# METHOD FOR MEASUREMENT OF WATER VAPOR CONCENTRATION IN WOODSTOVE STACK GASES,

by

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(ABSTRACT)

An instrument (differential flow water meter) to measure the water vapor concentration in stack gases was developed. This is intended for use as a standard reference as well as a practical method for the determination of the moisture content of stack gases from wood stoves. The accuracy of the instrument was tested by generating gas mixtures with known water vapor content and comparing the measured concentrations with the actual values.

Several tests were made under actual operating conditions, i.e., testing the water vapor concentration of stack gases from a wood stove under different firing conditions. The accuracy of the results was further checked by weighing the condensed catch and comparing the measured and predicted values. For each of the tests a wet and dry bulb technique was also used to measure the stack gas moisture content. A comparison of the results obtained using these two methods and the WHA (Wood Heating Alliance) standard method was also done. The results show that the wet and dry bulb method overpredicts the moisture content as compared to the differential flow water meter.

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# Nomenclature

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A	=	area of cross section of nozzle, $m^2$
С	=	constant of proportionality for LFWM
c <sub>D</sub>	=	discharge coefficient for orifice plate of DFWM
ΔΗ	=	average pressure-drop, kPa
L	=	length, m
m	Ξ	mass, kg
μ	=	viscosity, kg/m-s
• n <sub>G1</sub>	=	wet flow rate, kmol/min
· ⊥ n <sub>G</sub>	=	dry flow rate, kmol/min
n	=	number of chemical species in a mixture
P <sub>bar</sub>	=	barometric pressure,abs, kPa
ΔP	=	pressure-drop, kPa
Q	=	volume flow rate, cc/min
Re	=	Reynolds number
R	=	radius, m
ρ	=	density, kg/m <sup>3</sup>
δΡ	=	vacuum at inlet to nozzles, kPa
x	=	mole fraction of a species in a mixture
У	=	mole fraction of water vapor in a wet mixture
V	=	volumetric flow rate, m <sup>3</sup> /min

#### 1.0 INTRODUCTION

#### 1.1 GENERAL

This development of a water vapor sensor was a part of a DOE sponsored project (contract DE-ASO5-83CE23858) (1) to develop technology for efficiency measurement of wood burning and other solid fuel appliances. Accurate measurement of the water vapor concentration history of wood stove stack gases is necessary to :

1. Estimate the heat losses from a wood stove accurately. The sensible enthalpy of the flue gas sample depends on the specific heat of the mixture and hence on its moisture content. Traditional stack loss methods (1) determine the moisture content assuming that all of the hydrogen in the fuel is converted to water vapor and methane. This assumption is incorrect however, as some of the hydrogen is also converted to hydrocarbons other than methane. Since these hydrocarbons are not considered in the estimation of the moisture content, there may be some errors in the calculation. The preferential evolution of water vapor in the earlier part of the burn cycle is also not considered and the water vapor is assumed to be evolved uniformly throughout the burn cycle.

2. To convert dry basis gas concentrations to wet basis. Wet basis concentrations are needed to estimate the flue gas velocity by the tracer gas method (2). Since measurement of wet basis concentrations is difficult, dry basis measurements can be made and converted to wet basis, if the water vapor concentration is known accurately.

#### 1.2 EXISTING REFERENCE METHODS

Because of the numerous problems associated with the wood stove stack gas, such as the presence of condensible hydrocarbons, high temperatures, etc., a suitable reference method has not been developed yet. In some wood stove applications, the 'Method 7 sampling train', developed by the Oregon Department of Environmental Quality (3), has been used for this purpose. The major drawback of this method is that the method is not real time as it gives the average water vapor concentration over the entire burn cycle. It is also labor intensive. The wet and dry bulb method has also been used as a practical method (4).

#### 1.3 RESEARCH OBJECTIVE AND SCOPE

A letter survey of manufacturers of water vapor sensors was done to find any available sensor which can be used to

measure the stack gas water vapor concentration. However, no suitable sensor was found. The objective of this research was therefore to :

- Develop a water vapor sensor to be used as a reference and/or practical method.
- Test the accuracy of the sensor by comparing its readings when gases with known water vapor concentrations are passed through it.
- 3. Test the sensor under actual operating conditions by measuring the water vapor concentrations of stack gases for a complete burn cycle. Simultaneously, the water vapor concentration history is also measured by the wet and dry bulb method. Thus the results obtained from these two methods can be directly compared for the same operation cycle. Several test runs were made under different firing conditions.

#### 1.4 A BRIEF SUMMARY OF THE WORK DONE

A literature search for different techniques of measuring water vapor concentrations was carried out. These methods were analyzed for their possible use for measuring the moisture content of stack gases.

Two types of water meters have been developed, both of which measure wet and dry flow. These flow rates are measured by creating a pressure-drop due to sample flow and then calculating the flow rate by theoretical or empirical relations. The main difference between the two instruments is the method by which the pressure drop is created.

Initially a laminar flow water meter was developed. The sample gas is passed through two coils of tubing and the pressure drops due to the resistances of the two coils are measured. A dryer between the two coils ensures wet gas flow through one coil and dry flow through the other. The concentration of water vapor is then calculated as a function of the pressure drops, the viscosities of the wet and dry mixtures, and their densities. The major problem with this method was in calculating the viscosity of the wet mixture.

Therefore a second instrument, named the differential flow water meter, was developed. The instrument essentially consists of a pair of sharp-edge orifices, with a moisture trap in between. A constant dry gas flow rate is maintained, by means of a pressure regulator and a needle valve, and the pressure drops across the two orifices are measured. The water vapor concentration in the sample gas is a function of these pressure drops.

The condensation of organics or deposition of particulates in the instruments could cause a drift in the calibration constants of the instruments. This results in

errors in the calculation of the water vapor concentration. A filtering system was designed to remove most of the particulates.

The meter has been tested for a range of concentrations, and has been proved to be quite accurