efficiency and low emission of pollutants<sup>2</sup>. Heat transfer to the room takes place (mainly) away from the firebox, in the walls of the heater where the surface area is high to maximize heat transfer. Another definition of a masonry heater has the additional requirement that the firebox effluent travel horizontally or downward through a masonry duct for a distance at least the length of the largest firebox dimension before leaving the masonry heater.<sup>3</sup> This additional requirement makes sure that fireplaces are not included in the definition. The ASTM definition may include fireplaces.

Masonry heaters are heat-storage systems. The heat developed by the rapidly burning wood in the firebox is stored in the masonry body of the heater and then released slowly to the room. In this manner a masonry heater achieves an even heat output over a long period of time. In contrast, iron stoves achieve an even heat output by slowing combustion, by restricting the air to the fire.

Masonry heaters vary in size and can weigh from 800 kg (1764 lb) to 4500 kg (9900 lb) or more. In Sweden, Germany,

and Austria they have traditionally been built of tile. In Russia and Finland they have been built with brick and soapstone. In many Eastern European countries they have been finished in stucco. Today they are still built out of these same traditional materials; new possibilities in materials include the castable refractories.

## **2.2 ORIGIN OF MASONRY HEATERS**

Masonry heaters started appearing during a period of extreme cold in most of Europe, termed the Little Ice Age (approximately 1550-1850 A.D.). During this time period efficiency became an important issue and many countries held competitions to find the most efficient masonry heater. Many of the designs coming from this time are still used today, for example the Swedish Kakelugn and the Finnish contraflow.<sup>4</sup>

Although masonry heaters are more common than iron stoves in the colder regions of Europe and Asia, they are relatively new in North America. Numerous designs have been introduced in North America during the last two decades and it is anticipated that they will become increasingly popular as their technical and aesthetic attributes become known.

### 2.3 WOOD-BURNING AS A SOURCE OF POLLUTION

The drive to cleaner, more efficient wood-burning appliances stems from the fact that they are a significant source of pollution. The combustion of wood produces carbon monoxide, particulate matter, and hydrocarbons, which are exhausted into the atmosphere.

The use of wood as a residential house heating fuel in the United States has been estimated to contribute up to 90% of the polynuclear organic material (POM) attributable to stationary sources and 50% from all sources<sup>5</sup>. In the United States in 1981, wood-burning appliances accounted for only 3% of the total residential stationary fuel usage but produced 53% of the total particulate emissions with an aerodynamic diameter of 10 micrometers or less (PM<sub>10</sub>, believed to pose the greatest problem for health), and 85% of the total carbon monoxide emissions from residential appliances<sup>6</sup>. During the winter, residential wood combustion is at a maximum, and in 1980 accounted for 20 to 73% of the total United States particulate emissions<sup>7</sup>.

The concern over the pollution produced by residential wood-burning appliances is reflected in the Environmental Protection Agency (EPA) regulations promulgated on February 26, 1988<sup>8</sup>. Prototypes of each new model stove must pass an emissions test performed in an approved laboratory for that

model line to be certified for manufacture and sale. These regulations are for appliances under 800 kg and therefore do not include masonry heaters.

#### **2.4 EMISSIONS TESTING**

Two sampling techniques available for measuring particulate emissions from wood heaters are EPA Methods 5G<sup>9</sup> and 5H<sup>10</sup>. EPA method 5G determines particulate emissions by sampling from a dilution tunnel, and EPA method 5H by sampling from the stack.

EPA method 5G uses a probe, two filters, a pump, and a gas meter. Samples are taken from the center of a dilution tunnel which combines the wood heater exhaust with ambient dilution air. The particulate matter is collected on the probe and glass fiber filters. Their catch is determined gravimetrically after removal of uncombined water. The filters are maintained at a temperature of no greater than 32°C to prevent volatiles from being in a gaseous state. In a gaseous state the volatiles would pass through the filters.

EPA method 5H uses a heated probe and two glass fiber filters separated by impingers immersed in an ice bath. The first filter is maintained at a temperature of no greater



than 120°C. The second filter and the impinger system are cooled such that the exiting temperature of the gas is no greater than 20°C. The particulate matter collected in the probe, filters, and impingers is determined gravimetrically after removal of uncombined water.

Method 5G is better suited for measuring masonry heater emissions than Method 5H. Because of the time-varying stack flow rates and concentrations of gases in the stack of a masonry heater, proportional sampling is more easily maintained with tunnel sampling.

Method 5G is not applicable to masonry heaters without modification. Emissions testing involves specification of applicable operating procedures, measurement procedures, and calculation procedures. All of these procedures must be modified to deal with the issues specific to masonry heaters such as their intermittent firing and lower concentrations of gases and particulate matter in the tunnel.

Carbon monoxide emissions can be determined with EPA Method 3<sup>11</sup> or continuous monitoring. The sample for both methods is drawn from the center of a dilution tunnel. EPA Method 3 uses grab samples from a single point. The accumulated sample is analyzed with a gas analyzer to determine the average carbon monoxide concentration. This method is not as accurate since carbon monoxide emissions

may vary by two orders of magnitude during a test. Continuous monitoring uses an infrared analyzer to continuously monitor carbon monoxide emissions using a dilution tunnel sample. This method is preferred for measuring masonry heater carbon monoxide emissions since carbon monoxide is measured continuously.

A test method for determining particulate matter and carbon monoxide emissions from masonry heaters has been proposed by Stern and Jaasma<sup>3</sup>. The proposed test method uses a modification of EPA method 5G and specifies the fueling protocol and laboratory measurement procedures for determination of both emission rates and factors. The test consists of five firings which are burn-rate weighted according to EPA Method 28<sup>12</sup> to obtain the overall emission totals for the test cycle. The time between firings is adjusted to give a low burn rate in the range 0.70-1.10 dry kg/hr for the first two firings, and a high burn rate in the range 2.10-3.10 dry kg/hr for the last three firings. (Two fixed burn rates, say 1.0 and 2.75 kg/hr, would be better since there would be less opportunity to get lower emission rates by testing at the lowest allowed burn rates.) This emissions testing method, with the changes described in the procedure section, was used to measure emissions in this work.

## 2.5 EMISSIONS RESULTS

Stern and Jaasma reported particulate matter and carbon monoxide emissions results measured during the development of their masonry heater emissions test method<sup>3</sup>. The emissions were measured for a Grundofen (multi-flow or Russian) and a Contraflow (Finnish fireplace) type masonry heater. A modified EPA Method 5G and continuous monitoring were used to measure emissions. Particulate matter factors ranged from 0.6 to 3.51 grams per kilogram of dry wood, and CO factors ranged from 37 to 88.8 grams per kilogram of dry wood. The averages for the two heaters of the EPA weighted average emission rates were 67 g/hr carbon monoxide, and 1.4 g/hr particulate matter.

Several field studies of woodstove emissions have been completed since 1985. McCrillis and Jaasma<sup>13</sup> have studied the correlation between the results of these field tests and laboratory testing using EPA Methods 5G and 5H. The field studies used one of two in-house sampling systems. A strong correlation between field and laboratory testing was found, and correlation formulas from either of the two field methods to EPA Method 5G, and from Method 5G to 5H are given. The 5G to 5H correlation is used in this work to convert the tunnel measured emission results to stack

values. Stack (Method 5H) values are useful for comparison to published data.

The results presented in this work are for laboratory tests of masonry heaters.

## **2.6 EFFICIENCY TESTING**

Efficiency testing of masonry heaters presents several difficulties particular to these appliances. In a masonry heater combustion of the wood takes place very rapidly, resulting in high and variable stack flow rates and time-varying concentrations of stack gases. If the losses are to be quantified accurately through stack measurements, the most accurate computation must take into account the variable stack flow rate. Using the average values of the gas concentrations when using a stack sampling method may not be accurate.

The high stack flow rate and the low concentrations of combustibles must be considered when determining dilution tunnel settings and sampling flow rates: dilution tunnel flow rates must be adjusted to handle the high flow of stack gases. When sampling to determine the loss due to smoke, the sample flow rate must be high enough to provide measurable smoke catches.

Masonry heaters are heavy appliances and it would be impractical to try to set them on a scale as is usually done with stoves in hot-to-hot tests. (In hot-to-hot tests a scale is used to determine test start and test stop times based on the weight of the fuel-bed.) In stoves the wall temperature and stove mass are usually taken as a measure of thermal storage; with a masonry heater this is inaccurate. Masonry heaters are massive thick-walled appliances with much temperature variation and their thermal storage cannot easily be accounted for.

The stored thermal energy in a masonry heater produces a draft and consequently a sensible loss even after combustion of the wood has stopped. This off-period sensible energy loss can be significant and must be measured. The thermal mass must be accounted for and a decision made on what constitutes a loss and what is considered useful heat.

The measurement of stack energy loss during the off-period of space heating equipment has been discussed by Kweller and Wise<sup>14</sup>. Kweller presents the apparatus and measurement procedures required for the measurement of stack flow rates using a tracer gas. The product of stack mass flow, specific heat of air, and temperature rise above room temperature are integrated over the off-cycle period to

obtain the off-cycle sensible energy loss. The tracer gas method was used in this work to measure both the on-period and off-period stack flow rates for calculation of the sensible energy loss.

#### 2.6.1 ROOM CALORIMETRY

Efficiency measurement methods can be subdivided into three types: room calorimetry, indirect flue loss, and direct flue loss.

A room calorimeter is a well insulated, low heat capacity device in which either water or air is circulated through wall and ceiling panels to transfer the heat generated inside the room to the outside. The useful heat output of an appliance is determined by measurements of the fluid flow and its temperature rise.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers at one time had a calorimeter room standard method for testing the performance of wood-burning appliances<sup>15</sup>. The method is applicable to open and closed combustion chamber appliances and specifies the measurement apparatus and calorimeter room as well as the fueling requirements. For closed combustion chamber appliances oak cordwood with an as-fired density range from

0.59-0.69 g/cm<sup>3</sup> (36.8-43.1 lb/ft<sup>3</sup>) and a dry basis moisture content between 19 and 25% is specified. The length of the fuel piece is 5/6 of the longest dimension of the firebox or grate. The standard is not meant for masonry heaters as it specifies a steel flue and a hot-to-hot test in which the appliance is set on a scale.

Room calorimetry is the most direct and accurate approach to measure efficiency, but it is expensive and non portable. Also, the test environment in a calorimeter room may significantly affect stove performance. If the calorimeter room wall temperatures differ significantly from normal room values, the radiant energy exchange will not simulate normal operating conditions<sup>16</sup>. Using the calorimeter room method with masonry heaters would be expensive and difficult as the unit would have to be built inside the room. The calorimeter room would also need a foundation strong enough to support the heavy heater and enough floor space for it.

#### **2.6.2 INDIRECT FLUE LOSS METHODS**

Flue (stack) loss methods compute efficiency by assessing the energy loss up the flue. Flue loss methods can be categorized as either indirect or direct depending on

the relative directness with which the losses are measured. Directness of measurement is a matter of degree; nonetheless the distinction is useful.

Indirect flue loss methods, also known as traditional stack loss methods, rely on atom balances to compute the chemical energy loss. An assumed chemical equation is used to account for the products of combustion. The assumed chemical equation usually includes carbon monoxide, methane, and sometimes hydrogen as the products of combustion that account for the chemical energy loss. The CO, CO<sub>2</sub>, and O<sub>2</sub> flue gas concentrations are measured with an Orsat or other gas analysis equipment. The fuel composition is known from ultimate analysis, and the ambient air and stack temperatures are measured with thermocouples. An atom balance is performed using the assumed chemical equation and the chemical loss is computed.

Indirect flue loss methods include the Oregon method<sup>17</sup>, WHA Protocol<sup>18</sup>, and the Canadian Standards Association method<sup>19</sup>. The methods differ from each other in the way they treat the CH<sub>4</sub> (gas or liquid), the number of data sets specified, fueling, weighting of results, the temperature dependence of the flue gas specific heat, and other features.



As an example of how methods differ, the Oregon method and WHA protocol may be compared: the Oregon method uses a pure tracer gas (sulfur dioxide or equivalent) to compute the stack flow rate for calculation of sensible energy loss. The WHA protocol uses carbon, hydrogen, and oxygen balances to determine flue gas volume per unit of fuel consumed. The Oregon method measures flue gas water with the Oregon Method 7 sampling system. The WHA protocol computes flue gas water using carbon, hydrogen, and oxygen balances. The Oregon method does not include temperature dependence in the specific heats of the flue gas component like the WHA protocol, nor does it include the  $\text{CH}_4$  term in computing sensible loss. The Oregon method specifies Douglas fir lumber with an as-fired density range from  $0.46\text{-}0.60\text{ g/cm}^3$  ( $28.7\text{-}37.4\text{ lb/ft}^3$ ) and a dry basis moisture content of 19-25%. Four tests at three different heat output rates are required by the Oregon method. The WHA protocol specifies oak cordwood with an as-fired density range from  $0.59\text{-}0.69\text{ g/cm}^3$  ( $36.8\text{-}43.1\text{ lb/ft}^3$ ) and a wet basis moisture content from 19 to 20%. Three tests at three different burn rates are specified.

In Germany's DIN Method 18890<sup>20</sup> the sensible and chemical energy losses are calculated using atom balances. Carbon monoxide and hydrogen are the products of combustion that account for the chemical energy loss. The loss due to

ash is considered to be 0.5% of the fuel energy input. The fuel is as specified by the manufacturer and the stove is loaded with enough fuel to maintain four hours of combustion at the rated heat output referred to an efficiency of 70%.

None of the above methods is applicable to masonry heaters without modification. They are hot-to-hot tests and do not deal with the issues specific to masonry heaters.

Sensitivity studies of various flue loss methods have been performed.<sup>21,22,23</sup> Indirect methods are very sensitive to the measured fuel composition and flue gas concentrations. Elemental analyses for Douglas fir have given dry-mass basis hydrogen contents from 5.7 to over 7%, a range which can give average calculated CH<sub>4</sub> concentrations different by 1 to 2 mole percent. This translates to an efficiency range of 10 or more percentage points.<sup>21</sup> Sensitivities to errors in measurements of flue gas CO<sub>2</sub>, CO, and O<sub>2</sub> are high and increase with increasing excess air and combustion efficiency. To get only a 1 percentage point efficiency error, fuel hydrogen and stack oxygen and carbon dioxide concentrations must all be measured to within 1% of their value for excess air ranging from 50% to 400%. Measurements of such accuracy are very difficult, and exceed the capabilities of instruments typically used in woodstove testing laboratories. Not accounting for creosote

accumulation and particulate emissions can distort computed efficiencies by 1 to 3 percentage points.<sup>23</sup>

### **2.6.3 DIRECT FLUE LOSS METHODS**

Direct flue loss methods are different from the indirect methods in that the chemical energy loss is measured relatively directly. Atom balances are not used to calculate the concentrations of gases which are supposed to account for the chemical energy loss.

Direct loss methods include the Total Combustible Carbon Method<sup>24</sup>, and the Combustibles Meter Method<sup>25</sup>. These methods use a dilution tunnel to combine the stack gases with ambient air. In the dilution tunnel the flow rate is high enough to be measured using a Pitot tube and the mass flow rate is maintained nearly constant. After subtracting ambient gas concentrations, (usually needed only for CO<sub>2</sub>) the concentrations of gases in the tunnel are directly proportional to the flow of each quantity up the flue. Thus the losses are directly proportional to real time concentrations.

The Total Combustible Carbon Method uses the difference in CO<sub>2</sub> concentration from incinerated and raw tunnel samples as a measure of incompletely oxidized carbon. The chemical

energy loss is calculated by using an estimate of the heating value of the incompletely oxidized carbon. The mass of dry stack gas, used for the sensible loss calculation, is computed using a carbon atom balance based on CO<sub>2</sub> measurements in the stack (raw sample) and tunnel (raw and incinerated samples).

The Combustibles Meter Method uses a flame combustibles meter to measure the temperature rise of a filtered tunnel sample as it goes through a flame. The chemical energy content of the sample is proportional to its temperature rise. The filter catch is multiplied times an estimated smoke heating value to calculate the chemical loss due to smoke. The stack flow rate is measured directly using a Pitot tube or tracer gas. These two direct efficiency measurement methods are described in detail in the procedure section.

The British Standards Institution has a standard flue loss method for the thermal testing of domestic solid fuel burning appliances<sup>26</sup>. In this method, flue gas carbon monoxide, carbon dioxide, hydrogen, and methane concentrations are measured. The gas concentrations can be measured using either a sample storage method or a continuous gravimetric method. In the sample storage method the flue gases are extracted at a constant rate and stored

in a polymethylmethacrylate holder. The analysis is subsequently made on any suitable instrument. In the continuous gravimetric method the flue gases are passed through a train with a series of absorption tubes. The flue gas composition is determined by the increase in weight of the various absorption tubes.

An assessment of various flue loss methods, including direct methods, has been performed by Shelton and Jaasma<sup>22</sup>. Direct methods require measurements with an accuracy of only 2 to 20% of their values to avoid a 1 percentage point distortion in computed overall energy efficiency. For the fuel, only the higher heating value and hydrogen content need to be known. Indirect methods on the other hand require accuracies of 1 to 5%. Direct methods underestimate chemical energy loss by the amount of material (creosote) deposited prior to the sampling point.

The Total Combustible Carbon Method and the Combustibles Meter Method were taken as the bases for the methods developed and described in the current work.

## **2.7 RELATED COMPUTER MODELS**

A woodstove thermal storage system has been modeled by Zurigat and Ghajar<sup>27</sup>. The behavior of a thermal mass around

a woodstove was simulated using a one-dimensional explicit finite-difference method. The temperature variations were assumed to be significant only in the x-direction (across the storage wall), and the heat loss from the edges where the walls meet was assumed to be negligible. The stove was modeled as a constant temperature surface, and radiative heat exchange was included in the analysis. The stove surface temperatures were obtained from experimental data; this was done to account for the variations in heat flux encountered during normal stove operation.

The authors concluded that the results of the simulation were in good agreement with experiments, demonstrating the predictive capability of the analysis used. They also concluded that the simulation program developed is an effective tool for sizing thermal mass storage systems.

## Chapter 3

### METHODS AND CALCULATIONS

#### 3.1 EMISSIONS

Carbon monoxide and particulate matter emission factors and rates were calculated in accordance with the "Test Method for Determination of Masonry Heater Emissions"<sup>3</sup> developed by Stern et al. The separate emissions results were weighted according to burn rates following the procedure of EPA Method 28<sup>12</sup> for wood heaters to obtain the overall emissions totals for the test cycle.

#### 3.2 EFFICIENCY

Two direct efficiency measurement methods, the Total Combustible Carbon Method for Determination of Energy Efficiency of Wood Heaters<sup>25</sup> (TCC) and the Combustibles Meter Method<sup>26</sup> (CM), were modified and further developed for use on masonry heaters. The modifications and additions to these methods addressed issues specific to masonry heaters: How to account for the thermal storage of these appliances? Is the sensible loss significant during the off-period when there is no more combustion? How to measure the sensible

loss during both the on and off periods? What is considered useful heat (delivered to the home) and how do you account for it?.

In both methods the energy efficiency was calculated as follows:

$$\text{Energy efficiency \%} = 100 \frac{\text{Energy input} - \text{Losses}}{\text{Energy input}}$$

where the energy input is calculated by multiplying the dry mass of wood  $m_{dw}$  (main load plus kindling) times the assumed (for purposes of the current work) higher heating value of the dry wood fuel (19,810 kJ/kg). The losses are the latent, chemical, and the on-period and off-period sensible energy losses. The only loss that occurs during the off-period is the sensible loss.

There was no measurable amount of unburned fuel (charcoal) left at the end of a test for either of the two appliances tested, and therefore no charcoal energy was subtracted from the energy input. Any charcoal produced fell through the combustion chamber grate into the ash pan.

The features of the two efficiency testing methods are summarized in Table 1. A more detailed explanation of the calculation of each of the losses follows.



Table 1. Summary of features of the TCC and CM efficiency measurement methods.

LOSS	TCC	CM
LATENT	Same for both methods. Theoretical calculation based on the amount of water which would be produced if all the hydrogen in the as-fired fuel, whether existing as absorbed water or dry wood, would be emitted as water. This is consistent with the use of lower heating values for the chemical energy loss.	
ON-PERIOD SENSIBLE	Uses the theoretical water emission, and a dry stack flow calculated using a carbon balance which requires stack and tunnel data. Loss is computed using average values of one minute data.	The dry stack flow rate is measured using CO <sub>2</sub> tracer gas. The water content in the stack is assumed to be 1.2CO <sub>2</sub> S (theoretical for 100% combustion efficiency, 25% MCd, and 3 mole % water in air).
	Stack gas and room temperatures are measured using thermocouples.	
OFF-PERIOD SENSIBLE	Same for both methods. The wet stack flow rate during the off-period is measured using CO <sub>2</sub> tracer gas. Stack gas and room temperatures are measured using thermocouples. Loss is computed using a summation of 5 minute data.	
CHEMICAL	Measures combustible emissions in terms of incompletely oxidized carbon. An assumed lower heating value per mole of carbon is assigned to the combustible emissions.	Uses a combustibles meter to measure the lower heating value of a filtered tunnel sample. The loss due to the smoke is calculated by assigning a lower heating value to the filter catch.

### 3.2.1 LATENT LOSS

The latent energy loss calculation used for both the Total Combustible Carbon Method and Combustibles Meter Method is a theoretical calculation. The moisture content of the fuel is known by resistance meter measurements of the fuel, and the hydrogen content of the dry wood is known from its elemental analysis. The mass fraction of hydrogen in the dry wood ( $H_w$ ) used in this work is an average value for Douglas fir. An assumed value saves the cost and difficulty of accurate elemental analysis. The latent loss can therefore be calculated under the assumption that all of the hydrogen in the as-fired fuel, whether existing as absorbed water or dry wood, will be emitted as water vapor. The latent loss is then:

$$\text{Latent loss} = m_{H_2O} h_{fg}$$

$$m_{H_2O} = m_{dw} (9 H_w + MC_d)$$

The factor of 9 appears in the equation because 9 kg of water forms for each kg of hydrogen in the fuel.

The calculation of latent loss based on the maximum amount of water which could be produced (as opposed to the water which was actually produced) is exactly consistent with the use of lower heating value for the chemical energy loss.

### 3.2.2 ON-PERIOD SENSIBLE LOSS (TCC METHOD)

The Total Combustible Carbon Method sensible loss calculation depends on total theoretical water emission, dry stack flow, stack gas composition, and stack gas temperature. The dry stack flow is calculated via an improved carbon balance which requires both stack and tunnel data<sup>21</sup>.

The dry CO<sub>2</sub> concentration which would be measured in incinerated stack gas is computed as follows:

$$CO_{2SI} = CO_{2S} \frac{CO_{2TI} - CO_{2A}}{CO_{2T} - CO_{2A}}$$

The dry stack gas molecular weight is computed assuming that the oxygen and incinerated carbon dioxide concentrations add up to 21% and that the nitrogen concentration is 79%:

$$M_{ds} = \frac{44(CO_{2SI}) + 32(21 - CO_{2SI}) + 28(79)}{100}$$

The dry stack gas is calculated using a carbon balance:

$$m_{ds} = \frac{M_{ds} C m_{dw}}{12 (CO_{2SI}/100)}$$

The sensible loss is given by:

$$\text{Sensible loss} = (\dot{m}_{dS} C_{dS} + \dot{m}_{H_2O} C_{H_2O}) (T_g - T_r)$$

where  $T_g$  and  $T_r$  are time-averaged stack and ambient temperatures in Kelvins, and  $C_{dS}$  is the average constant-pressure specific heat of the dry gas in kJ/kg K; approximated by the second order polynomial:

$$C_{dS} = 1.003 + 3.488 \cdot 10^{-5} (T_g - T_r) + 2.036 \cdot 10^{-7} (T_g - T_r)^2$$

### 3.2.3 ON-PERIOD SENSIBLE LOSS (CM METHOD)

The on period sensible loss used in the Combustibles Meter Method relies on stack flow measurements using carbon dioxide as a tracer gas. The wet stack mass flow rate can be computed at any time using a mass balance of the carbon dioxide in the stack and tunnel:

$$\dot{m}_S = \dot{m}_T \frac{CO_{2T} - CO_{2A}}{CO_{2S}(1-W/100) - CO_{2A}}$$

where  $W$  is the mole percentage water content in the wet stack sample assumed to be 1.2 times  $CO_{2S}$ . This assumption is based on the theoretical water emission from combustion of Douglas fir wood ( $C_{44}H_{63.6}O_{25.5}$ ) with 25%  $MC_d$  on ambient air with 3 mole percent water (if 22%  $MC_d$  and no water in the air is used, the error in the computed overall average efficiency is a maximum of 0.3 percentage points).

The wet tunnel flow rate is measured using a Pitot tube. The molecular weight of the tunnel and stack gas is assumed constant at 29 g/g-mole.

The sensible loss is computed using the wet stack mass flow rate and a specific heat weighted for the water content in the stack.

$$\text{Sensible loss} = \dot{m}_S TL [C_{DS}(1-W_m/100)+C_{H_2O}(W_m/100)] (T_g - T_r)$$

where  $W_m$  is the mass fraction of water in the stack computed as follows:

$$W_m = W (18/29)$$

#### 3.2.4 CHEMICAL ENERGY LOSS (TCC METHOD)

The Total Combustible Carbon Method measures the combustible carbon emissions and uses an assumed heating value per mole of carbon. The combustible carbon emissions are obtained by measuring the carbon dioxide concentrations of raw and incinerated tunnel samples. The assumed lower heating value of the carbon-containing combustible emissions is 400,000 kJ/(kg-mole) of carbon. Lower heating values are used because the latent loss calculation assumes all the hydrogen in the fuel is emitted as water. Thus the sum of the latent and chemical losses is correct.

$$\text{Chemical loss} = [m_{dw} C / 12] \frac{(\text{CO}_{2\text{TI}} - \text{CO}_{2\text{T}})}{(\text{CO}_{2\text{TI}} - \text{CO}_{2\text{A}})} \text{LHV}_{\text{CE}}$$

### 3.2.5 CHEMICAL LOSS (CM METHOD)

The flame combustibles meter (FCM) is used to measure the lower heating value of a sample coming from the dilution tunnel. To avoid possible equipment problems the sample is filtered before going into the FCM. This means that the chemical loss due to smoke (particulate matter) is not measured by the FCM. The smoke loss is quantified by weighing the filters in the FCM sample line and by arbitrarily assigning a lower heating value of 30 MJ/kg to the catch.

The lower heating value of dry Douglas fir is about 19 MJ/kg, the lower heating value of liquid hydrocarbon fuels is roughly 42 MJ/kg, the lower heating value of carbon (graphite) is 33 MJ/kg, and the lower heating value of smoke (LHV<sub>S</sub>) is expected to be roughly 30 MJ/kg<sup>25</sup>. The efficiency calculation is not very sensitive to the assumed LHV<sub>S</sub>: an error of 10 MJ/kg in the assumed value would affect the efficiencies measured in this work by only 0.1 to 0.3 percentage points. The chemical loss in the CM method is computed as follows:

$$\text{Chemical loss} = \text{Gas loss} + \text{Smoke loss}$$

$$\text{Gas loss} = \dot{m}_T * TL * LHV_G$$

$$\text{Smoke loss} = \text{CATCH} * LHV_S * \dot{m}_T * TL / m_{\text{samp}}$$

The total sample mass  $m_{\text{samp}}$  is obtained by multiplying the measured total sample flow times its density at the measured sample temperature, ambient pressure, and average molecular weight of the dry tunnel gas (assumed constant at 29 g/ g-mole).

### 3.2.6 OFF-PERIOD SENSIBLE LOSS

The off-period sensible loss was measured from the end of each firing to the beginning of the next. The end of a firing occurred when the carbon monoxide concentration in the tunnel dropped to within 5 ppm of ambient and combustion had stopped. The 5 ppm requirement alone is not sufficient since carbon monoxide readings within 5 ppm of ambient were measured near the beginning of the firing when the appliance was burning very cleanly. The additional requirement of stopped combustion means that no flame is visible in the combustion chamber of the heater.

The time interval from the beginning of the last firing to the end of the last off-period sampling was set equal to

the time interval between the last two firings (since a subsequent firing did not determine the end of the off period).

The off-period sensible energy loss was computed as follows:

$$\text{Off-period loss} = \sum [ C_{ds} \dot{m}_S \Delta t (T_g - T_r) ]$$

where the dry stack flow is computed using a mass balance of the carbon dioxide in the tracer gas supply (bottle) and stack.  $CO_{2A}$  is negligible compared to  $CO_{2S}$  and is not included in the equation:

$$\dot{m}_S = \dot{Q}_{CO_2} \frac{CO_{2B} - CO_{2S}}{CO_{2S}} \rho_S$$

where:

$\rho_S$  = density of air at the stack temperature  $T_g$

$C_{ds}$  = the specific heat of air at  $T_g$

$\Delta t$  = the time interval between measurements (5 minutes)

$CO_{2B} = 100 \%$ .



### 3.2.7 CORRECTION FOR TRACER GAS FLOW

The raw and incinerated tunnel CO<sub>2</sub> concentrations, and the raw stack CO<sub>2</sub> concentrations measured during the on-period were corrected for the introduced CO<sub>2</sub> tracer gas as follows:

$$CO_{2T} = CO_{2T}(\text{uncorrected}) - 29/44 (\dot{N}_{CO_2}/\dot{N}_T) 100$$

$$CO_{2TI} = CO_{2TI}(\text{uncorrected}) - 29/44 (\dot{N}_{CO_2}/\dot{N}_T) 100$$

$$CO_{2S} = CO_{2S}(\text{uncorrected}) - M_{dS}/44 (\dot{N}_{CO_2}/\dot{N}_S) 100$$

Where 29 is the assumed molecular weight of the tunnel, 44 the molecular weight of CO<sub>2</sub>, and M<sub>dS</sub> the molecular weight of the stack gas.

## 3.3 COMPUTER MODEL

### 3.3.1 CONTRAFLOW HEAT EXCHANGER

Contraflow refers to the counter-flow heat exchanger configuration of the masonry heater. This is a heat exchanger where the hot gases flow up a channel from the combustion chamber and then flow down a channel between the first channel and the room.

In the contraflow exchanger, the hot flue gases lose energy to the walls of the heater as they flow from the combustion chamber to the stack. There is heat transfer from channel to channel through the dividing slab, to the room from the heater's wall, and within the flowing gas itself. All occur simultaneously and influence each other. The heat transfer processes are complex and three dimensional. The model presented is a simplified approximation.

### **3.3.2 FINITE DIFFERENCE MODEL**

The computer model was developed to predict the temperatures in the contraflow heat exchanger of the TU2500L. The results of the model were compared to temperatures measured during heater testing.

The model is one dimensional and uses the implicit finite difference method. The heat transfer coefficients in the contraflow channels of the masonry heater are calculated based on the measured stack flow rate and flue gas temperature at the exit of the fire chamber. The flow rate through the channels is taken to be 1/2 of the measured stack flow rate at the temperature measured by a thermocouple located centrally in the channel at the exit of

the fire chamber. The flow rate is taken as 1/2 the stack flow rate because of symmetry about the heater's centerline. Radiative heat exchange is not included in the model.

Figure 1 outlines the one dimensional finite difference model of the contraflow heat exchanger. There is a wall with room air on one side and hot gases on the other, and an internal slab with hot gases flowing on both sides. The room is assumed to be at a constant temperature, and the temperature of the hot gases is assumed to be the same in the two channels of the heater and constant for a time increment  $\Delta t$ . The validity of this assumptions is discussed in section 5.4.1.

The temperature is computed at discrete points referred to as nodes. Because of symmetry the model only takes into account one half of the masonry heater and hence the adiabatic boundary shown in Figure 1.

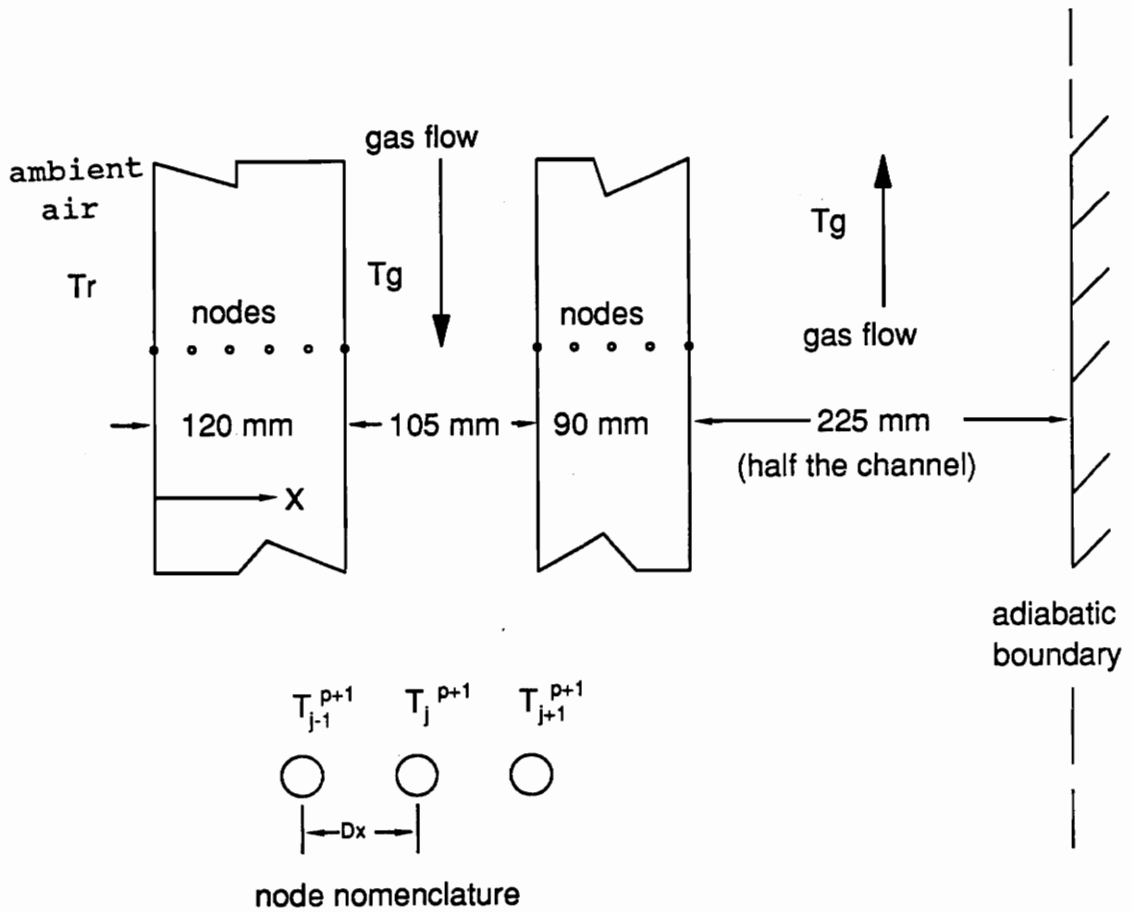


Figure 1. Finite Difference Model of the Contraflow Heat Exchanger in the TU2500L

### 3.3.3 FINITE DIFFERENCE EQUATIONS

The finite difference equations were derived from the one-dimensional transient conduction heat transfer equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

which in implicit finite difference form for a node  $j$  is:

$$T_j^p = T_j^{p+1} (1+2Fo) - Fo T_{j-1}^{p+1} - Fo T_{j+1}^{p+1}$$

where the Fourier number is defined as:

$$Fo = \alpha \frac{\Delta t}{(\Delta x)^2}$$

and  $\alpha$  is the thermal diffusivity of soapstone.

For the case of a node with a convection boundary to the right, the finite difference equation becomes:

$$T_j^p = (1+2Fo+2BiFo)T_j^{p+1} - 2FoT_{j-1}^{p+1} - 2BiFoT_g$$

where the Biot number is:

$$Bi = \frac{H \Delta x}{k}$$

and  $T_g$  and  $k$  are the temperature and conductivity of the gas with which convection takes place. If convection takes

place to the left of the node,  $T_{j+1}^{p+1}$  replaces  $T_{j-1}^{p+1}$  in the previous equation.

An equation is written for each of the nodes and the initial temperatures of the system become the temperatures at time  $p$ . The equations can then be solved simultaneously for the temperatures at time  $p+1$ . For the next time step the newly calculated temperatures become the temperatures at time  $p$ , and the temperatures at  $p+1$  can be calculated again.

#### 3.3.4 HEAT TRANSFER COEFFICIENTS

The heat transfer coefficient for convection from the outside surface of the heater to the room, was taken as the average for the 1.5 m tall, constant temperature (assumed), outside surface of the heater. The mean Nusselt number was computed using a correlation for free convection heat transfer from a constant temperature vertical plate<sup>28</sup>:

$$Nu_m = 0.1 (Ra)^{1/3}$$

valid for Rayleigh numbers greater than  $10^9$ ; where the Rayleigh number is defined as:

$$Ra = \frac{g \beta (T_s - T_r) L^3}{(V \alpha)},$$

and L is height of the outside wall (1.5 m).

The average heat transfer coefficient  $H_m$ , was then computed using the definition of the Nusselt number:

$$H_m = \frac{Nu_m k}{L}$$

All the properties ( $\alpha$ ,  $\beta$ ,  $k$ ,  $V$ ) are those of air, and were evaluated at the average of the room and the wall temperatures, using curve fits of published property tables.<sup>28</sup>

For the convection on the inside channels, the average combined entry length Nusselt numbers were calculated using the following correlation for an abrupt contraction entrance<sup>29</sup>:

$$Nu_m = Nu \left( 1 + \frac{6}{L/Dh} \right)$$

where L is the length of the channel, equal to 0.9 m in the model (0.9 m is the distance from the exit of the fire chamber to the top of the contraflow heat exchanger).

The fully developed Nusselt number Nu was calculated using the Colburn equation for fully developed turbulent flow in a smooth tube<sup>29</sup>:

$$\text{Nu} = 0.023 \text{ Re}_{\text{Dh}}^{4/5} \text{ Pr}^{1/3}$$

All the properties are those of air evaluated at the mean of the wall and convecting gas temperatures using curve fits of published property data. The curve fits were valid for the temperature range 250 to 1000 K which covers the range of temperatures encountered.



## Chapter 4

### APPARATUS AND PROCEDURE

#### 4.1 MASONRY HEATER DESCRIPTION

Two masonry heaters were used for testing the two efficiency measurement methods developed. The two heaters were also tested for emissions of particulate matter and carbon monoxide. Emissions were measured to evaluate performance and to determine the compatibility of the efficiency and emissions testing methods.

The first of the heaters, a Tulikivi TU2500L, is referred to as the contraflow because of the counter-flow heat exchanger it uses to exchange heat. In this heater the hot flue gases flow out of the combustion chamber and travel to the top of the heater where they turn to flow down a channel until they finally exit at the bottom and rear of the heater. The contraflow heater has a mass of 2585 kg, width of 1.2 m, depth of 0.742 m, and height of 1.95 m. It has a single glass door for loading the wood and an adjustable damper for control of air flow.

The second heater, a Tulikivi LU2600, is a heater-bake oven combination with a mass of 2516 kg, width of 1.17 m,

depth of 0.93 m, and height of 1.59 m. It has a single glass door with a damper for the loading of the wood into the firebox. Underneath the firebox there is a second combustion chamber with its own damper for combustion of the coals when the appliance is used as a bake oven.

## **4.2 EXPERIMENTAL APPARATUS**

### **4.2.1 STACK**

The heaters were fitted to a 15 ft. (4.6 m) tall, lined masonry chimney, fitted with a probe and a type K thermocouple at the top, in the center of the stack (Figure 2). The probe was used to draw sample for the measurement of stack carbon monoxide and carbon dioxide. The gas sample was drawn through an ice bath to condense the water vapor in the stream and through a glass fiber filter to remove particulates. The thermocouple at the top of the chimney was used to measure stack temperature for the calculation of on-period and off-period sensible energy loss. The heat transfer from the masonry chimney to the room was considered useful delivered heat.

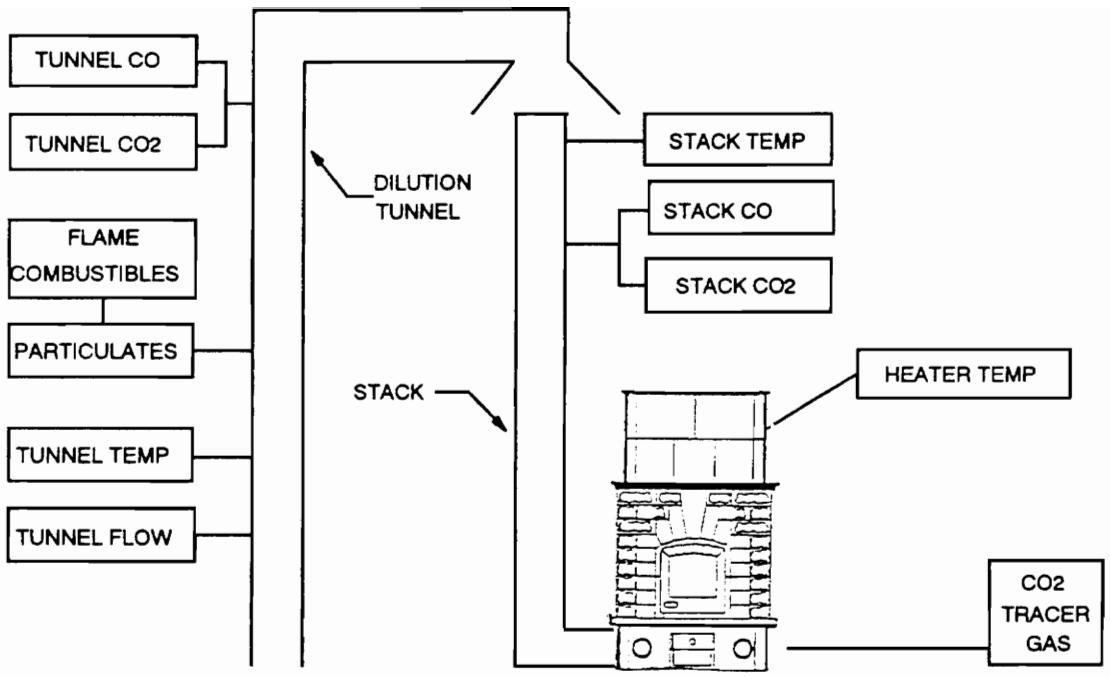


Figure 2. Stack and Tunnel Sampling System

#### **4.2.2 DILUTION TUNNEL**

The stack gases exhausted by the heater were collected by a dilution tunnel (Figure 2). The dilution tunnel was the same as specified in EPA method 5G for woodstoves with the following exceptions<sup>3</sup>:

- a) The wet tunnel flow was 1500 kg/hr +/-10 % to ensure collection of all chimney effluent.
- b) The tunnel diameter was 0.30 m (12 in.) to accommodate the additional flow without requiring additional blower capacity.
- c) Baffles were removed to help accommodate the additional flow without increasing blower capacity.

The dilution tunnel was fitted with two probes for gas sampling, a standard Pitot tube for measuring the tunnel flow rate, and two probes for the particulate measurement sample trains and flame combustibles meter gas sampling.

#### **4.2.3 TUNNEL GAS SAMPLING SYSTEM**

Two tunnel gas samples were used to determine raw and incinerated carbon monoxide and carbon dioxide concentrations of tunnel gas. The incinerated gas sample

was passed through an incinerator with catalyst pellets maintained at 440°C. After passing through the incinerator, the sample passed through glass fiber filters to remove any remaining particulates. A pump was used to draw the gas sample through the incinerator, filters, and lines and to deliver the gas to the analyzers (Figure 3). Raw tunnel samples followed a similar path but did not pass through an incinerator. Room air was sampled using a pump and delivered to the tunnel analyzers to measure the ambient carbon monoxide and carbon dioxide concentrations.

A one minute cycle multiplexing system was used to deliver the raw tunnel, incinerated tunnel, and ambient samples to the tunnel analyzers. Each sample was delivered to the tunnel analyzers for 20 seconds and was exhausted outside the laboratory for 40 seconds during each one minute cycle.

#### **4.2.4 STACK SAMPLING SYSTEM**

The raw stack sample was drawn continuously by a pump through the lines, condensation trap, and filter and delivered to the stack gas analyzers (Figure 3). Raw stack carbon monoxide and carbon dioxide concentrations were measured during the on-period, and stack carbon dioxide was measured during the off-period. Stack gas carbon dioxide

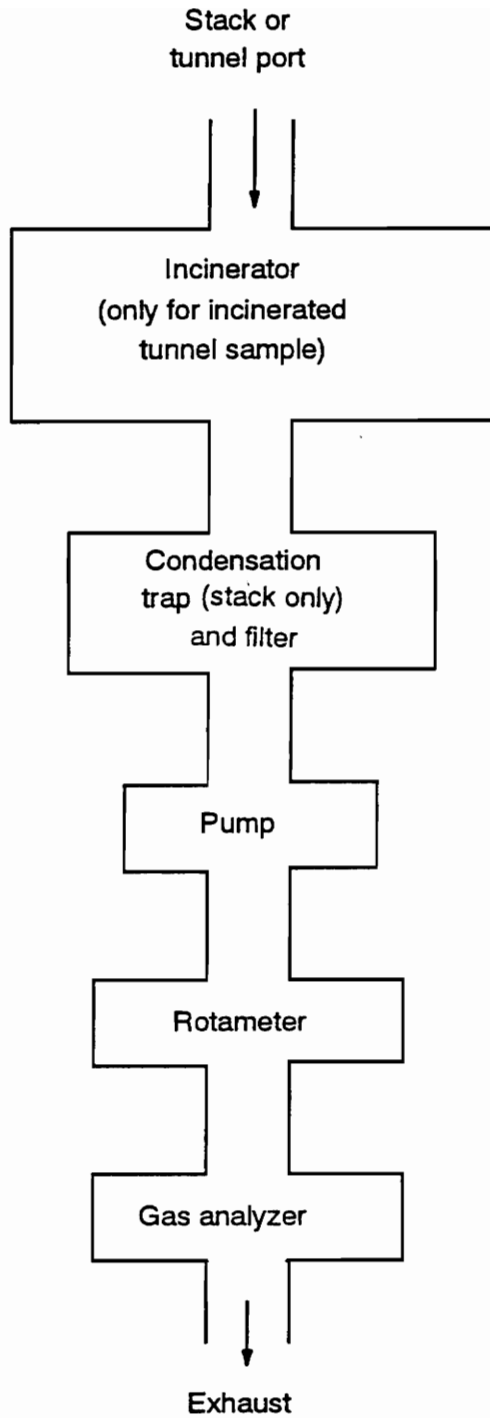


Figure 3. Gas Sampling Flowchart

concentrations were measured during the off-period as tracer gas was being injected in the stack. Carbon dioxide was injected in the stack in order to measure stack flow rate during both the on-period and off-period.

#### **4.2.5 PITOT TUBE**

The Pitot tube in the dilution tunnel was connected to an inclined manometer for setting the tunnel flow rate at the beginning of each test and a Schaevitz P2061-2wd pressure sensor for continuous reading by the data acquisition system during testing.

#### **4.2.6 PARTICULATE MATTER SAMPLING SYSTEM**

Particulate samples were taken in accordance with EPA method 5G for sampling from a dilution tunnel (Figure 4). This was accomplished by drawing part of the tunnel gas through each of the two sample trains with a pump. Each train consisted of a stainless steel probe beveled at 45 degrees at one end, two filter holders, and two 47 mm diameter Gelman glass fiber filters type A/E . The probe was beveled and the bevel was positioned to face downstream of the oncoming flow to avoid the sampling of large

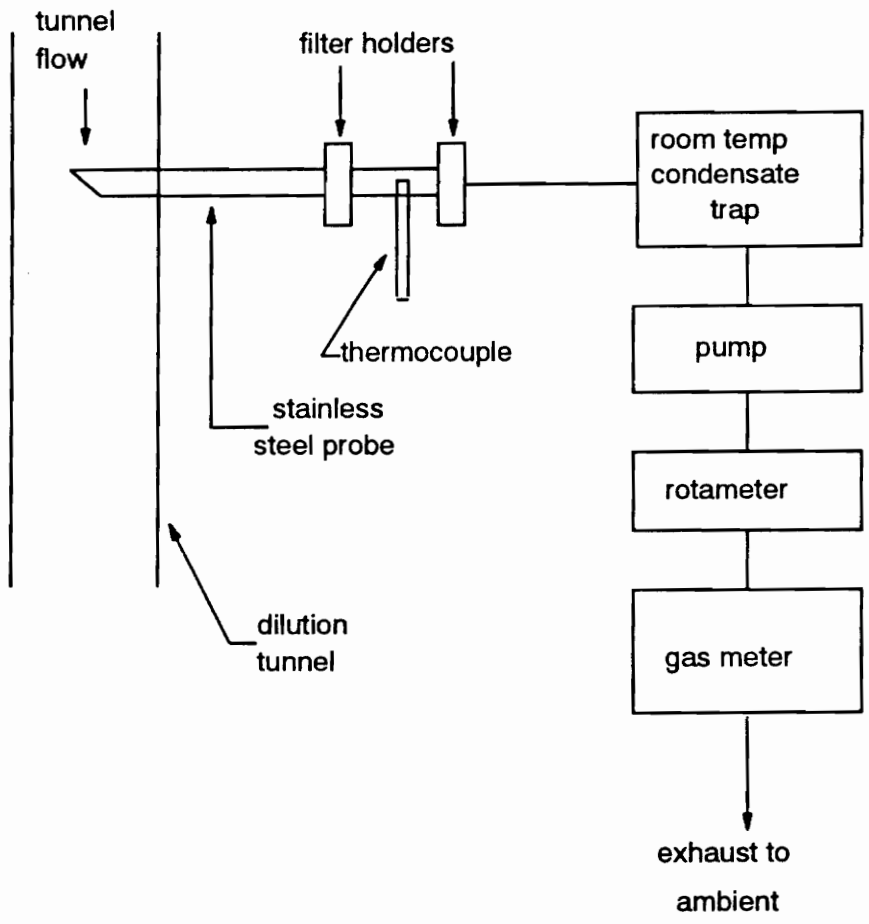


Figure 4. Particulate Matter Train Setup



particles which are not a significant air pollution concern. The flow rate through the trains was adjusted to about 9 ambient l/min. A dry gas meter was used to determine the total flow through each sample train.

Method 5G requires the temperature of the sample gas stream to be below 32°C between the two filter holders. This is to ensure that organics are not in a gaseous state. In a gaseous state organics would pass through the filters. The temperature between the 2 filters was checked for compliance with this requirement using a type-K thermocouple.

#### **4.2.7 FLAME COMBUSTIBLES METER**

A model A1FFAH0101 Control Instruments flame combustibles meter was used to measure the chemical energy content (lower heating value) of the tunnel gas. The flame combustibles meter (Figure 5) alternately measured the filtered raw tunnel sample coming from one of the particulate matter trains and the incinerated tunnel sample when it was bypassed from the analyzers.

The level of combustibles in the raw tunnel sample is very low. To avoid errors due to instrument drift and changing sample specific heat (due to changing background

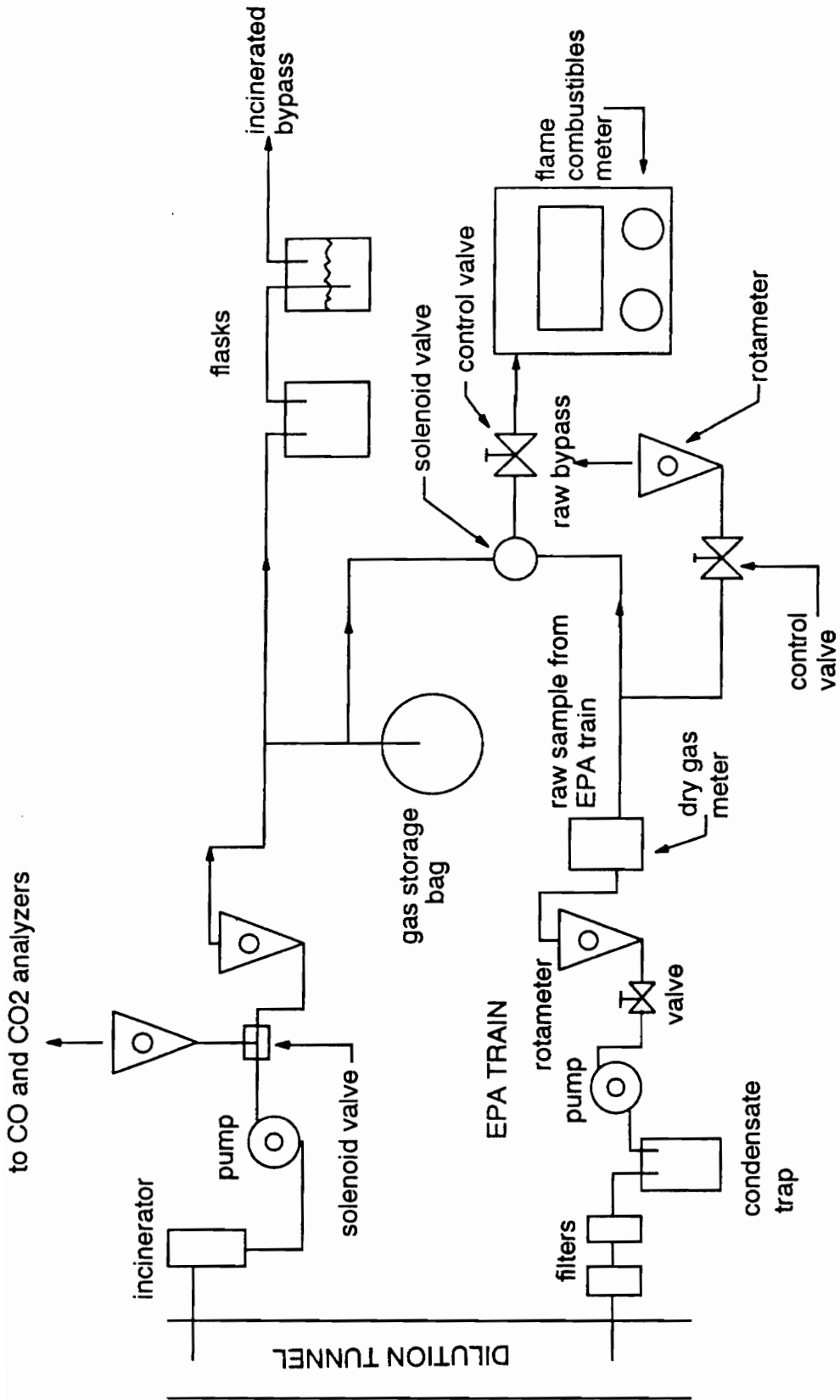


Figure 5. Flame Combustibles Meter Sampling System

gas carbon dioxide), the flame combustibles meter alternately sampled raw and incinerated tunnel samples to provide a periodic zero reference.

The incinerated tunnel sample flow rate is only a fraction of that required by the flame combustibles meter. The incinerated tunnel sample is normally bypassed from the tunnel analyzers for 40 seconds of each minute. Thus 40 seconds of incinerated tunnel sample flow are available to the flame combustibles meter. These 40 seconds of available incinerated tunnel sample were delivered to the flame combustibles meter within 20 seconds as follows: 20 of the 40 seconds of available incinerated tunnel sample flow were stored in a bag; the stored sample was put together with the other 20 seconds of available flow and delivered to the flame combustibles meter. For the other 40 seconds of every minute the flame combustibles meter was sampling the filtered raw tunnel sample coming from one of the particulate matter trains.

Any excess gas in the storage bag was exhausted through two glass flasks, one of which was partially filled with water to prevent ambient air from flowing into the bag.

The flame combustibles meter can measure the lower heating value of tunnel mixtures to within +/- 0.5 kJ/kg. The flame combustibles meter can therefore measure chemical

energy loss to within less than 1 percentage point of the fuel energy input (for the fuel loads and tunnel flow rates encountered during testing in this work).

#### **4.2.8 TRACER GAS SYSTEM**

The thermal mass of a masonry heater is enough to produce measurable stack flow rates even after the combustion of wood has stopped and points to the need to measure sensible energy loss during the off-period.

Toward the end of a firing during the on-period, the emission of carbon dioxide from combustion of the wood decreases to the point that accurate stack flow rate measurement using only the "natural tracer" carbon dioxide gas is no longer possible. Carbon dioxide is therefore introduced during both the on and off periods of the appliance in order to measure the sensible energy loss. The flow rates of introduced carbon dioxide tracer gas are different for the on and off periods. These flow rates are chosen to provide measurable concentrations of carbon dioxide with the available analyzers.

Airco welding grade carbon dioxide with a purity of 99.998 % was injected at the bottom of the stack to allow for the measurement of stack flow rate (Figure 6). The flow

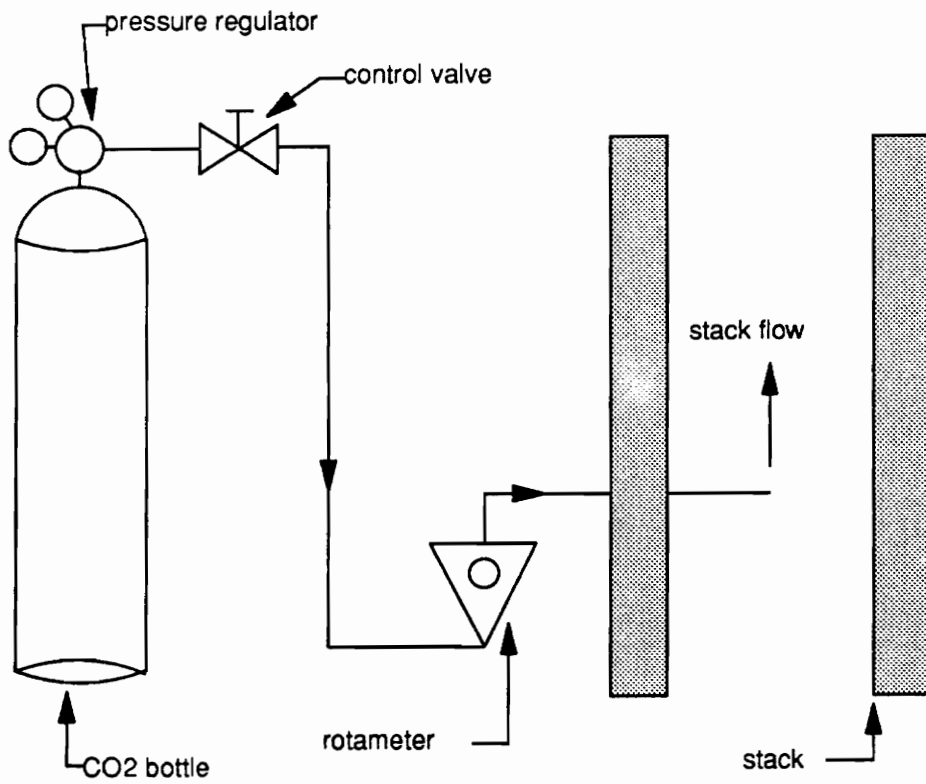


Figure 6. Tracer Gas System

of carbon dioxide during the on-period was controlled using a Matheson type 603 rotameter which was calibrated using a dry gas meter. During the off-period, a Matheson type 602 rotameter was used. This rotameter was calibrated using a bubble flow meter.

For the on-period, the introduced flow rate of carbon dioxide was 3.874 l/min (0.1 g/s) while the stack flow rates ranged from about 100 g/s (first 5 minutes after ignition when the loading door is opened) to about 30 g/s, with an average of about 40 g/s. For the off-period carbon dioxide was introduced at a rate of 0.2 l/min (0.006 g/s) while the stack flow rates ranged from 2 to 4 g/s. The flow rates of introduced CO<sub>2</sub> were clearly negligible.

During the on-period, the tunnel and stack carbon dioxide concentrations were needed. During the off-period only the stack carbon dioxide concentration was necessary.

#### **4.2.9 INCINERATOR**

The incinerated tunnel sample was used for the measurement of incinerated CO<sub>2</sub> and CO concentrations in the tunnel. The tunnel sample was incinerated using an incinerator containing a 50/50 mix of Englehard #2253701 and #1243801 catalyst at a temperature of 440°C. The efficiency

of the incinerator was measured by passing 0.3% methane in air through the incinerator. The incinerated gas was then passed through a rotameter and analyzed using an infrared CO<sub>2</sub> analyzer. The efficiency of the incinerator was computed by dividing the CO<sub>2</sub> concentration in the incinerated gas by the concentration of CH<sub>4</sub> in the raw gas (0.3%). For the flow rate used in this work (1600 cc/min) the measured incinerator efficiency was 100%.

#### **4.2.10 ANALYZERS**

The exhaust gas concentrations from the tunnel and stack were determined with infrared CO and CO<sub>2</sub>, and paramagnetic O<sub>2</sub>, gas analyzers. The stack CO<sub>2</sub> and CO concentrations were measured using Horiba PIR-2000 gas analyzers with 0 to 25 and 0 to 5 percent ranges, respectively. The stack O<sub>2</sub> concentration was measured using a Horiba MPA-21A gas analyzer with a range from 0 to 25 percent. Tunnel CO concentrations were measured with a Horiba AIA-23 gas analyzer with a range from 0 to 0.5 percent. Tunnel CO<sub>2</sub> concentrations were measured with a Horiba PIR-2000 with a 0.0 to 2.5 percent range.

#### **4.2.11 AMBIENT PRESSURE**

Ambient pressure was measured using a Datametrics 600A absolute pressure transducer. Ambient pressure readings were used to correct gas analysis readings for ambient pressure variation.

#### **4.2.12 THERMOCOUPLES**

All temperatures were measured with type K thermocouples. One thermocouple was located at the top of the chimney in the center of the flue to measure stack gas temperature, another in the center of the dilution tunnel to measure tunnel gas temperature, and one between the two filter holders of one of the EPA particulate matter sampling trains. Thermocouples were also placed in the contraflow masonry heater as shown in Figure 7. These thermocouples were used to verify on the numerical model.

#### **4.2.13 DATA ACQUISITION**

Three data acquisition systems were used. At one minute intervals during the on period, a 32 channel computerized data acquisition system was used to display and



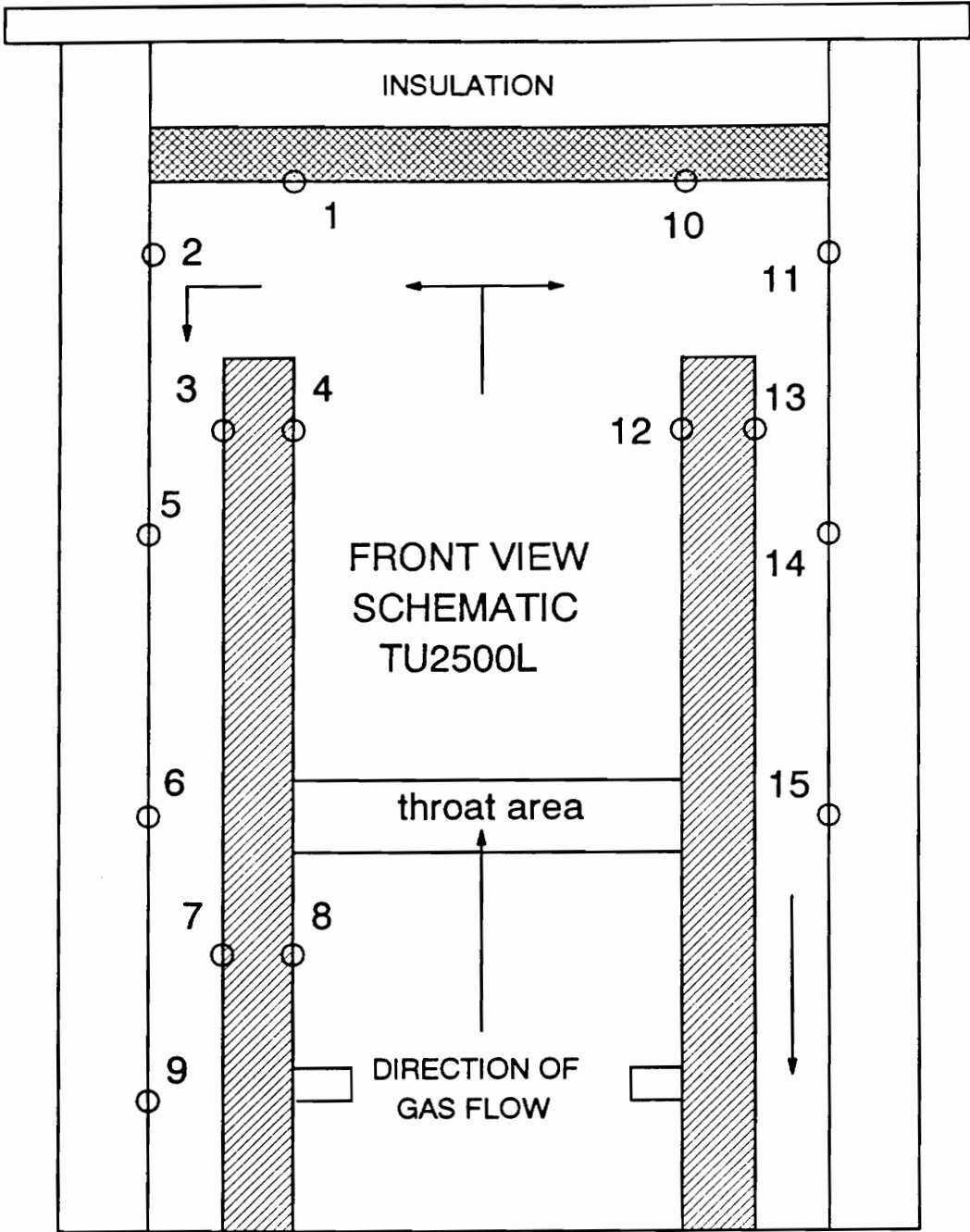


Figure 7. Thermocouple Placement in the contraflow masonry heater

store the measured ambient, tunnel, and stack carbon monoxide, oxygen, and carbon dioxide concentrations; tunnel and stack flow rates; ambient, stack, and tunnel temperatures; ambient pressure; and the lower heating value of the raw tunnel sample. This same computer controlled the switching of the solenoids used to direct the gas samples to the analyzers.

At 5 minute intervals during the off-period, a Campbell Scientific 21X Datalogger was used to store the ambient and stack temperatures and the stack carbon dioxide concentration.

The 15 temperatures measured by the thermocouples placed in the contraflow (Figure 7) were stored every five minutes by a computer with four Data Translation series 2801 data acquisition boards.

### **4.3 PROCEDURE**

#### **4.3.1 PREPARATION**

Before a test, the filters in the sample lines were changed, the Pitot tube was cleaned, the fuel load was readied, the analyzers were calibrated, the particulate matter sample trains were assembled, and the flow rate in

the dilution tunnel was set. All analyzers were zeroed using nitrogen and spanned with known gas concentrations. A coefficient of discharge for the dilution tunnel was found by injecting a known flow rate of carbon monoxide in the dilution tunnel. The coefficient of discharge was necessary to compute the tunnel flow rate.

#### **4.3.2 PARTICULATE MATTER SAMPLING TRAINS**

The filters and probe used for each sample train were desiccated with Drierite for at least twenty four hours before use. Each was weighed on a Mettler AE163 scale to 0.0001 g. The filters and probe were weighed again at the completion of the test run, desiccated for 24 to 36 hours, and weighed again. The filters and probe were then desiccated and weighed every 2 hours until they stopped losing weight. The dry gas meter readings were taken before and after each run to determine the total flow through each train.

#### **4.3.3 FUEL LOAD**

The fuel used was untreated, air dried, standard grade, nominal 2" X 4" (3.8 X 8.9 cm actual) Douglas fir lumber

with a moisture content of 19-25% on a dry basis. The use of nominal 2" X 4" fuel is not in accordance with the test method for masonry heater emissions by Stern et al.<sup>3</sup> which specifies nominal 4" X 4" Douglas fir lumber. The 4" X 4" lumber was not used because it did not ignite consistently in several ignition tests. The as-fired fuel density was between 0.48 and 0.58 g/cm<sup>3</sup>. The mass of the main load was determined based on the firebox volume. The mass of the main load was chosen to give a loading density of 96 wet kg of main load fuel per cubic meter of firebox volume (6 lb/ft<sup>3</sup>) +/- 5%. Spacing of 13 mm (1/2 in.) was maintained between fuel pieces by protruding nails placed on all four sides of the 2X4's (Figure 8).

The kindling was 19 X 19 mm (3/4 X 3/4 inch) Douglas fir with a dry basis moisture content of less than 5%. The mass of kindling was a minimum of 1 kg (wet) but no more than 1 kg (wet) per 20 kg main load (wet). The length of the main pieces and the kindling was 5/6 of the longest horizontal firebox dimension. Moisture content measurements were taken prior to each test using an electric resistance moisture meter. Six half sheets of ordinary black and white, non-glossy newspaper balled to roughly 90 mm (3.5 inch) diameter were placed under the kindling to help start the fire. Both kindling and main load were loaded horizontally.

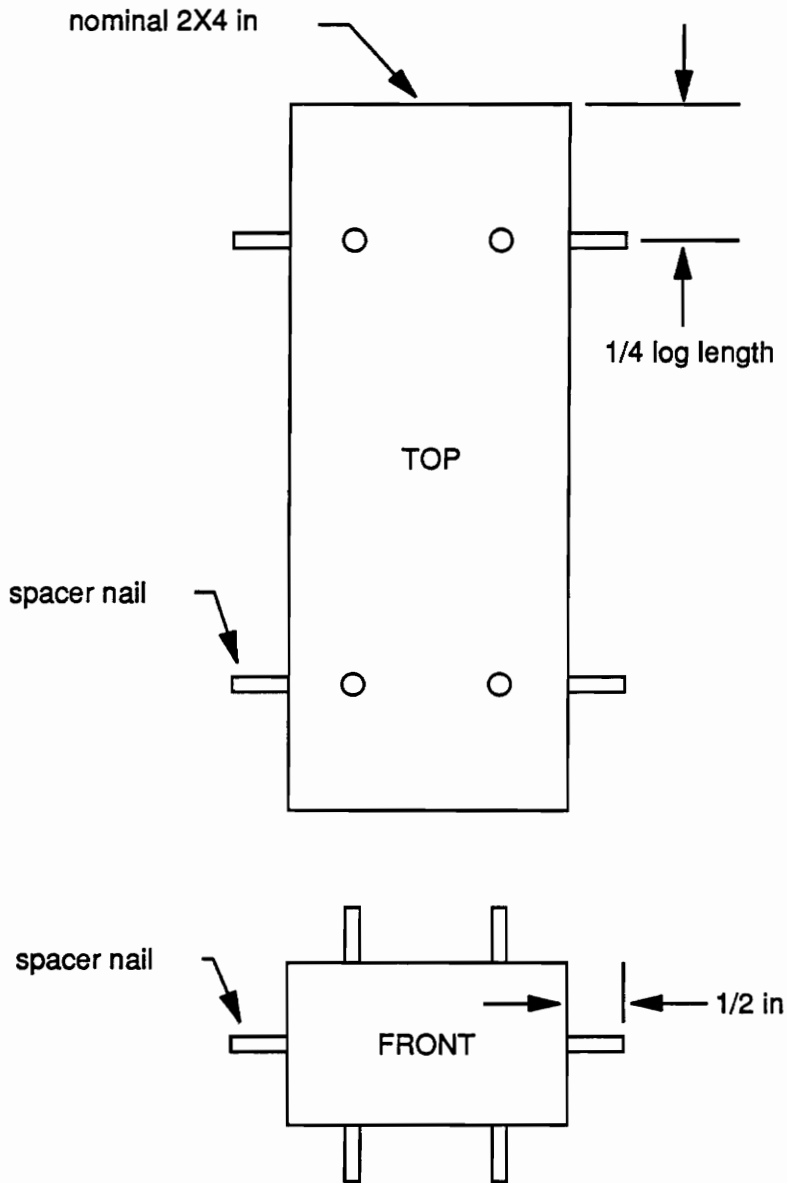


Figure 8. Main Load Fuel Piece

#### **4.3.4 FUELING**

The test cycle consisted of five firings (loadings) for all masonry heaters. The time interval between the first and second firings and the second and third firings was set to achieve a nominal low burn rate of between 0.70 and 1.10 dry kg/hr. The time interval between the third and fourth firings and the fourth and fifth firings was set to achieve a nominal high burn rate of between 2.10 and 3.30 kg/hr. The latter time interval was 1/3 of the low burn rate interval.<sup>3</sup>

All loads but the first were full size. Since the first load was burned in a cold masonry heater, this load was 75 to 100 % of a full load to reduce thermal shock to the heater.

#### **4.3.5 MASONRY HEATER OPERATION**

All loads were ignited with a hand-held propane torch. For the first firing the torch was used to help induce draft. No more than 5 grams of propane were used. For the first five minutes after ignition the air control damper was completely open and the loading door was open. At five minutes the door was latched closed and the air damper partially closed. After the first five minutes no more

adjustments to the damper were made and the door remained closed until the next loading.

When the emissions sampling ended, the dampers and air vents were fully closed and remained in this position until the next firing.

#### **4.3.6 SAMPLING**

Sampling began within 20 seconds of load ignition. Sampling for each of the firings ended when the carbon monoxide concentration in the dilution tunnel dropped to within 0.0005 mole % (5 ppm) of ambient and the fire was visibly out. The two requirements are necessary to determine the end of a firing, as carbon monoxide concentrations within 5 ppm of ambient were measured in the dilution tunnel near the beginning of a firing when the appliance burns very clean.

At the end of each firing the particulate matter train and the tunnel sampling pumps were turned off. The carbon dioxide tracer gas flow rate was reduced from 3.9 l/min to about 0.2 l/min and stack sampling for measurement of the off-period sensible loss continued until the next firing.

At the end of the fifth firing, the off-period sensible loss measurement continued for a time interval equal to that between the last two loadings. At this time the test officially ended and all sampling stopped.

The energy stored in the heater at the end of a test was assumed to be useful heat. In reality, the off-period sensible energy loss continues until the heater losses all its stored thermal energy and stack flow stops. This off-period sensible loss (after the end of a test) was measured for 2 tests with the contraflow. In each test the sensible loss continued for a period of about 2 days and accounted for an additional 2% of the fuel energy from the last fuel load.



## **Chapter 5**

### **RESULTS**

#### **5.1 PRELIMINARY TESTING**

A total of 8 load-ignition tests were performed on the contraflow heater to obtain a kindling and main load combination that would burn consistently. The tests were conducted with variations in the amount of kindling, the loading configuration (horizontal or vertical), and the size of the main load pieces (nominal 4X4's or 2X4's). It was determined that at least 1 kg of kindling was necessary to properly ignite the wood and that the 4X4's would not completely burn in either horizontal or vertical loading on a consistent basis. In every case the 2X4's burned vigorously and completely.

#### **5.2 EMISSIONS**

A full (five firings) emissions test was performed on the contraflow as described in the procedure section, but using 4X4's as the main fuel (Test 600). The results of this test can be compared to those obtained in the later tests with 2X4's as the main load. There was a significant amount of unburned wood at the end of each firing, and the

next load was simply placed on top of the unburned remains. After the last firing only charcoal remained. No correction to the results was made for the remaining charcoal.

Two emissions tests using nominal 2X4's as fuel were performed on the contraflow (Tests 602 and 603) and three (Tests 610, 611 and 615) on the heater-bake oven. The complete emissions test data and results are presented in Appendix 1. The weighted average (WTD. AVG.) results of the particulate matter (PM) and carbon monoxide (CO) emissions, for each test are presented in Table 2. Both the PM and CO emissions were lower when using 2X4's instead of 4X4's as the main fuel (compare Tests 602 and 603 with Test 600).

For the averaging the separate emissions results for each firing were weighted according to burn rates, following the procedure of EPA Method 28<sup>12</sup> for wood heaters.

Tests numbers 602 and 603 used similar fuel loads, loading intervals, and heater operation. The results of these two tests demonstrate the repeatability of the emissions test method: the particulate matter factors differ by only 4% and the CO factors by 8%.

Table 2. Emissions results. (Dilution tunnel values)

TEST #	FUEL SIZE	TOTAL FUEL MASS kg	EPA WTD. AVG. PM RATE g/hr	EPA WTD. AVG. PM FACTOR g/kg	EPA WTD. AVG. CO RATE g/hr	EPA WTD. AVG. CO FACTOR g/kg
CONTRAFLOW						
600	4x4	41.8	4.2	2.65	86.7	52.3
602	2x4	41.5	1.3	1.07	70.9	49.2
603	2x4	41.8	1.5	1.03	61.1	45.3
BAKE OVEN						
610	2x4	28.5	6.3	4.72	161.9	103.1
611	2x4	29.1	7.7	5.2	208.0	147.9
615	2x4	54.7	9.0	5.3	133.2	78.3

The bake oven has two air inlets that can be operated independently. For Tests 610 and 615, both air inlets were operated according to the manufacturer's instructions: for the first 5 minutes after ignition the loading door and fire chamber air inlets were open, and the ash chamber inlet was closed. At 5 minutes the loading door was closed, the fire chamber inlet remained open, and the ash chamber inlet was opened about 20%. When the coals reached a charcoal stage

they were pushed back to the grate, and the fire chamber air inlet was closed.

For Test 611 the bake oven was operated with only the fire chamber door open upon ignition. When the coals were pushed to the coal grate, the fire chamber air door was closed and the ash chamber air door was opened. This was done to check the effect of air inlet position and accounts for the difference in the results of Test 611 (compared to Tests 610 and 615).

Test 615 used a larger load of wood than that used in the two previous tests with the bake oven, and larger than that specified in the procedure section. This was done to check whether a larger load of wood would improve the performance of the appliance. The results can be compared to those of Test 610 which used the same air inlet positions: CO emissions decreased, while PM emissions increased. The larger load of wood did not reduce emissions significantly and the measured efficiency remained about the same (see Section 5.3).

Since the EPA regulations for wood heater emissions are expressed as stack equivalent (EPA Method 5H<sup>10</sup>) values, it is customary to present emissions results in this manner. Emissions results using dilution tunnel measurements (EPA Method 5G<sup>9</sup>) can be converted to stack measurement

equivalents (EPA Method 5H<sup>10</sup>) using the following correlation<sup>14</sup> :

$$\text{Method 5H} = 1.619 (5G)^{0.905}$$

The emissions results presented in Table 2 were converted to Method 5H values using the previous correlation and are presented in Table 3

Table 3. Emissions results. 5H equivalent values.

TEST #	FUEL SIZE	EPA	EPA	EPA	EPA
		WTD. AVG. PM RATE g/hr	WTD. AVG. PM FACTOR g/kg	WTD. AVG. CO RATE g/hr	WTD. AVG. CO FACTOR g/kg
600	4x4	5.9	3.7	86.7	52.3
602	2x4	2.1	1.7	70.9	49.2
603	2x4	2.3	1.6	61.1	45.3
610	2x4	8.6	6.4	161.9	103.1
611	2x4	10.3	7.0	208.0	147.9
615	2x4	11.8	6.9	133.2	78.3

### 5.3 EFFICIENCY

Three efficiency tests were performed on the contraflow heater (Tests 605, 606, and 607), and three on the heater-bake oven (Tests 610, 611, and 615).

For each firing of a test, the losses and efficiency were computed using the modified Total Combustible Carbon and Combustibles Meter methods as outlined in the calculation section.

The overall average efficiency for each test was calculated using EPA Method 28 to weight the individual firing cycle efficiencies based on burn rate.

The test data and complete results of the efficiency tests are presented in Appendix 2. Table 4 summarizes the results.

The measured overall average efficiencies, using the TCC and the CM methods, agree to within 1.3 percentage points of the fuel energy input.

Table 4. Efficiency results. Measured overall average efficiencies using the Total Combustible Carbon (TCC) and Combustibles Meter (CM) methods.

TEST #	APPLIANCE	% EFFICIENCY	% EFFICIENCY
		TCC METHOD	CM METHOD
605	Contraflow	67.9	67.1
606	Contraflow	65.0	65.6
607	Contraflow	64.2	65.9
610	Bake oven	59.7	58.4
611	Bake oven	66.4	66.1
615	Bake oven	58.6	* N.A.

\* The CM method was not available for this test

Figure 9 is a comparison of the sensible energy losses computed using the CM and TCC methods for Test 610 on the bake oven. Figure 10 is a comparison of the chemical energy losses for the same test. The latent and off-period sensible losses are (by definition) the same for both methods.

The losses measured with the two methods show good agreement and when averaged yield the results of Table 4.

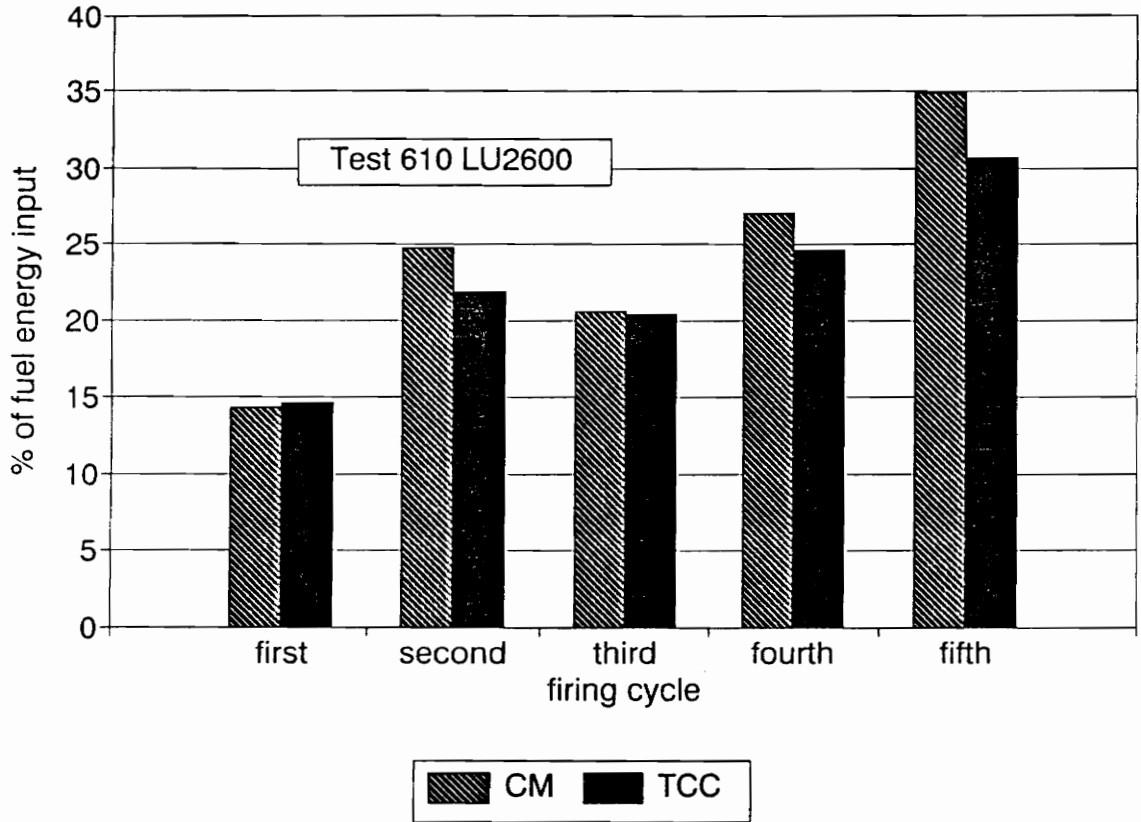


Figure 9. Comparison of on-period sensible energy losses using the TCC and CM methods. Results for one test with the bake oven.



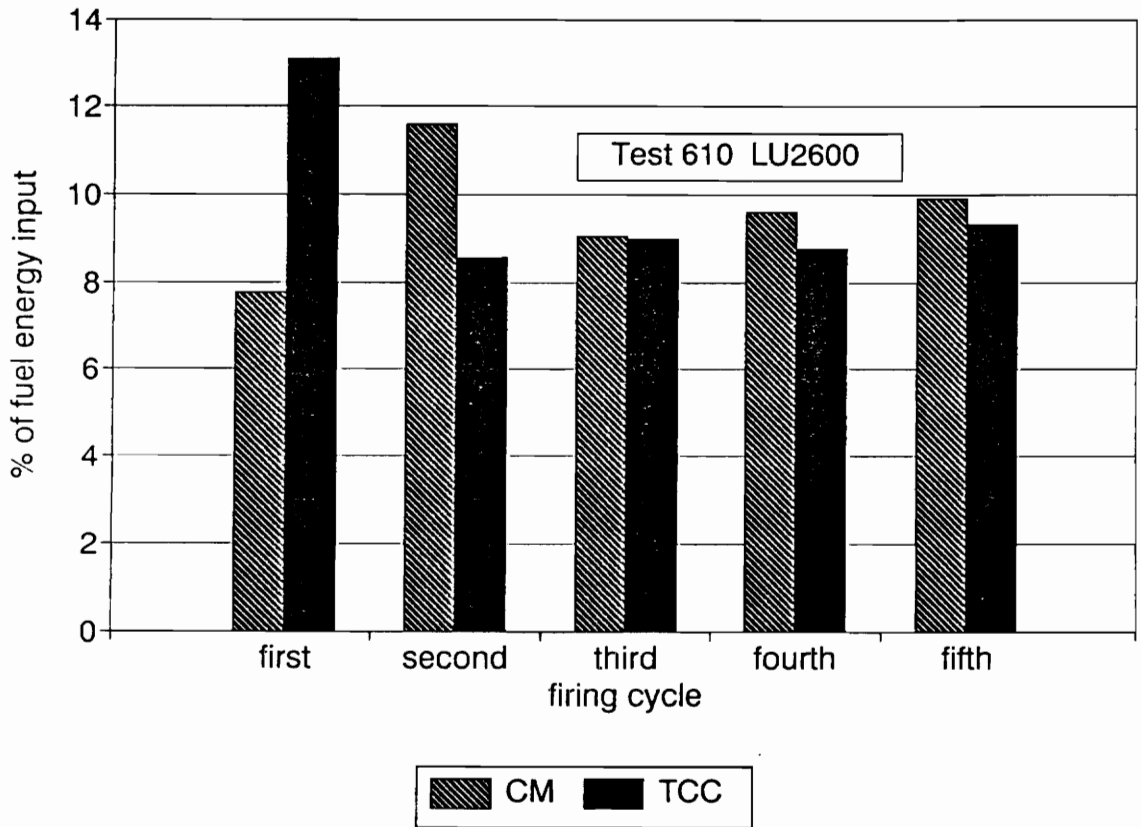


Figure 10. Comparison of chemical energy losses using the TCC and CM methods. Results for one test with the bake oven.

The agreement between the two somewhat independent test methods provides a check of the test data.

The chemical energy loss computed using either the TCC or CM methods can be compared to the part of that chemical loss which is due to CO. Figure 11 is a plot showing the ratios of chemical losses, TCC/CO and CM/CO, for the five efficiency tests on the two masonry heaters. The ratio of total chemical loss to CO loss is on the average about 1.8. Chemical energy losses could therefore be computed by multiplying the chemical loss due to CO by 1.8. This approximation would distort the overall efficiencies (for 5 load tests) measured in this work by an average of 0.3 percentage points with a standard deviation of 1 percentage point.

Figures 12 and 13 show the losses for the first and the fifth firing of Test 605 on the contraflow. The appliance tends to be more efficient in the earlier burns due to a smaller sensible loss. In the later burns the appliance has more stored thermal energy and the sensible energy loss accounts for a larger percentage of the fuel energy input.

Figure 14 shows typical stack flow rates measured during the on-period using CO<sub>2</sub> tracer gas. Tracer gas was introduced at a rate of 0.1 g/s which is about 1/400 of the average stack flow rate.

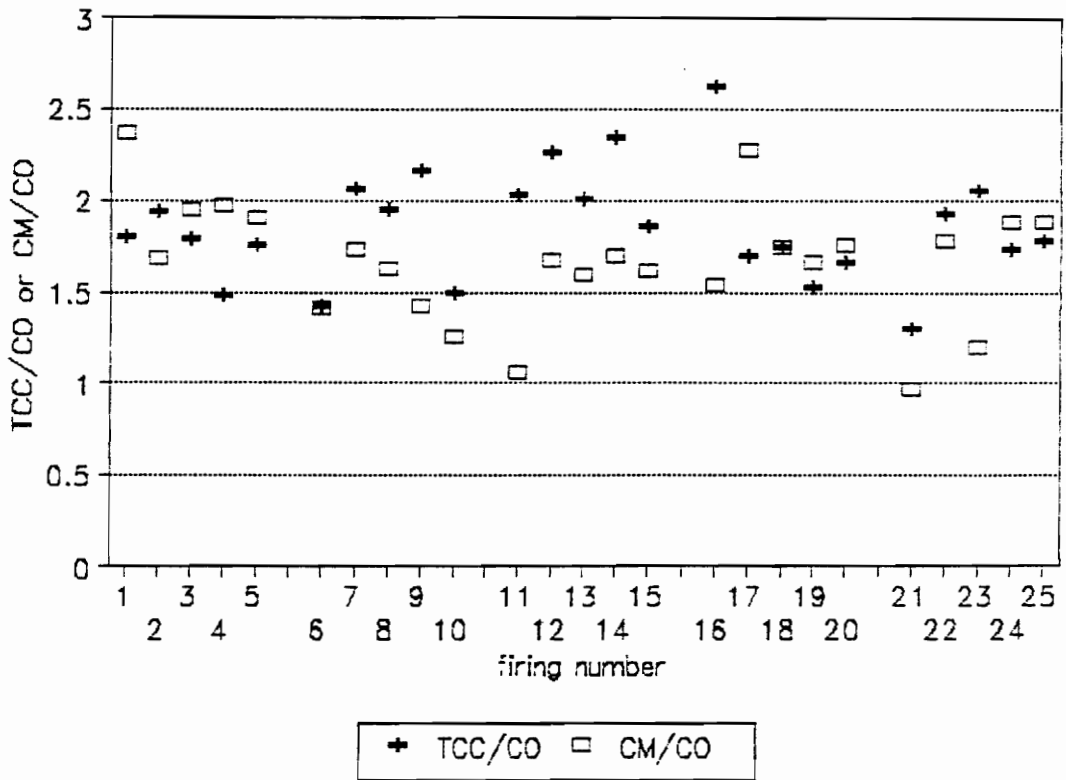


Figure 11. Ratio of total chemical energy losses to the chemical loss due to CO. Results for Tests 605, 606, 607, 610, and 611.

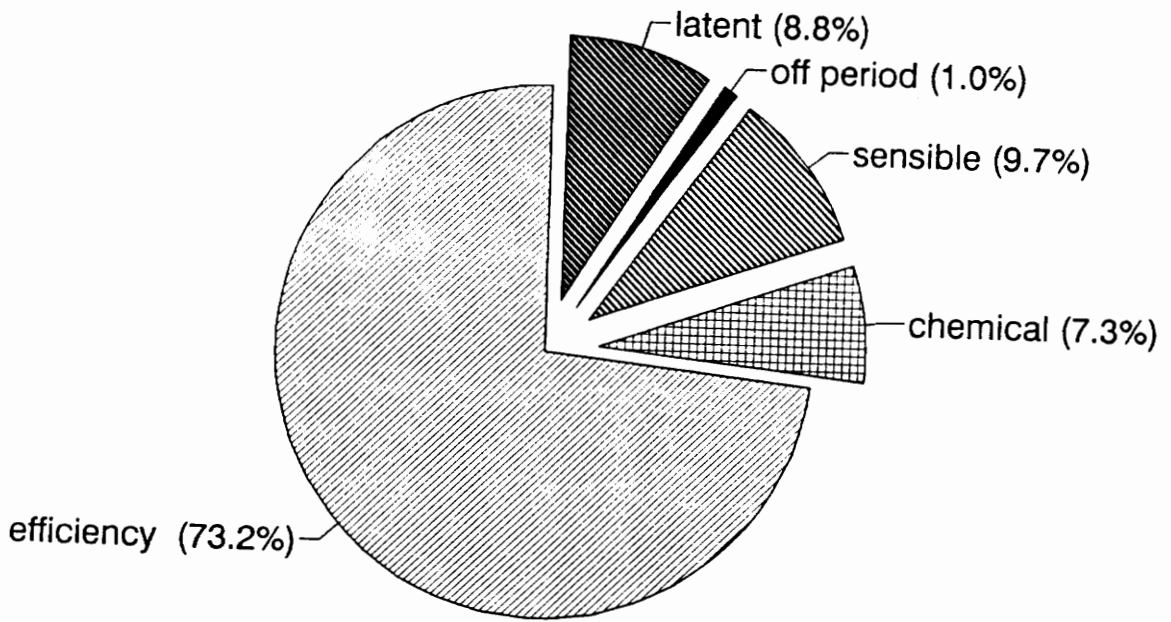


Figure 12. Distribution of energy losses for the first firing of one test with the contraflow heater.

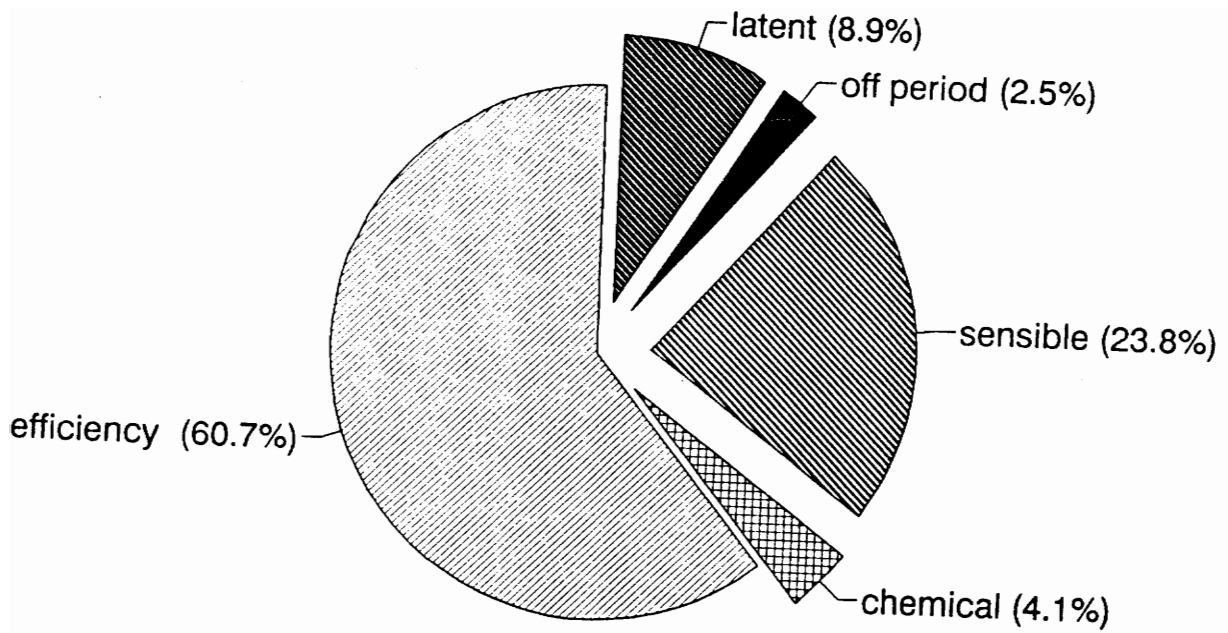


Figure 13. Distribution of energy losses for the fifth firing of one test with the contraflow.

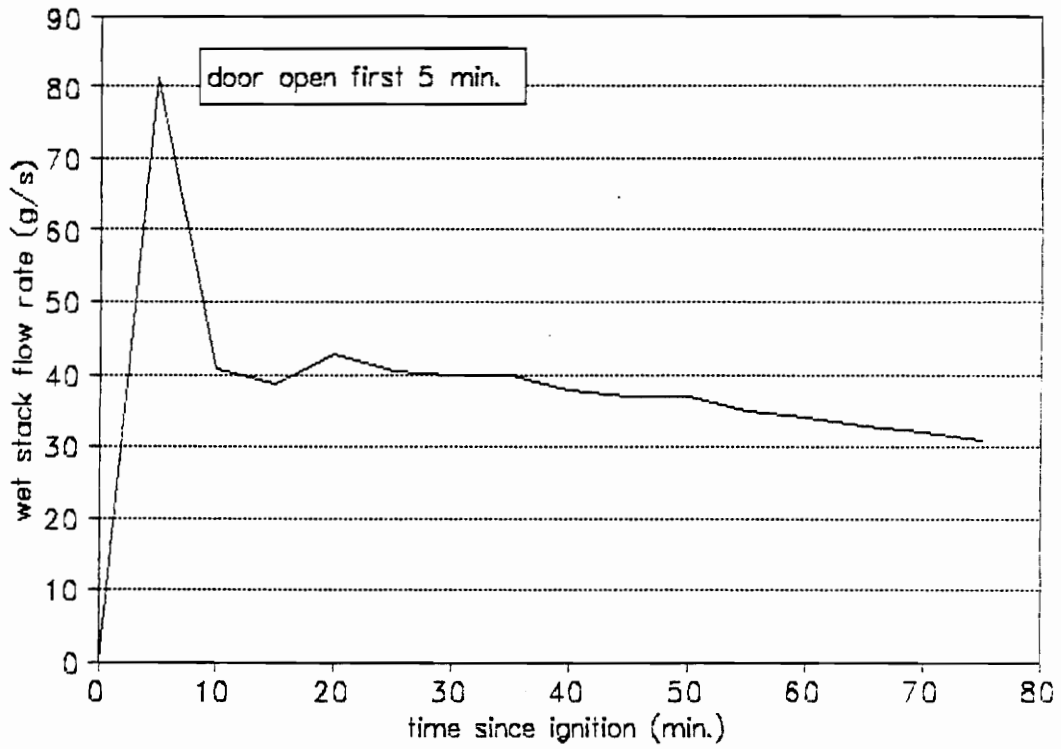


Figure 14. Typical masonry heater stack flow rates during the on-period. Results for one firing with the contraflow

For the tests performed, the off-period sensible loss ranged from 0.2 to 2.5% of the fuel energy input; on the average it accounted for about 1 percentage point of the fuel energy input. This loss is probably less than would occur in a field situation where draft values would be greater than those with laboratory tests using a chimney which vents into the room in which the appliance is located.

Figure 15 shows a typical profile of the stack flow rate during the off-period. The stack flow rate was measured using CO<sub>2</sub> tracer gas which was introduced at a rate of 0.006 g/s or about 1/500 of the off-period stack flow rate. Stack flow rates for a typical firing (on and off periods) are shown together for comparison in Figure 16.

The repeatability of the efficiency test method applied to one appliance can be seen from the results of the 3 tests on the contraflow (Tests 605, 606 and 607). For the CM method, the average of the measured efficiencies for the three tests was 65.9% with a standard deviation of 0.83 percentage points. The average of the TCC measured efficiencies was 65.70% with a standard deviation of 1.61 percentage points. For Tests 610 and 615 the average of the TCC computed overall energy efficiencies was 59.13% with a standard deviation of 0.56 percentage points.

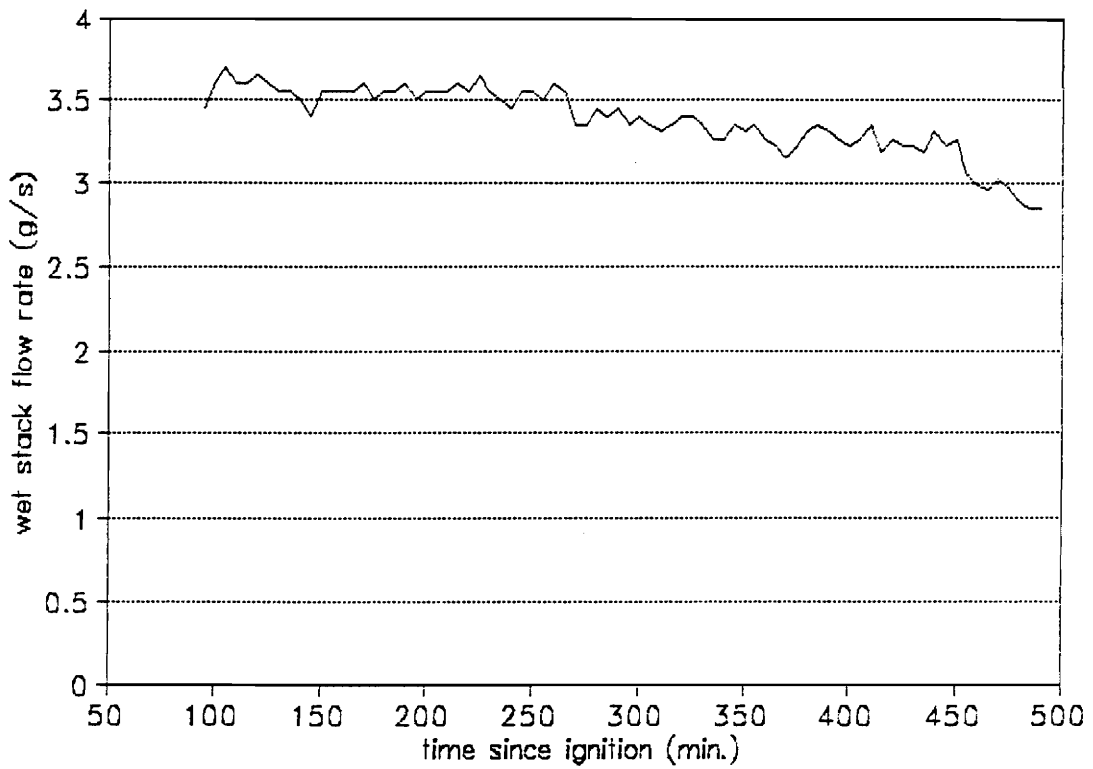


Figure 15. Typical stack flow rates during the off-period.  
Results for one firing with the contraflow



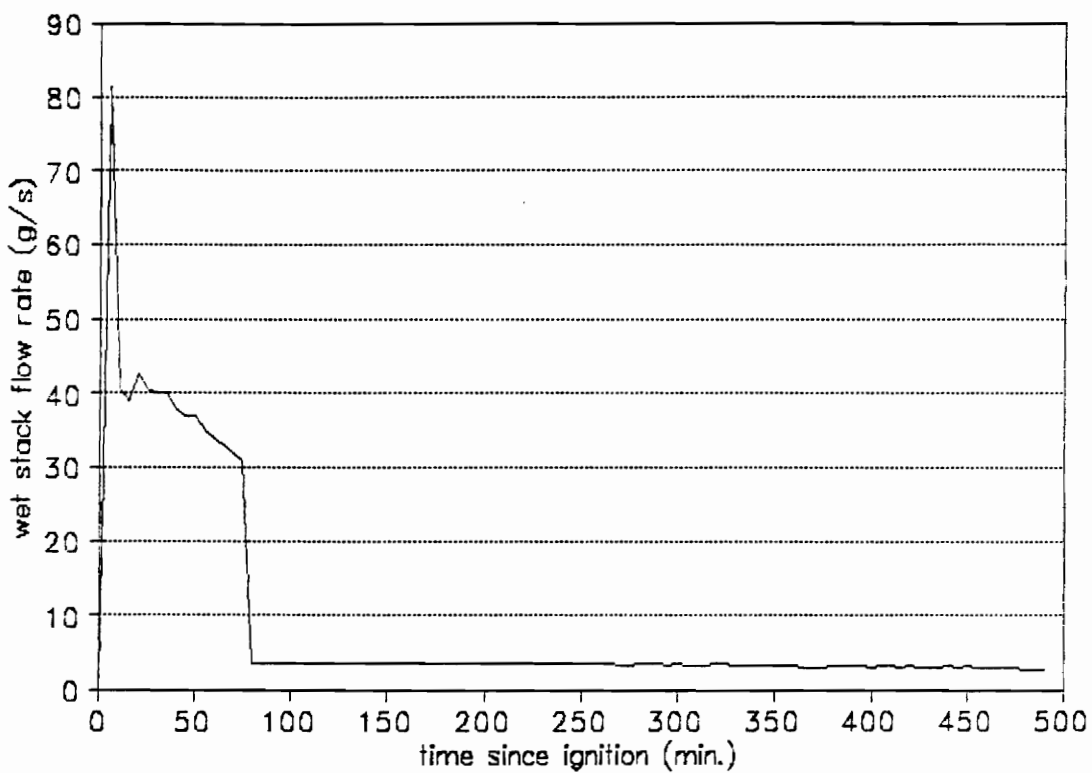


Figure 16. Stack flow rates during the on and off periods. Results for one firing with the contraflow.

### 5.3.1 SENSITIVITY ANALYSIS

The sensitivity of the two efficiency measurement methods to errors in measured values and assumed parameters was analytically studied. The 5 efficiency tests on two appliances (Tests 605, 606, 607, 610 and 611 on Appendix 2) were used as the baseline data for the study. Each of the measured or assumed values studied was increased by its maximum probable error while all other parameters remained at their baseline values. The changes in the computed overall efficiency are presented in Table 5.

It is interesting to note that the TCC method does not require absolute accuracy of tunnel CO<sub>2</sub> measurements. A simultaneous error in CO<sub>2</sub>T<sub>I</sub>, CO<sub>2</sub>T, and CO<sub>2</sub>A (for example a 5% increase in all three values because the instrument was misspanned) does not have an effect on the measured efficiency. The issue of interest is the repeatability of the CO<sub>2</sub> instrument; this was checked with a 0.5 mol % sample (a typical tunnel value) and found to be 0.5% of value. In the worst case (CO<sub>2</sub>T<sub>I</sub> measured 0.5% high and CO<sub>2</sub>T measured 0.5% low) this gives a maximum of 0.8 percentage points error in computed overall average energy efficiencies.

From the results of Table 5 it can be seen that the TCC and CM methods require accuracies of measurement of 4% or less accuracy (assuming linearity in sensitivity) to achieve

a corresponding accuracy of 1 percentage point in the computed overall energy efficiency within the 5 baseline data sets. All sensitivities are less than 1.5 percentage points except that for  $LHV_{CE}$ . If the maximum probable inaccuracy due to the assumed value of  $LHV_{CE}$  is not tolerable the CM method should be used.

The TCC and CM methods are insensitive to measured and assumed values compared to traditional stack loss methods which are very sensitive to absolute accuracy of gas concentration measurements and elemental analysis.<sup>23</sup>

Table 5. Sensitivity of the TCC and CM methods to measured and assumed values.

PARAMETER	ASSUMED ERROR (% OF VALUE)	CHANGE IN OVERALL AVERAGE EFFICIENCY (PERCENTAGE POINTS)	
		TCC	CM
$MC_d$	+3	-0.1	-0.2
$\dot{m}_T$	+5	0	-1.2 to -1.3
simultaneous error on $CO_{2T}$ $CO_{2TI}$ , and $CO_{2A}$	+4	0	-0.8 to -0.9
$CO_{2S}$	+4	0.5 to 0.7	0.5 to 0.8
$LHV_G$	+5	0	-0.7
$LHV_{CE}$	+30	-1.5 to -3.6	0
$LHV_S$ (assumed at 30 MJ/kg)	+10	0	-0.01 to -0.1
Hw (assumed at 0.0583)	+10	-0.7	-0.7

## 5.4 COMPUTER MODEL

### 5.4.1 VERIFICATION OF ASSUMPTIONS

#### 5.4.1.1 ONE DIMENSIONALITY

The computer model is based on the assumption that the temperature variation in the walls of the heater is negligible in the vertical ( $y$ ) direction. Consequently, the surfaces of the walls of the heater are assumed to be at a uniform temperature. This assumption was checked using measured temperatures within the heater.

Figure 17 is a plot of the temperatures measured at two points on the inside surface of the heater's wall, for one firing of the contraflow. The two measurement points (corresponding to thermocouples 5 and 9 of Figure 7) had the same horizontal position ( $x$ ), but were separated by a vertical ( $y$ ) distance of 0.7 m. The two temperatures differed by no more than 7.5%.

For the 1.5 m tall outside wall, the temperature variation could therefore be up to about 16% (from top to bottom). On the average, however, (for the firing cycle) this variation would be on the order of 12%.

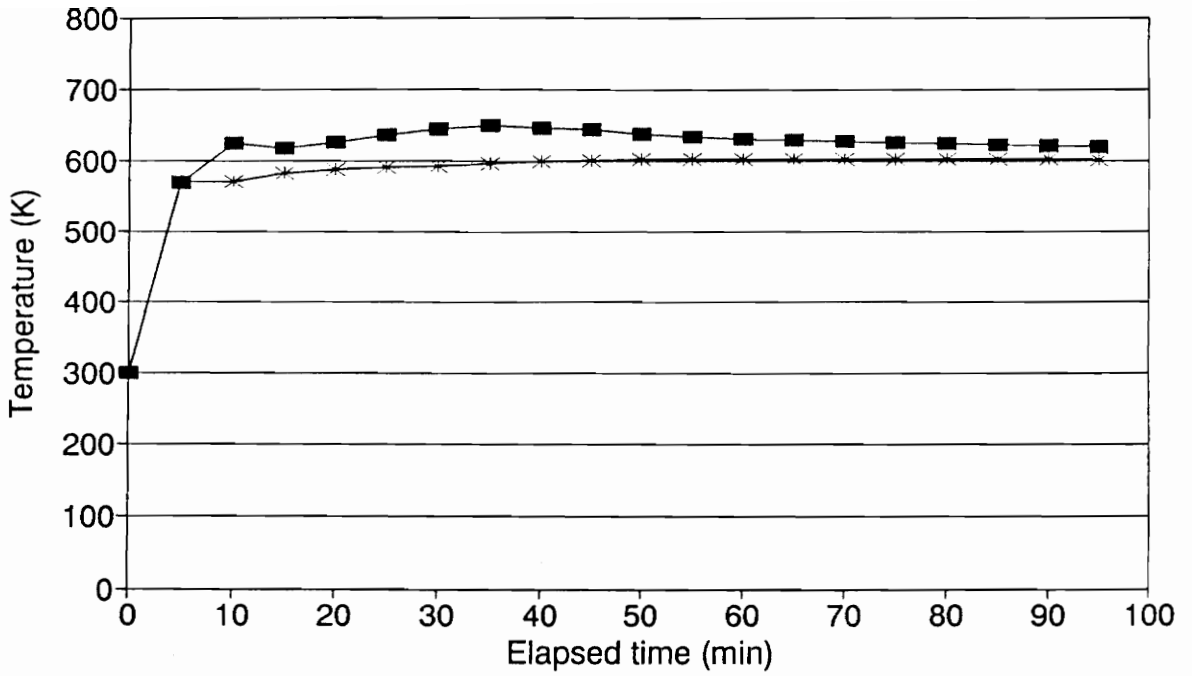


Figure 17. Measured variation of temperature with vertical (y) distance. Results for two points spaced 0.7 m. (Contraflow, Test 605)

#### **5.4.1.2 SYMMETRY**

The assumption of symmetry about the centerline of the masonry heater can be verified by looking at the temperatures at corresponding points in each of the "halves" of the heater. Figure 18 is a plot of two such corresponding points (thermocouples 4 and 12 in Figure 7). The temperatures on each halve differ by no more than 4.5% during the first 35 minutes of the firing cycle, when the wood burn rate is high and by less than 1% for the rest of the cycle. Thermocouples 6 and 15 were also checked and found to differ by less than 5%. The assumption of symmetry about the centerline of the heater is therefore reasonable.

#### **5.4.1.3 GAS TEMPERATURES**

The room temperature did not vary by more than a couple of degrees Celsius during a firing cycle, making the constant room temperature assumption valid.

The assumption that the temperature of the flue gas is constant in the channels of the heater is about as accurate as that of uniform temperature slabs. It is only a first approximation. In reality the hot flue gases lose their energy to the walls of the heater as they flow through the channels.

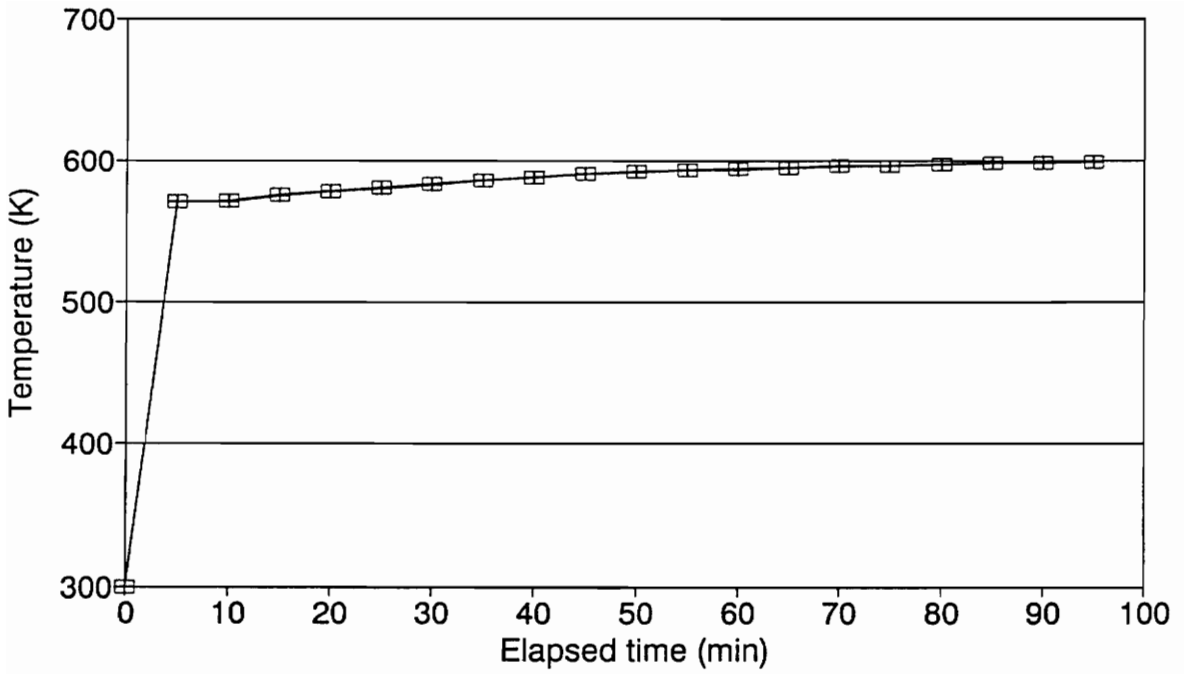


Figure 18. Check on the assumption of symmetry about the heater's centerline. Results for two symmetrically placed thermocouples in the contraflow. Data shown by open square and plus symbols.

#### 5.4.2 ANALYTICAL VS. EXPERIMENTAL RESULTS

In Figures 19,20, and 21 the temperatures predicted by the model are compared with the temperatures measured with the thermocouples. The comparison, in each case, is made against the temperature measured with a thermocouple located in the corresponding position in the masonry heater. The results are for the first firing of a test and the time base starts with ignition of the wood load. Figures 19, 20, and 21 show the temperatures measured by thermocouple numbers 4, 3 and 5 of Figure 7, respectively.

In each case the temperatures predicted by the model follow the measured temperatures. The discrepancy between the results is greatest during the first 35 minutes of the firing cycle; when the burn rate is high. The results differ by a maximum of 12%; this occurs during the first 5 minutes after ignition, when the kindling is burning rapidly. After the first 35 minutes or so after ignition, the results of the model more closely follow the measured temperatures. For the firing cycle depicted, the results differed by 4% or less during the second half of the 90 minute long cycle.



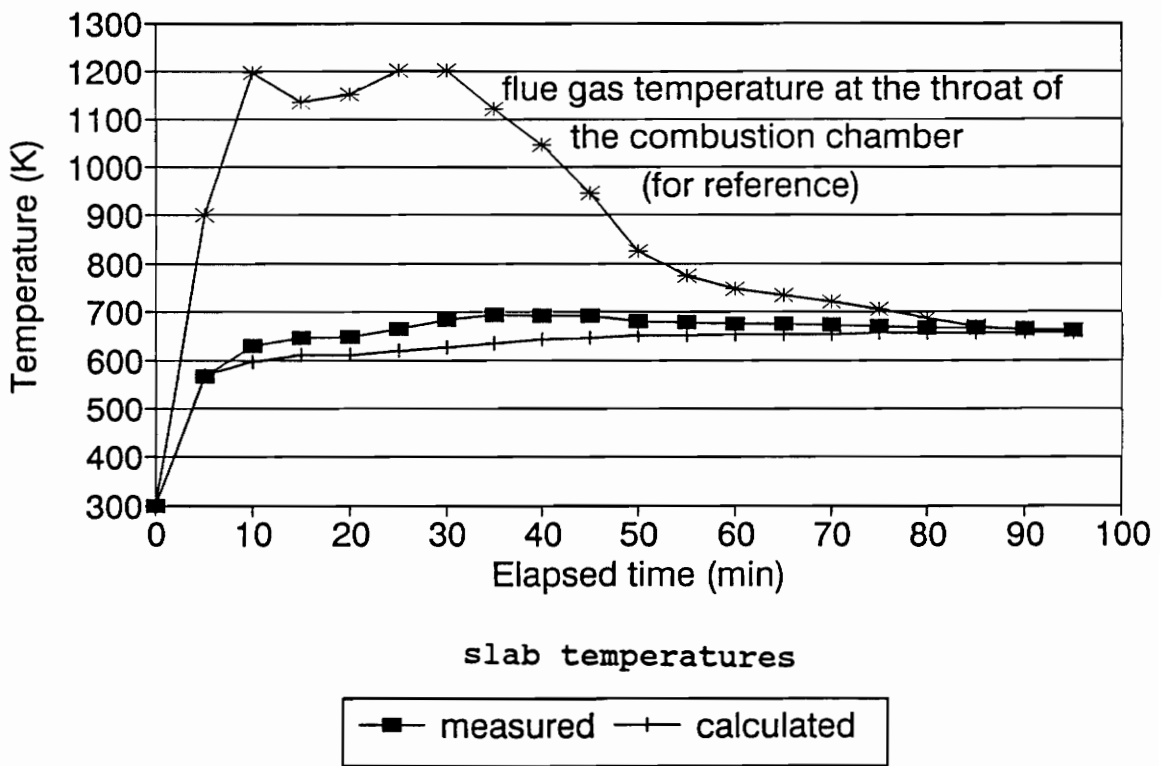


Figure 19. Comparison of measured and predicted temperatures. Results for the right surface of the contraflow's internal slab.

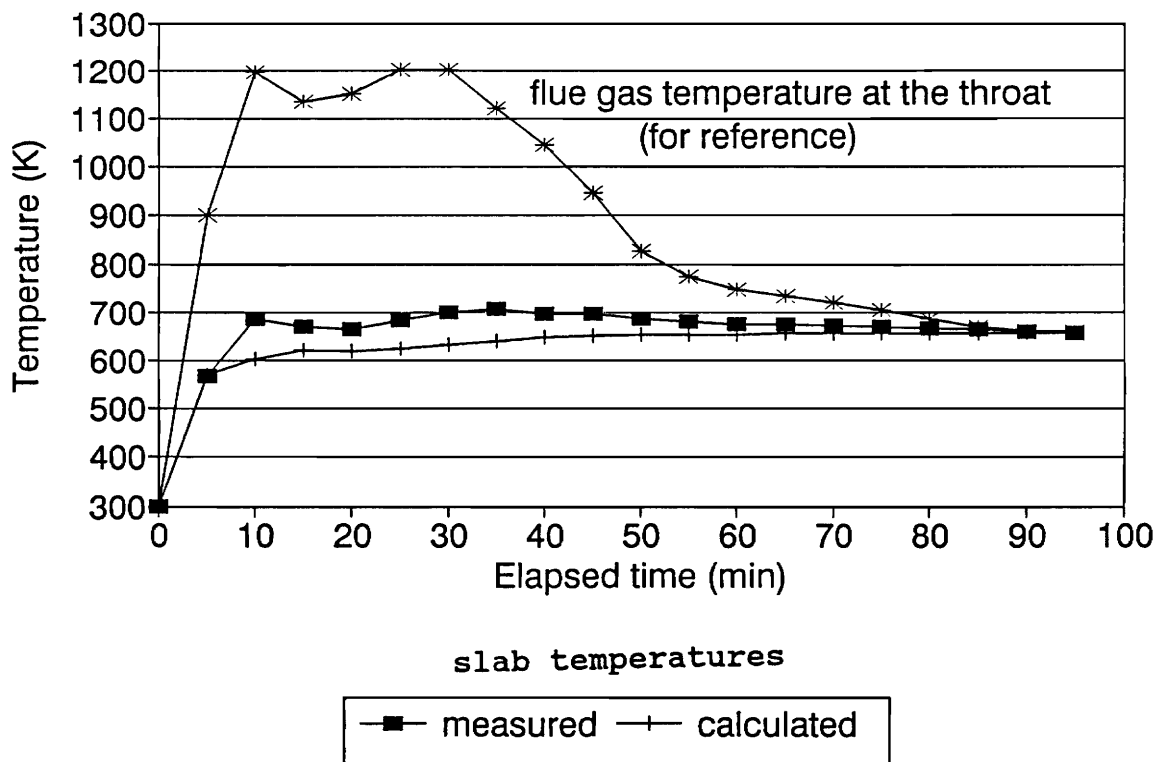


Figure 20. Comparison of measured and predicted temperatures. Results for the left surface of the contraflow's internal slab.

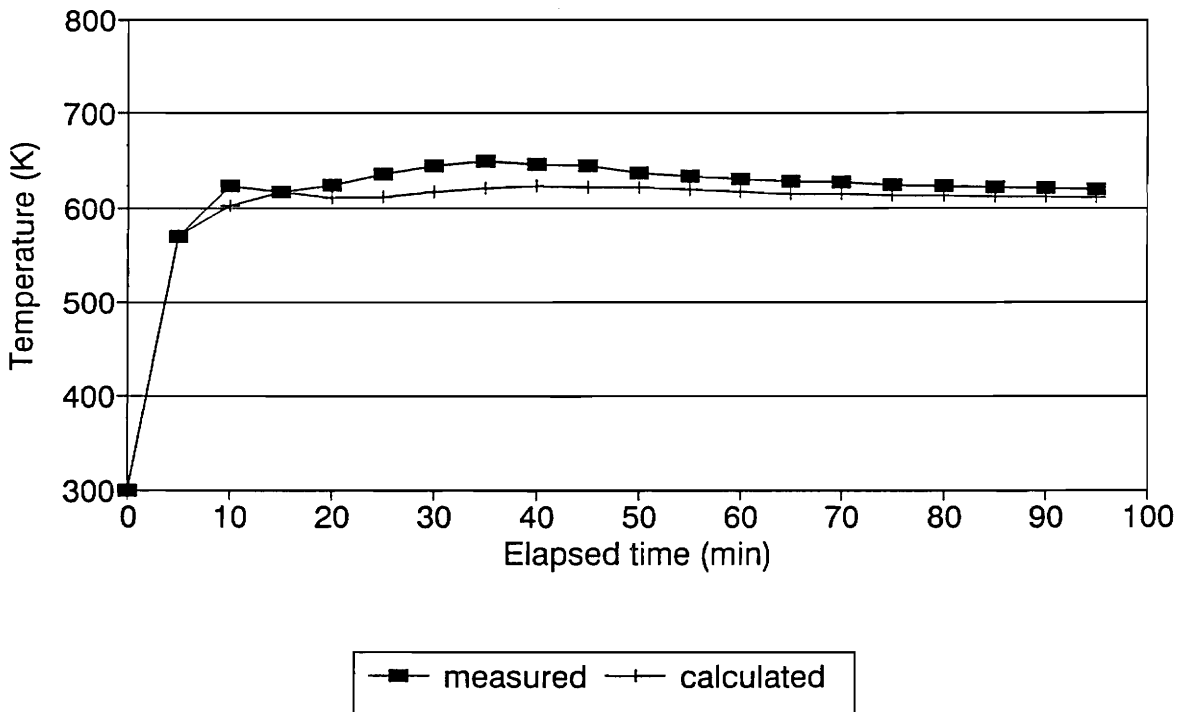


Figure 21. Comparison of measured and predicted temperatures. Results for the interior surface of the contraflow's wall.

## Chapter 6

### CONCLUSIONS

Two direct efficiency measurement methods, the Combustibles Meter and Total Combustible Carbon, have been adapted for application to masonry heaters. The test methodology was verified in 5 tests performed on two masonry heaters (6 tests for the TCC method).

The testing procedure developed uses a fueling schedule similar to that proposed in the masonry heater emissions test method proposed by Stern and Jaasma<sup>3</sup>, and allows simultaneous testing of efficiency, and carbon monoxide and particulate matter emissions. The compatibility of the efficiency and emissions testing was verified in 3 tests on one appliance.

The two methods yielded repeatable results. For the CM method, the average of the measured overall efficiencies for 3 tests on the same appliance was 65.9% with a standard deviation of 0.83 percentage points. For the same 3 tests, the average of the TCC measured efficiencies was 65.70% with a standard deviation of 1.61 percentage points.

For the 6 efficiency tests performed, the measured overall average efficiencies measured using the TCC and CM

methods, agree to within 1 1/3 percentage points of the fuel energy input. The TCC, a much cheaper and easier to implement method than the CM, is therefore a convenient and relatively accurate method for manufacturers to measure the efficiency of their heaters.

A sensitivity analysis using the baseline data from five tests showed that the TCC and CM methods require accuracies of measurement of 4% or less accuracy, to achieve a corresponding accuracy of 1 percentage point in the computed overall energy efficiency. Sensitivities to assumed values are small.

The one-dimensional computer model of the contraflow heat exchanger of one of the appliances tested gives results that follow the experimental data. For the limited testing performed, the model-predicted temperatures differ by a maximum of 12% from the thermocouple measured temperatures. The difference in the results is greatest at the beginning of the firing cycle when the burn rate is high. Toward the end of the firing cycle (last 45 minutes of a 90 minute long test) when the burn rate is lower, the predicted and measured temperatures differ by no more than 5%.

The developed computer model relies on measured stack flow rates and flue gas temperature at the exit of the combustion chamber; it is simple to implement and yields

results accurate enough for certain applications. The model could be used to predict the effects of changing thermal properties or geometry (such as wall thickness and channel width) on the heat transfer characteristics of a heater.

## Chapter 7

### RECOMMENDATIONS

The fuel load for the tests performed in this work consisted of Douglas fir nominal 2X4's, placed in the firebox at a density of 96 wet kg of fuel per cubic meter of firebox volume. The kindling was 3/4 X 3/4 inch Douglas fir with a dry basis moisture content of less than 5%. The mass of kindling was a minimum of 1 kg (wet) but no more than 1 kg (wet) per 20 kg (wet) main load. This fuel load was chosen after wood loads consisting of nominal 4X4's and/or less than 1 kg of kindling failed to ignite. It is not known whether this type of load would ignite properly in other masonry heaters. Ignition tests with several different kinds of masonry heaters are needed to show if the current firing practice has wide applicability.

The computer model could be improved by including the effects of radiation and surface roughness. The heat transfer coefficients used are for smooth surfaces, in reality the channel surfaces are not smooth but coated with creosote, and the joints between the bricks are of rougher cement.

Extending the model to include the off-period would allow a better analysis of the effects of the stored thermal energy of the heater.

Adding another dimension to the model would be a more difficult but substantial improvement.



## Chapter 8

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**A P P E N D I X     1**

**E M I S S I O N S     R E S U L T S**

RUN NUMBER	RUN NUMBER	APPLIANCE	FIRING INTERVAL (hrs)	TEST LENGTH (min)	NUMBER MAINLOAD PIECES (kg)	MAINLOAD PIECE LENGTH (in)
600A	600A	2500L	10.0	46	3.25	14.8
600B	600B	2500L	10.0	105	4.00	14.8
600C	600C	2500L	3.0	116	4.00	14.8
600D	600D	2500L	3.0	129	4.00	14.8
600E	600E	2500L	3.0	93	4.00	14.8
602A	602A	2500L	10.0	85	8.00	14.8
602B	602B	2500L	10.0	70	11.00	14.8
602C	602C	2500L	3.3	60	11.00	14.8
602D	602D	2500L	3.3	100	11.00	14.8
602E	602E	2500L	3.3	82	11.00	14.8
603A	603A	2500L	10.0	59	9.00	14.8
603B	603B	2500L	10.0	73	11.00	14.8
603C	603C	2500L	3.3	66	11.00	14.8
603D	603D	2500L	3.3	67	11.00	14.8
603E	603E	2500L	3.3	54	11.00	14.8
610A	610A	LU2600	6.0	145	6.00	17.0
610B	610B	LU2600	6.0	163	7.00	17.0
610C	610C	LU2600	2.0	120	6.00	17.0
610D	610D	LU2600	2.0	120	6.00	17.0
610E	610E	LU2600	2.0	136	6.00	17.0
611A	611A	LU2600	6.0	201	6.00	17.0
611B	611B	LU2600	6.0	185	6.00	17.0
611C	611C	LU2600	2.0	120	6.00	17.0
611D	611D	LU2600	2.0	120	7.00	17.0
611E	611E	LU2600	2.0	175	6.50	17.0
615A	615A	LU2600	10.0	168	11.00	17.0
615B	615B	LU2600	10.0	184	13.00	17.0
615C	615C	LU2600	3.3	161	13.00	17.0
615D	615D	LU2600	3.3	167	13.00	17.0
615E	615E	LU2600	3.3	135	13.00	17.0

RUN NUMBER	CALC		MAIN DRY M.C. (%)	KINDLING WET FUEL MASS (kg)	ASSUMED KINDLING M.C. (%)	CALC	
	MAINLOAD WETFUEL MASS (kg)	MAINLOAD AVG DENS (g/cm <sup>3</sup> )				DRY FUEL MASS (kg)	TOTAL FUEL MASS (kg)
600A	5.8	0.606	20.3	1.03	5.0	5.8	
600B	7.8	0.658	20.3	1.02	5.0	7.4	
600C	7.6	0.645	20.5	1.03	5.0	7.3	
600D	7.8	0.654	20.5	1.00	5.0	7.4	
600E	7.6	0.641	20.3	1.01	5.0	7.3	
602A	6.0	0.592	20.5	1.05	5.0	6.0	
602B	7.5	0.538	20.5	1.03	5.0	7.2	
602C	7.6	0.547	20.5	1.06	5.0	7.3	
602D	7.5	0.539	20.5	1.01	5.0	7.2	
602E	7.7	0.551	20.3	1.03	5.0	7.4	
603A	6.1	0.533	20.6	1.02	5.0	6.0	
603B	7.5	0.539	20.4	1.05	5.0	7.2	
603C	7.5	0.537	20.3	1.01	5.0	7.2	
603D	8.0	0.575	20.0	1.04	5.0	7.7	
603E	7.5	0.534	20.2	1.00	5.0	7.2	
610A	4.1	0.473	22.3	1.06	5.0	4.4	
610B	5.1	0.496	22.0	1.06	5.0	5.2	
610C	4.7	0.540	22.0	1.01	5.0	4.8	
610D	4.5	0.509	22.5	1.12	5.0	4.7	
610E	4.8	0.546	22.6	1.04	5.0	4.9	
611A	4.4	0.497	22.4	1.06	5.0	4.6	
611B	4.7	0.530	22.6	1.06	5.0	4.8	
611C	4.7	0.532	23.0	1.07	5.0	4.8	
611D	5.3	0.516	22.9	1.05	5.0	5.3	
611E	4.9	0.520	22.6	1.04	5.0	5.0	
615A	8.5	0.528	22.6	1.11	5.0	8.0	
615B	10.3	0.540	20.5	1.05	5.0	9.5	
615C	10.4	0.548	20.2	1.07	5.0	9.7	
615D	10.4	0.548	22.1	1.01	5.0	9.5	
615E	9.9	0.519	21.5	1.00	5.0	9.1	



RUN NUMBER	AVG. AMB. P (torr)	AVG. AMB T (C)	AVG. TUNFLO (g/s)	AVG. CO2 TUN (mol %)	AVG. CO TUN (mol %)	AVG STACK TEMP (C)
600A	712	25.0	445	0.244	0.0162	54.9
600B	711	25.6	402	0.310	0.0172	71.1
600C	710	24.2	413	0.221	0.0144	67.2
600D	710	24.9	424	0.207	0.0179	75.5
600E	710	25.7	426	0.248	0.0164	84.1
602A	712	27.1	419	0.326	0.0146	55.8
602B	713	26.8	430	0.475	0.0184	68.4
602C	711	25.3	425	0.591	0.0188	75.3
602D	713	27.1	417	0.354	0.0244	74.1
602E	710	26.1	405	0.435	0.0130	82.7
603A	711	27.5	417	0.364	0.0188	60.9
603B	710	27.0	419	0.486	0.0191	68.4
603C	708	26.5	417	0.736	0.0194	90.7
603D	709	26.5	416	0.631	0.0207	82.3
603E	708	26.5	417	0.736	0.0194	90.7
610A	707	25.5	424	0.179	0.0122	65.2
610B	708	25.8	421	0.219	0.0129	87.4
610C	709	24.9	421	0.246	0.0168	99.1
610D	710	24.7	422	0.245	0.0182	113.1
610E	711	24.6	422	0.229	0.0163	121.3
611A	710	23.4	423	0.158	0.0196	47.1
611B	710	23.5	418	0.181	0.0146	65.5
611C	709	23.5	416	0.230	0.0180	67.3
611D	710	23.6	412	0.270	0.0218	102.9
611E	710	23.8	411	0.206	0.0147	110.8
615A	714	23.6	428	0.277	0.0143	88.1
615B	714	23.7	421	0.293	0.0177	108.9
615C	713	22.6	417	0.314	0.0189	119.4
615D	712	23.1	418	0.332	0.0191	141.0
615E	711	23.5	428	0.373	0.0202	160.4

RUN NUMBER	METER A INITIAL (1)	METER A FINAL (1)	METER B INITIAL (1)	METER B FINAL (1)	PROBE A PRE (g)	PROBE A POST (g)
600A	3645	4123	8970	9438	55.5480	55.5485
600B	4126	5142	9440	10403	54.4800	54.4810
600C	5140	8261	403	3577	61.2547	61.2554
600D						
600E						
602A	9101	9900	4519	5308	56.6159	56.6159
602B	658	1314	5971	6607	58.3581	58.3582
602C	1315	3624	6618	8815	61.8185	61.8185
602D						
602E						
603A	3625	4408	8816	9567	55.5480	55.5484
603B	4414	5151	9575	10286	56.3148	56.3152
603C	9678	11570	4600	6304	58.1687	58.1691
603D						
603E						
610A	4322	5215	1593	3035	135.4624	135.4626
610B	5227	6310	3038	4652	113.6295	113.6295
610C	6314	8815	4655	8052	138.4190	138.4212
610D						
610E						
611A	6463	7766	6066	8006	135.7747	135.7755
611B	7774	8963	8020	10803	135.6155	135.6149
611C	8964	10509	805	3502	117.6256	117.6262
611D						
611E						
615A	3485	5143	7104	8790	136.1867	136.1872
615B	5147	6948	8791	10697	143.1130	143.1146
615C	6950	10786	697	5030	109.9732	109.9753
615D						
615E						

RUN NUMBER	PROBE B PRE (g)	PROBE B POST (g)	FILTER 1A PRE (g)	1A POST (g)	FILTER 2A PRE (g)	2A POST (g)
600A	56.3138	56.3143	0.1193	0.1251	0.1193	0.1197
600B	54.1668	54.1674	0.1189	0.1255	0.1187	0.1193
600C	56.7119	56.7127	0.1184	0.1421	0.1176	0.1187
600D						
600E						
602A	56.5608	56.5610	0.1195	0.1224	0.1194	0.1196
602B	58.1686	58.1690	0.1189	0.1228	0.1189	0.1191
602C	54.1670	54.1673	0.1202	0.1263	0.1197	0.1203
602D						
602E						
603A	56.7118	56.7120	0.1197	0.1223	0.1190	0.1191
603B	61.2550	61.2554	0.1187	0.1214	0.1194	0.1193
603C	54.4805	54.4808	0.1184	0.1281	0.1195	0.1197
603D						
603E						
610A	141.6951	141.6962	0.1141	0.1229	0.1141	0.1150
610B	143.8244	143.8261	0.1143	0.1202	0.1145	0.1161
610C	134.0436	134.0463	0.1141	0.1265	0.1144	0.1159
610D						
610E						
611A	138.4190	138.4195	0.1151	0.1220	0.1146	0.1149
611B	132.8463	132.8461	0.1146	0.1283	0.1150	0.1154
611C	137.7206	137.7207	0.1150	0.1301	0.1148	0.1158
611D						
611E						
615A	129.0256	129.0257	0.1144	0.1290	0.1146	0.1165
615B	141.9787	141.9798	0.1143	0.1351	0.1142	0.1160
615C	138.5622	138.5645	0.1141	0.1646	0.1140	0.1164
615D						
615E						

RUN NUMBER	FILTER 1B		FILTER 2B		CALC	CALC
	PRE (g)	POST (g)	PRE (g)	POST (g)	PROBE A DELTA (g)	PROBE B DELTA (g)
600A	0.1189	0.1242	0.1190	0.1191	0.0005	0.0005
600B	0.1178	0.1243	0.1188	0.1192	0.0010	0.0006
600C	0.1184	0.1421	0.1194	0.1205	0.0007	0.0008
600D						
600E						
602A	0.1192	0.1221	0.1196	0.1198	0.0000	0.0002
602B	0.1194	0.1229	0.1192	0.1195	0.0001	0.0004
602C	0.1204	0.1259	0.1196	0.1199	0.0000	0.0003
602D						
602E						
603A	0.1186	0.1199	0.1196	0.1208	0.0001	0.0002
603B	0.1186	0.1214	0.1188	0.1189	0.0004	0.0004
603C	0.1187	0.1280	0.1190	0.1193	0.0004	0.0003
603D						
603E						
610A	0.1149	0.1270	0.1142	0.1147	0.0002	0.0011
610B	0.1142	0.1219	0.1140	0.1146	0.0000	0.0017
610C	0.1145	0.1294	0.1132	0.1152	0.0022	0.0027
610D						
610E						
611A	0.1148	0.1227	0.1153	0.1156	0.0008	0.0005
611B	0.1146	0.1306	0.1139	0.1147	-0.0006	-0.0002
611C	0.1150	0.1318	0.1139	0.1149	0.0006	0.0001
611D						
611E						
615A	0.1148	0.1303	0.1140	0.1154	0.0005	0.0001
615B	0.1149	0.1365	0.1145	0.1162	0.0016	0.0011
615C	0.1150	0.1705	0.1141	0.1167	0.0021	0.0023
615D						
615E						

	CALC	CALC	CALC	CALC	CALC	CALC
RUN NUMBER	FILTER A DELTA (g)	FILTER B DELTA (g)	CATCH A TOT. g (g)	CATCH B TOT. g (g)	CO RATE (g/hr)	CO FACTOR (g/kg)
600A	0.0062	0.0054	0.0067	0.0059	19.2	33.0
600B	0.0072	0.0069	0.0082	0.0075	42.2	56.7
600C	0.0248	0.0248	0.0255	0.0256	133.5	54.7
600D					189.3	76.9
600E					125.6	51.8
602A	0.0031	0.0031	0.0031	0.0033	30.2	50.4
602B	0.0041	0.0038	0.0042	0.0042	32.1	44.5
602C	0.0067	0.0058	0.0067	0.0061	83.6	37.9
602D					177.0	81.9
602E					75.0	33.9
603A	0.0027	0.0025	0.0028	0.0027	31.3	52.0
603B	0.0026	0.0029	0.0030	0.0033	33.9	46.3
603C	0.0099	0.0096	0.0103	0.0099	92.9	43.0
603D					100.1	43.5
603E					76.0	35.4
610A	0.0097	0.0126	0.0099	0.0137	72.4	98.7
610B	0.0075	0.0083	0.0075	0.0100	85.6	99.4
610C	0.0139	0.0169	0.0161	0.0196	245.8	101.4
610D					267.2	113.4
610E					270.9	110.5
611A	0.0072	0.0082	0.0080	0.0087	161.0	211.2
611B	0.0141	0.0168	0.0135	0.0166	108.9	136.0
611C	0.0161	0.0178	0.0167	0.0179	260.6	108.2
611D					312.4	117.9
611E					306.1	122.0
615A	0.0165	0.0169	0.0170	0.0170	59.5	74.5
615B	0.0226	0.0233	0.0242	0.0244	79.4	83.4
615C	0.0529	0.0581	0.0550	0.0604	220.4	75.9
615D					231.8	81.4
615E					203.1	74.6

RUN NUMBER	CALC SAMP. DENSITY (g/l)	CALC MASS FLOW A (g/s)	CALC MASS FLOW B (g/s)	CALC P.M. RATE (A) (g/hr)	CALC P.M. RATE (B) (g/hr)	CALC P.M. RATE (AVG) (g/hr)
600A	1.1081	0.1920	0.1879	1.55	1.40	1.47
600B	1.1042	0.1781	0.1689	1.85	1.79	1.82
600C	1.1081	0.1705	0.1734	6.9951	6.9076	6.95
600D	1.1054					
600E	1.1012					
602A	1.0994	0.1722	0.1701	0.75	0.81	0.78
602B	1.1017	0.1721	0.1667	1.05	1.08	1.07
602C	1.1055	0.1758	0.1673	1.5846	1.5161	1.55
602D	1.1009					
602E	1.1010					
603A	1.0970	0.2074	0.1989	0.56	0.57	0.56
603B	1.0969	0.1845	0.1780	0.68	0.73	0.73
603C	1.0958	0.1848	0.1664	2.3230	2.4790	2.40
603D	1.0980					
603E	1.0958					
610A	1.0980	0.1316	0.1820	5.32	5.32	5.32
610B	1.0986	0.1456	0.1813	3.62	3.87	3.75
610C	1.1031	0.1464	0.1661	7.7320	8.2940	8.01
610D	1.1048					
610E	1.1068					
611A	1.1096	0.1505	0.1786	3.75	3.44	3.59
611B	1.1093	0.1492	0.2782	6.30	4.15	5.22
611C	1.1090	0.0873	0.1201	13.1666	10.2628	11.71
611D	1.1093					
611E	1.1096					
615A	1.1161	0.1836	0.1867	3.96	3.90	3.93
615B	1.1149	0.1819	0.1924	5.60	5.34	5.47
615C	1.1181	0.1544	0.1744	15.0019	14.5849	14.79
615D	1.1146					
615E	1.1115					

RUN NUMBER	CALC P.M. FACTOR (A) (g/kg)	CALC P.M. FACTOR (B) (g/kg)	CALC P.M. FACTOR (AVG) (g/kg)	CALC P.M. PRECISION (%)	CALC DRY B. R. (kg/hr)	CALC AVG B. R. (kg/hr)
600A	2.66	2.40	2.53	10.5	0.58	0.75
600B	2.49	2.40	2.44	3.6	0.74	
600C	2.86	2.83	2.85	1.3	2.44	2.442
600D					2.46	
600E					2.42	
602A	1.26	1.36	1.31	7.5	0.60	0.72
602B	1.45	1.50	1.48	3.2	0.72	
602C	0.72	0.69	0.71	4.4	2.20	2.193
602D					2.16	
602E					2.21	
603A	0.94	0.94	0.94	0.5	0.60	0.73
603B	0.94	1.07	1.01	13.1	0.72	
603C	1.05	1.13	1.09	6.5	2.16	2.202
603D					2.30	
603E					2.15	
610A	7.25	7.25	7.25	0.1	0.73	0.86
610B	4.20	4.50	4.35	6.8	0.86	
610C	3.21	3.44	3.32	7.0	2.42	2.411
610D					2.36	
610E					2.45	
611A	4.92	4.51	4.71	8.7	0.76	0.80
611B	7.86	5.19	6.52	41.0	0.80	
611C	5.22	4.07	4.64	24.8	2.41	2.52
611D					2.65	
611E					2.51	
615A	4.96	4.88	4.92	1.7	0.80	0.95
615B	5.88	5.61	5.75	4.8	0.95	
615C	5.31	5.16	5.24	2.8	2.90	2.82
615D					2.85	
615E					2.72	

RUN NUMBER	EPA STV.STD PROB.(P) (%)	CALC EPA WEIGHTING FACTOR (K)	CALC AVG PM RATE (g/hr)	EPA STOVE WTD. AVG. P.M. RATE (g/hr)	CALC AVG PMFACTOR (g/kg)	EPA STOVE WTD.AVG. P.M. FACTOR (g/kg)
600A	0.185	0.959	1.86	4.20	2.49	2.65
600B						
600C	0.959	0.815	6.951		2.846	
600D						
600E						
602A	0.164	0.936	1.01	1.26	1.39	1.07
602B						
602C	0.936	0.836	1.550		0.707	
602D						
602E						
603A	0.171	0.936	0.70	1.50	0.97	1.03
603B						
603C	0.936	0.829	2.401		1.090	
603D						
603E						
610A	0.263	0.957	5.00	6.31	5.80	4.72
610B						
610C	0.957	0.737	8.013		3.324	
610D						
610E						
611A	0.220	0.965	4.51	7.73	5.62	5.18
611B						
611C	0.965	0.780	11.715		4.644	
611D						
611E						
615A	0.328	0.980	5.05	9.01	5.33	5.20
615B						
615C	0.980	0.672	14.793		5.238	
615D						
615E						



RUN NUMBER	CALC AVG CORATE (g/hr)	EPA STOVE WTD.AVG. CO RATE (g/hr)	CALC AVG COFACTOR (g/kg)	EPA STOVE WTD.AVG. CO FACTOR (g/kg)	CALC FRACTION OF MAIN LOAD
600A	33.4	86.7	44.8	52.3	0.78
600B					1
600C	149.5		61.1		1
600D					1
600E					1
602A	34.3	70.9	47.5	49.2	0.83
602B					1
602C	111.9		51.2		1
602D					1
602E					1
603A	35.8	61.1	49.4	45.3	0.83
603B					1
603C	89.7		40.6		1
603D					1
603E					1
610A	85.4	161.9	99.0	103.1	0.85
610B					1
610C	261.3		108.4		1
610D					1
610E					1
611A	139.3	208.0	173.6	147.9	0.95
611B					1
611C	293.0		116.0		1
611D					1
611E					1
615A	74.8	133.2	79.0	78.3	0.85
615B					1
615C	218.4		77.3		1
615D					1
615E					1

**A P P E N D I X    2**

**E F F I C I E N C Y    R E S U L T S**

## INPUT

RUN NUMBER	APPLIANCE	DATE	FIRING INTERVAL min	TEST LENGTH min
605A	TU2500L	4/12/91	600	91
605B		4/12/91	600	102
605C		4/12/91	200	64
605D		4/12/91	200	81
605E		4/12/91	200	87
606A	TU2500L	5/16/91	540	78
606B		5/16/91	540	72
606C		5/16/91	180	101
606D		5/16/91	180	120
606E		5/16/91	180	71
607A	TU2500L	5/24/91	540	129
607B		5/24/91	540	117
607C		5/24/91	180	110
607D		5/24/91	180	112
607E		5/24/91	180	90
610A	LU2600	7/14/91	360	145
610B		7/14/91	360	163
610C		7/14/91	120	120
610D		7/14/91	120	120
610E		7/14/91	120	136
611A	LU2600	7/31/91	360	201
611B		7/31/91	360	185
611C		7/31/91	120	120
611D		7/31/91	120	120
611E		7/31/91	120	175
615A	LU2600	9/9/91	600	168
615B		9/9/91	600	184
615C		9/10/91	200	161
615D		9/10/91	200	167
615E		9/10/91	200	135

INPUT			INPUT		
+	+	+	+	+	+
RUN	MAIN LOAD	MAIN LOAD	KINDLING	KINDLING	
NUMBER	WET MASS	AVG DRY MC	WET MASS	DRY MC	
+	kg	%	kg	%	+
+	+	+	+	+	+
605A	6.2480	21.5	1.0615		5
605B	7.8517	21.8	1.0408		5
605C	7.6663	21.0	1.0528		5
605D	8.0523	21.3	1.1609		5
605E	7.9343	21.9	1.0120		5
606A	6.1756	22.0	1.0134		5
606B	7.8237	22.1	1.0710		5
606C	7.7123	21.4	1.0050		5
606D	7.5681	22.0	1.0177		5
606E	7.6496	22.0	1.0376		5
607A	6.6613	21.8	1.0647		5
607B	7.5133	22.0	1.0423		5
607C	8.1719	22.2	1.0120		5
607D	7.6508	22.6	1.0569		5
607E	7.7099	22.2	1.0845		5
610A	4.1471	22.3	1.0617		5
610B	5.0744	22.0	1.0563		5
610C	4.7421	22.0	1.0098		5
610D	4.6414	22.5	1.1220		5
610E	4.7922	22.6	1.0431		5
611A	4.3608	22.4	1.0602		5
611B	4.6500	22.6	1.0630		5
611C	4.6680	23.0	1.0731		5
611D	5.2797	22.9	1.0544		5
611E	4.9440	22.6	1.0354		5
615A	8.5014	22.6	1.1058		5
615B	10.2648	20.5	1.0546		5
615C	10.4102	20.2	1.0418		5
615D	10.4146	22.1	1.0075		5
615E	9.8685	21.5	0.9986		5

INPUT

RUN NUMBER	AVG STACK TEMPERATURE Celsius	AVG ROOM TEMPERATURE Celsius	AVG PRESSURE Torr
605A	82	23.88	718.7769
605B	129.8	23.52	718.5445
605C	151.5	23.34	716.9648
605D	162.3	23.36	716.182
605E	169.2	23.47	713.8616
606A	119.5025	24.64	711.2443
606B	154.2024	24.33	709.9881
606C	135.5411	24.51	709.816
606D	154.3393	24.65	709.326
606E	187.9774	24.73	708.5649
607A	91.5891	24.30	711.5498
607B	123.6362	24.52	711.2498
607C	132.8195	24.62	711.5452
607D	151.4822	24.91	711.0294
607E	174.9922	25.20	710.0369
610A	65.2135	25.48	707.6407
610B	87.4458	25.84	708.2482
610C	99.0888	24.88	708.7581
610D	113.0811	24.74	709.6398
610E	121.2526	24.65	710.6774
611A	47.0665	23.41	709.5266
611B	65.4795	23.55	709.6776
611C	67.34	23.50	709.3578
611D	102.9385	23.61	709.79
611E	110.8069	23.79	710.4334
615A	88.0677	23.55	714.0382
615B	108.8801	23.68	713.5474
615C	119.377	22.56	712.8936
615D	141.0418	23.13	712.0685
615E	160.3779	23.45	710.8628

INPUT

   RUN   NUMBER	AVG   TUN FLOW   g/s	AVG CO2   RAW TUN   mol %	AVG CO2   INC TUN   mol %	AVG CO2   RAW STACK   mol %
605A	480.5500	0.3601	0.3799	3.9320
605B	424.4024	0.4058	0.4287	3.4307
605C	418.4680	0.5971	0.6213	5.2600
605D	447.8755	0.5014	0.5288	4.6973
605E	432.1536	0.4767	0.4955	4.2348
606A	426.8229	0.4183	0.4400	3.7059
606B	423.4291	0.5543	0.5814	4.5605
606C	426.5598	0.4168	0.4427	3.9479
606D	423.6779	0.3640	0.3844	2.8099
606E	440.5524	0.5525	0.5664	4.7376
607A	427.9369	0.2943	0.3135	2.9409
607B	425.8296	0.3613	0.3821	3.2984
607C	420.6607	0.3919	0.4141	3.5342
607D	428.6043	0.3691	0.3917	3.1719
607E	428.5712	0.4455	0.4650	3.7757
610A	424.0620	0.1791	0.2003	1.6447
610B	421.3897	0.2186	0.2361	1.7579
610C	421.0089	0.2457	0.2679	2.2524
610D	422.3596	0.2451	0.2667	2.2126
610E	421.9354	0.2285	0.2494	1.9277
611A	423.1840	0.1582	0.1766	2.1873
611B	417.5153	0.1813	0.2028	2.1663
611C	416.4582	0.2297	0.2553	4.2549
611D	412.2908	0.2697	0.2986	3.1385
611E	410.8370	0.2062	0.2275	2.0259
615A	427.7333	0.2774	0.3012	2.0832
615B	421.0644	0.2934	0.3207	2.4993
615C	416.7212	0.3136	0.3469	2.5072
615D	418.1376	0.3320	0.3622	2.5486
615E	428.4457	0.3732	0.4007	2.9656



INPUT

   RUN   NUMBER	PM   METER   INIT (1)	PM   METER   FINAL (1)	PROBE   INITIAL   grams	PROBE   FINAL   grams
605A	4001.00	4356.52	117.6247	117.6247
605B	4359.45	5066.19	114.1310	114.1320
605C	5184.63	7794.89	112.1250	112.1258
605D				
605E				
606A	6318.60	7013.89	110.1299	110.1295
606B	7013.89	7664.75	138.1613	138.1613
606C	7664.75	10306.57	116.3409	116.3409
606D				
606E				
607A	349.23	1501.66	110.2871	110.2870
607B	1502.60	2551.61	137.7787	137.7784
607C	2551.61	5360.74	143.0236	143.0233
607D				
607E				
610A	1592.56	3034.70	141.6951	141.6962
610B	3037.50	4652.10	143.8244	143.8291
610C	4654.74	8051.94	134.0436	134.0463
610D				
610E				
611A	6065.57	8006.33	138.4190	138.4195
611B	8019.56	10802.25	132.8463	132.8461
611C	804.84	3501.63	137.7206	137.7207
611D				
611E				
615A	3484.89	5142.81	136.1867	136.1872
615B	5147.20	6948.03	143.1130	143.1146
615C	6949.50	10785.77	109.9732	109.9735
615D				
615E				



	INPUT		INPUT	
+	+	+	+	+
	FILTER 1	FILTER 1	FILTER 2	FILTER 2
RUN	INITIAL	FINAL	INITIAL	FINAL
NUMBER	grams	grams	grams	grams
+	+	+	+	+
605A	0.1233	0.1233	0.1229	0.1244
605B	0.1226	0.1243	0.1227	0.1239
605C	0.1227	0.1297	0.1218	0.1238
605D				
605E				
606A	0.1240	0.1255	0.1234	0.1242
606B	0.1229	0.1231	0.1141	0.1161
606C	0.1132	0.1222	0.1142	0.1151
606D				
606E				
607A	0.1153	0.1158	0.1146	0.1155
607B	0.1144	0.1158	0.1136	0.1146
607C	0.1136	0.1234	0.1142	0.1158
607D				
607E				
610A	0.1149	0.1270	0.1142	0.1155
610B	0.1142	0.1219	0.1140	0.1154
610C	0.1145	0.1294	0.1132	0.1152
610D				
610E				
611A	0.1148	0.1227	0.1153	0.1156
611B	0.1146	0.1306	0.1139	0.1147
611C	0.1150	0.1318	0.1139	0.1149
611D				
611E				
615A	0.1144	0.1290	0.1146	0.1165
615B	0.1143	0.1351	0.1142	0.1160
615C	0.1141	0.1646	0.1140	0.1164
615D				
615E				

CALC

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+-----+-----+
|          | TRACER CO2 |
| RUN      | FLOW        |
| NUMBER   | l/min       |
+-----+-----+

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+-----+-----+
| TOTAL    | TOTAL       |
| WET MASS | DRY MC      |
| kg       | Fraction    |
+-----+-----+

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605A	3.874	7.31	0.1910
605B	3.874	8.89	0.1983
605C	3.874	8.72	0.1907
605D	3.874	9.21	0.1927
605E	3.874	8.95	0.1999
606A	3.874	7.19	0.1960
606B	3.874	8.89	0.2004
606C	3.874	8.72	0.1951
606D	3.874	8.59	0.1998
606E	3.874	8.60	0.1997
607A	3.874	7.73	0.1948
607B	3.874	8.56	0.1993
607C	3.874	9.18	0.2030
607D	3.874	8.71	0.2046
607E	3.874	8.79	0.2008
610A	3.874	5.21	0.1877
610B	3.874	6.13	0.1907
610C	3.874	5.75	0.1902
610D	3.874	5.76	0.1909
610E	3.874	5.84	0.1945
611A	3.874	5.42	0.1900
611B	3.874	5.71	0.1933
611C	3.874	5.74	0.1964
611D	3.874	6.33	0.1995
611E	3.874	5.98	0.1955
615A	3.874	9.61	0.2057
615B	3.874	11.32	0.1906
615C	3.874	11.45	0.1882
615D	3.874	11.42	0.2059
615E	3.874	10.87	0.1998

CALC

RUN   NUMBER	TOTAL   DRY MASS   kg	WOOD   WATER   kg	CORRECTED   CO2 RAW   TUN mol %	CORRECTED   CO2 INC   TUN mol %
605A	6.1371	4.3925	0.3455	0.3653
605B	7.4207	5.3654	0.3892	0.4121
605C	7.3228	5.2386	0.5803	0.6045
605D	7.7245	5.5417	0.4857	0.5131
605E	7.4560	5.4025	0.4604	0.4792
606A	6.0107	4.3321	0.4018	0.4235
606B	7.4097	5.3729	0.5377	0.5648
606C	7.2942	5.2503	0.4003	0.4262
606D	7.1557	5.1847	0.3474	0.3678
606E	7.2412	5.2455	0.5365	0.5504
607A	6.4661	4.6527	0.2779	0.2971
607B	7.1339	5.1649	0.3448	0.3656
607C	7.6339	5.5555	0.3752	0.3974
607D	7.2285	5.2720	0.3527	0.3753
607E	7.3238	5.3134	0.4291	0.4486
610A	4.3855	3.1244	0.1625	0.1837
610B	5.1488	3.6835	0.2019	0.2194
610C	4.8329	3.4548	0.2290	0.2512
610D	4.8394	3.4632	0.2284	0.2500
610E	4.8850	3.5135	0.2118	0.2327
611A	4.5556	3.2557	0.1416	0.1600
611B	4.7878	3.4374	0.1644	0.1859
611C	4.7988	3.4602	0.2128	0.2384
611D	5.2805	3.8243	0.2526	0.2815
611E	5.0015	3.6022	0.1891	0.2104
615A	7.9679	5.8201	0.2609	0.2847
615B	9.5076	6.8004	0.2767	0.3040
615C	9.6383	6.8709	0.2967	0.3300
615D	9.4717	6.9202	0.3152	0.3454
615E	9.0571	6.5622	0.3568	0.3843

CALC

   RUN   NUMBER	CORRECTED   CO2 RAW   STACK %	CORRECTED   CO2 INC   STACK mol %	STACK   MOLECULAR   WEIGHT	STACK   SPEC. HEAT   kJ/kg.K
605A	3.7593	4.0192	29.3223	1.0057
605B	3.3050	3.5258	29.2631	1.0090
605C	5.1397	5.3735	29.4848	1.0108
605D	4.5809	4.8694	29.4243	1.0117
605E	4.1224	4.3112	29.3573	1.0123
606A	3.5710	3.7905	29.2949	1.0081
606B	4.4483	4.6964	29.4036	1.0109
606C	3.8120	4.0967	29.3316	1.0093
606D	2.6055	2.8817	29.1858	1.0109
606E	4.6364	4.7700	29.4124	1.0141
607A	2.7542	2.9912	29.1989	1.0062
607B	3.1767	3.3970	29.2476	1.0084
607C	3.4029	3.6348	29.2762	1.0091
607D	3.0548	3.2797	29.2336	1.0106
607E	3.6661	3.8522	29.3023	1.0127
610A	1.4653	1.7297	29.0476	1.0047
610B	1.6138	1.7932	29.0552	1.0059
610C	2.0917	2.3378	29.1205	1.0067
610D	2.0725	2.3097	29.1172	1.0076
610E	1.7976	2.0179	29.0821	1.0082
611A	1.9351	2.3069	29.1168	1.0039
611B	1.9496	2.3065	29.1168	1.0048
611C	3.9541	4.5552	29.3866	1.0049
611D	2.9448	3.3510	29.2421	1.0070
611E	1.8362	2.1056	29.0927	1.0075
615A	1.9480	2.1683	29.1002	1.0061
615B	2.3549	2.6370	29.1564	1.0074
615C	2.3746	2.6931	29.1632	1.0082
615D	2.4292	2.7102	29.1652	1.0099
615E	2.8640	3.1231	29.2148	1.0115

CALC

  RUN  NUMBER	DRY STACK   GAS   kg	AIR TO   FUEL   RATIO	ENERGY   INPUT   kJ	SENSIBLE   LOSS TCC   kJ
605A	189.54	30.41	121575.59	11563.93
605B	260.73	34.66	147004.09	29042.35
605C	170.10	22.75	145064.41	23309.95
605D	197.60	25.11	153022.46	29238.42
605E	214.93	28.35	147702.93	33204.30
606A	196.65	32.24	119071.75	19588.02
606B	196.39	26.03	146786.51	27109.08
606C	221.09	29.83	144499.00	25883.61
606D	306.80	42.40	141755.04	41499.78
606E	189.02	25.63	143447.63	32917.21
607A	267.20	40.85	128093.29	13688.27
607B	260.02	35.97	141322.37	26962.04
607C	260.29	33.62	151226.91	29562.36
607D	272.76	37.26	143196.17	36158.13
607E	235.84	31.73	145085.44	37288.90
610A	311.77	70.62	86876.36	12681.00
610B	353.17	68.12	101997.31	22317.56
610C	254.85	52.26	95739.75	19526.12
610D	258.26	52.89	95868.61	23571.91
610E	298.04	60.54	96771.49	29673.88
611A	243.41	52.96	90245.96	5928.54
611B	255.86	52.96	94845.44	11054.54
611C	131.06	26.83	95064.73	6062.57
611D	195.07	36.47	104605.85	16159.54
611E	292.54	58.02	99079.53	26244.66
615A	452.69	56.34	157843.55	30095.23
615B	445.03	46.33	183346.24	39296.46
615C	441.85	45.37	190935.35	44395.98
615D	431.49	45.08	187634.68	52931.78
615E	358.66	39.12	179421.96	51383.61

CALC

  RUN  NUMBER	SENSIBLE  LOSS FCM  kJ	LATENT  LOSS  kJ	CHEMICAL  LOSS TCC  kJ	CHEM GAS  LOSS FCM  kJ
605A	11741.24	10726.59	6718.72	8558.85
605B	29043.01	13102.41	7868.24	6579.07
605C	22279.46	12792.61	5396.29	5742.32
605D	30599.32	13532.93	7749.34	10121.54
605E	34826.61	13192.84	5530.07	5804.28
606A	18810.04	10579.04	5894.27	5760.08
606B	26571.11	13120.53	6629.77	5385.21
606C	27263.63	12821.34	8581.15	6931.81
606D	42376.86	12660.99	7830.10	4866.74
606E	33941.42	12809.44	3434.00	2690.89
607A	16972.72	11361.81	8674.31	4478.47
607B	32181.44	12612.59	7835.56	5667.76
607C	30049.62	13566.59	8247.05	6272.63
607D	38227.15	12874.23	8393.39	5784.06
607E	37094.19	12975.26	5992.23	4999.78
610A	12341.75	7629.74	11350.28	5732.86
610B	25210.59	8995.07	8723.65	10872.11
610C	19582.49	8436.68	8615.10	8177.14
610D	25822.88	8457.21	8415.35	8758.66
610E	33675.55	8579.89	9031.58	9049.56
611A	7722.00	7950.50	12432.36	8786.36
611B	13880.64	8394.08	12545.10	10989.14
611C	6924.27	8449.85	10722.93	5759.52
611D	17421.28	9338.94	10838.04	11285.62
611E	27497.07	8796.55	10836.43	10840.12
615A	29334.90	14212.61	13708.47	0.00
615B	37775.22	16606.63	17223.49	0.00
615C	39836.53	16778.74	19299.15	0.00
615D	53015.17	16899.11	16629.69	0.00
615E	56144.62	16024.99	12727.65	0.00



   RUN   NUMBER	CYCLE   EFFIC   FCM %	AVG CYCLE   EFF   TCC %	AVG CYCLE   EFF   FCM %	BURN RATE   kg/hr 
605A	73.23	69.59	68.98	0.61
605B	64.72			0.74
605C	70.64	66.01	64.81	2.20
605D	62.88			2.32
605E	60.92			2.24
606A	69.02	67.15	68.02	0.67
606B	67.02			0.82
606C	66.68	62.18	62.49	2.43
606D	56.87			2.39
606E	63.91			2.41
607A	73.29	66.48	67.61	0.72
607B	61.93			0.79
607C	66.31	61.44	61.97	2.54
607D	59.23			2.41
607E	60.38			2.44
610A	68.89	61.75	61.65	0.73
610B	54.42			0.86
610C	61.70	56.91	54.24	2.42
610D	54.61			2.42
610E	46.43			2.44
611A	72.03	68.23	67.85	0.76
611B	63.67			0.80
611C	77.20	64.14	63.99	2.40
611D	63.12			2.64
611E	51.65			2.50
615A	70.27	60.76	69.50	0.80
615B	68.72			0.95
615C	69.37	55.32	63.13	2.89
615D	61.67			2.84
615E	58.34			2.72



RUN NUMBER	AVG BURN RATE kg/hr	EPA STV. ST PROB %	EPA WEIGHTING FACTOR	OVERALL EFFICIENCY TCC
605A	0.76	0.192	0.94	67.94
605B				
605C	2.25	0.940	0.81	
605D				
605E				
606A	0.83	0.240	0.96	64.95
606B				
606C	2.41	0.955	0.76	
606D				
606E				
607A	0.80	0.220	0.96	64.22
607B				
607C	2.47	0.961	0.78	
607D				
607E				
610A	0.88	0.282	0.96	59.58
610B				
610C	2.43	0.957	0.72	
610D				
610E				
611A	0.80	0.220	0.96	66.40
611B				
611C	2.51	0.965	0.78	
611D				
611E				
615A	0.96	0.338	0.98	58.57
615B				
615C	2.82	0.980	0.66	
615D				
615E				

CALC		COMPARISON	
RUN NUMBER	OVERALL EFFICIENCY FCM	LATENT LOSS % POINTS	OFF PERIOD SEN LOSS % POINTS
605A	67.05	8.82	1.00
605B		8.91	1.93
605C		8.82	1.14
605D		8.84	1.55
605E		8.93	2.52
606A	65.57	8.88	1.34
606B		8.94	2.16
606C		8.87	0.60
606D		8.93	0.66
606E		8.93	1.49
607A	65.09	8.87	1.01
607B		8.92	2.24
607C		8.97	0.50
607D		8.99	0.83
607E		8.94	1.50
610A	58.48	8.78	0.36
610B		8.82	0.45
610C		8.81	0.00
610D		8.82	0.00
610E		8.87	0.00
611A	66.13	8.81	0.19
611B		8.85	0.47
611C		8.89	0.00
611D		8.93	0.00
611E		8.88	0.00
615A	66.93	9.00	1.39
615B		8.82	1.51
615C		8.79	0.20
615D		9.01	0.24
615E		8.93	0.72

## COMPARISON

RUN NUMBER	FCM ON SEN LOSS % POINTS	TCC ON SEN LOSS % POINTS	CHEM LOSS FCM % POINTS	CHEM LOSS TCC % POINTS
605A	9.66	9.51	7.28	5.53
605B	19.76	19.76	4.69	5.35
605C	15.36	16.07	4.05	3.72
605D	20.00	19.11	6.73	5.06
605E	23.58	22.48	4.05	3.74
606A	15.80	16.45	4.96	4.95
606B	18.10	18.47	3.78	4.52
606C	18.87	17.91	4.98	5.94
606D	29.89	29.28	3.65	5.52
606E	23.66	22.95	2.01	2.39
607A	13.25	14.59	3.57	6.77
607B	22.77	19.08	4.12	5.54
607C	19.87	19.55	4.34	5.45
607D	26.70	25.25	4.25	5.86
607E	25.57	25.70	3.62	4.13
610A	14.21	14.60	7.76	13.06
610B	24.72	21.88	11.60	8.55
610C	20.45	20.39	9.04	9.00
610D	26.94	24.59	9.63	8.78
610E	34.80	30.66	9.91	9.33
611A	8.56	6.57	10.42	13.78
611B	14.64	11.66	12.37	13.23
611C	7.28	6.38	6.62	11.28
611D	16.65	15.45	11.30	10.36
611E	27.75	26.49	11.72	10.94
615A	18.58	19.07	0.75	8.68
615B	20.06	20.86	0.89	9.14
615C	20.86	23.25	0.78	10.11
615D	28.25	28.21	0.83	8.86
615E	31.29	28.64	0.72	7.09

**A P P E N D I X    3**

**C O M P U T E R    C O D E**

MAURICIO F. GUTIERREZ VA TECH 1991

MASONRY HEATER CONTRAFLOW HEAT EXCHANGER

COMPUTER SIMULATION USING THE FINITE DIFFERENCE METHOD

---

VARIABLE NAMES

K=THE THERMAL CONDUCTIVITY OF SOAPSTONE W/mK  
KGAS=THERMAL CONDUCTIVITY OF AIR W/mK  
BI=THE BIOT NUMBER (0,1 or 2) dimensionless  
(0,1 or 2 for: room, channel 1, or channel 2 respectively)  
FO=THE FOURIER NUMBER dimensionless  
RHO=THE DENSITY OF SOAPSTONE kg/m3  
CP=THE SPECIFIC HEAT OF SOAPSTONE J/kg.K  
L1=THE THICKNESS OF THE OUTER WALL m  
L2=THE THICKNESS OF THE INNER WALL m  
W1=THE DISTANCE BETWEEN THE INNER AND OUTER WALLS m  
W2=DISTANCE BETWEEN INNER WALL AND ADIABATIC BOUNDARY m  
DEPTH=THE DEPTH OF THE WALLS AND CHANNELS m  
HEIGHT=THE HEIGHT OF THE MASONRY HEATER WALL m  
T=ELAPSED TIME IN THE CALCULATIONS s  
N=NUMBER OF NODES IN A CERTAIN SLAB (1 or 2)  
DX=THE SPACE INCREMENT m  
DT=THE TIME INCREMENT s  
MSTACK=THE STACK MASS FLOW RATE kg/s  
TROOM=ROOM TEMPERATURE C  
TGAS=INPUT STACK FLOW TEMPERATURE C  
TIN=INITIAL TEMPERATURE OF THE SYSTEM C  
U=VISCOSITY OF AIR Ns/m2  
PR=PRANDTL NUMBER FOR AIR  
RE=REYNOLDS # BASED ON HYDRAULIC DIAMETER (1 or 2) dimensionless  
PATM=ATMOSPHERIC PRESSURE kPa  
DH=HYDRAULIC DIAMETER (1, or 2) m  
NUI=NUSSELT NUMBER FOR FULLY DEVELOPED FLOW (0,1 or 2) dimensionless  
NU=NUSSELT NUMBER (0,1 or 2) dimensionless  
H=HEAT TRANSFER COEFFICIENT W/m2.K  
(0,1, or 2 depending on position as before)  
RA=THE RALEIGH NUMBER dimensionless  
COUNT=FIVE MINUTE INTERVAL COUNTER

---

COMMENTS: This program reads stack flow and temperature data from a data file named TUL.DAT; the data is used to simulate the heat transfer in a contraflow heat exchanger. The analysis is 1D, and uses no radiative heat exchange. Convection heat transfer coefficients are calculated and the analysis performed assuming the gas temperature is the same in both channels of the heat exchanger.

LAST REVISION: January 1992

C

C

C

C

Define the variables, set the time step counter

```
INTEGER N1,N2,IF,L,COUNT
REAL K,KGAS,BI0,BI1,BI2,FO,RHO,CP
REAL L1,L2,W1,W2,DEPTH,HEIGHT,T,DX,DT,MSTACK
REAL TROOM,TGAS,TIN,U,PR,RE1,RE2,DH1,DH2
REAL NU0,NUI1,NUI2,NU1,NU2,RA
REAL A(100),B(100),C(100),D(100),V(100)
```

C

C

C

Inputs

C

Soapstone properties

```
K=6.4
RHO=3065.0
CP=1000.0
TIN=25.00001
```

C

Room air properties

```
TROOM=25.0
```

C

Geometry

```
L1=0.12
L2=0.09
W1=.105
W2=.45
DEPTH=.300
HEIGHT=1.5
```

C

Differential increments

```
DX=1.E-2
DT=60.
```

C

Calculate the number of nodes in each of the slabs

```
N1=INT(L1/DX)+1
N2=INT(L2/DX)+1
IF=1
L=N1+N2
```

C

Set the initial temperatures

```
DO 10 J=1,N1+N2
V(J)=TIN
CONTINUE
```

10

C

Start the time counters

```
T=0.
COUNT=0
```

C

Write the titles for the output to be printed

```

WRITE(*,*)'          T(min) VRS SURFACE TEMPERATURES'
WRITE(*,*)

C          Read the stack mass flow rate and temperature
C          from the file TUL.DAT; values are read every
C          five minutes. This is the beginning of the
C          calculation loop

OPEN(5,FILE='B:TUL.DAT')

100      IF(COUNT.EQ.5.OR.COUNT.EQ.0)THEN
          READ(5,*,END=200)MSTACK,TGAS
          WRITE(*,*)
          COUNT=0
          ENDIF

C
C          Calculate the heat transfer coefficients
C          and with this the Biot and Fourier numbers
C          0 refers to heat exchange to the room
C          1 refers to the channel between the two walls
C          2 refers to the channel next to the adiabatic
C          boundary
C
C          Fourier number for the soapstone

FO=K*DT/(RHO*CP*DX**2)

C          Biot number for the heat exchange to the room
C          Uses the free convection correlation from I&DW p.430
C          Obtains the raleigh number from a function subprogram
C          and the thermal conductivity at the average of the room
C          and wall temperature from a subroutine

NU0=0.1*RA(TROOM,V(1),HEIGHT)**(1./3.)
CALL PROP(TROOM,V(1),U,PR,KGAS)
HO=NU0*KGAS/HEIGHT
BIO=HO*DX/K

C          Biot numbers for the convection in the two channels
C          The Nusselt numbers for fully developed turbulent flow
C          are calculated using I&DW eqtn 8.57 (p. 394). The average
C          combined entry length Nusselt numbers are calculated using
C          Kay's eqtn. 9-36 for an abrupt contraction entrance.
C          Properties are evaluated at the average of the gas and
C          wall temperatures

DH1=2.*W1*DEPTH/(W1+DEPTH)
CALL PROP(TGAS,V(N1),U,PR,KGAS)
RE1=MSTACK/U/(W1+DEPTH)
NUI1=0.023*RE1**(4./5.)*PR**(1./3.)
NU1=NUI1*(1.+6./(.9/DH1))
C          WRITE(*,*)'RE1=',RE1,'NU1=',NU1
H1=NU1*KGAS/DH1
BI1=H1*DX/K

```

```

DH2=2.*W2*DEPTH/(W2+DEPTH)
CALL PROP(TGAS,V(N1+N2),U,PR,KGAS)
RE2=2.*MSTACK/U/(W2+DEPTH)
NUI2=0.023*RE2**(4./5.)*PR**(1./3.)
NU2=NUI2*(1.+6./(.9/DH2))
C WRITE(*,*)'RE2=',RE2,'NU2=',NU2
H2=NU2*KGAS/DH2
BI2=H2*DX/K

C
C Set up the equations in matrix form for solution
C using the subroutine TRIDAG
C

C Fill up Matrix D

      D(1)=V(1)+2.*BI0*FO*TROOM
      DO 20 J=2,N1-1
      D(J)=V(J)
20      CONTINUE
      D(N1)=V(N1)+2.*BI1*FO*TGAS
      D(N1+1)=V(N1+1)+2.*BI1*FO*TGAS
      DO 30 J=N1+2,N1+N2-1
      D(J)=V(J)
30      CONTINUE
      D(N1+N2)=V(N1+N2)+2.*BI2*FO*TGAS

C Fill up column vectors A, B and C

      B(1)=1.+2.*FO+2.*BI0*FO
      C(1)=-2.*FO

      DO 40 J=2,N1-1
      A(J)=-FO
      B(J)=1.+2.*FO
      C(J)=-FO
40      CONTINUE

      A(N1)=-2.*FO
      B(N1)=1.+2.*FO+2.*BI1*FO
      C(N1)=0.0

      A(N1+1)=0.0
      B(N1+1)=1.+2.*FO+2.*BI1*FO
      C(N1+1)=-2.*FO

      DO 50 J=N1+2,N1+N2-1
      A(J)=-FO
      B(J)=1.+2.*FO
      C(J)=-FO
50      CONTINUE

      A(N1+N2)=-2.*FO
      B(N1+N2)=1.+2.*FO+2.*BI2*FO

C
C Call the subroutine to evaluate at time p+1
C

```



```

                CALL TRIDAG(IF,L,A,B,C,D,V)

                T=T+DT
                COUNT=COUNT+1

C      Output to the screen the time, and the two surface
C      temperatures for each of the slabs

        WRITE(*,60) T/60.,V(1),V(N1),V(N1+1),V(N1+N2)
60     FORMAT(3X,F10.1,4(F12.3))

C      Go to the next time step

        GOTO 100

200    END

C      *****
C      FUNCTION RA(TROOM,T1,HEIGHT)

C      FUNCTION FOR CALCULATING THE RALEIGH NUMBER FOR A
C      GIVEN VERTICAL PLATE CONDITION; PROPERTIES ARE EVALUATED
C      USING THE AVERAGE OF THE PLATE AND ROOM TEMPERATURES (TF)
C      WITH A CURVE FIT OF I&DW'S TABLE A.4
C
C      T1=PLATE TEMPERATURE C
C      TROOM=ROOM TEMPERATURE C
C      V=KINEMATIC VISCOSITY FOR AIR AT TF, m2/s
C      ALPHA=THERMAL DIFFUSIVITY FOR AIR AT TF, m2/s
C      BETA=THERMAL EXPANSION COEFFICIENT FOR AIR AT TF, 1/K
C      G=GRAVITATIONAL ACCELERATION, m2/s

        REAL RA,TROOM,T1,HEIGHT,TF,V,ALPHA,BETA,G
        TF=273.15+(TROOM+T1)/2.
        V=1.E-6*(-3.136+3.228E-2*TF+1.04E-4*TF**2)
        ALPHA=1.E-6*(-3.39+3.22E-2*TF+1.8E-4*TF**2)
        BETA=1./TF
        G=9.8
        RA=(G*BETA*(T1-TROOM)*HEIGHT**3)/(V*ALPHA)
        RETURN
        END

C      *****
C      SUBROUTINE PROP(TGAS,TSURF,U,PR,KGAS)

C      SUBROUTINE FOR CALCULATING THE VISCOSITY, PRANDTL
C      NUMBER AND THERMAL CONDUCTIVITY FOR AIR.
C      PROPERTIES ARE EVALUATED AT TF, THE AVERAGE OF THE GAS
C      (TGAS) AND SURFACE (TSURF) TEMPERATURES; AND ARE USED FOR
C      EVALUATION OF THE HEAT TRANSFER COEFFICIENTS IN THE
C      HEAT EXCHANGER'S CHANNELS. PROPERTIES ARE EVALUATED
C      USING CURVE FITS OF I&DW'S TABLE A.4, AND ARE VALID
C      FOR THE TEMPERATURE RANGE 250 TO 1000 K.

        REAL TGAS,TSURF,U,PR,KGAS,TF
        TF=273.15+(TGAS+TSURF)/2.
        U=1.E-7*(13.554+.67374*TF-3.808E-4*TF**2+1.1832E-7*TF**3)
        PR=8.007E-1-3.39199E-4*TF-1.5926E-7*TF**2+1.0536E-9*TF**3
+      -6.3071E-13*TF**4
        KGAS=1.E-3*(-2.4499+.11297*TF-6.2866E-5*TF**2+1.8907E-8*TF**3)

```

```

RETURN
END

C *****
SUBROUTINE TRIDAG(IF,L,A,B,C,D,V)

C SUBROUTINE FOR SOLVING A SYSTEM OF LINEAR SIMULTANEOUS
C EQUATIONS HAVING A TRIDIAGONAL COEFFICIENT MATRIX.
C THE EQUATIONS ARE NUMBERED FROM IF TO L, AND THEIR
C SUBDIAGONAL, DIAGONAL, AND SUPERDIAGONAL COEFFICIENTS
C ARE STORED IN THE ARRAYS A,B, AND C. THE KNOWN RIGHT
C HAND SIDE VECTOR IS STORED IN THE ARRAY D. THE COMPUTED
C SOLUTION VECTOR V(IF)...V(L) IS STORED IN THE ARRAY V.

REAL A(100),B(100),C(100),D(100),V(100)
REAL GAMMA(100),BETA(100)

C COMPUTE INTERMEDIATE ARRAYS BETA AND GAMMA
C
BETA(IF)=B(IF)
GAMMA(IF)=D(IF)/BETA(IF)
IFP1=IF+1
DO 1 I=IFP1,L
BETA(I)=B(I)-A(I)*C(I-1)/BETA(I-1)
GAMMA(I)=(D(I)-A(I)*GAMMA(I-1))/BETA(I)
1
C COMPUTE FINAL SOLUTION VECTOR
C
V(L)=GAMMA(L)
LAST=L-IF
DO 2 K=1, LAST
I=L-K
2 V(I)=GAMMA(I)-C(I)*V(I+1)/BETA(I)
RETURN
END

```

## VITA

The author was born in Sonsonate, El Salvador, on September the seventh, 1968. He lived in the city of Santa Ana and later in San Salvador where he obtained his Salvadoran and American High School degrees from the Escuela Americana. He attended the Universidad Americana in San Salvador for one year and continued at Virginia Polytechnic Institute and State University, where he obtained his Bachelor of Science in Mechanical Engineering in May of 1990. He became a candidate for the Master's Degree in Mechanical Engineering at Virginia Polytechnic Institute and State University in May, 1990.

His interests include swimming, bicycling, fishing, traveling and scuba diving.

A handwritten signature in cursive script, appearing to read "Mark Gutierrez". The signature is written in black ink and is centered on the page.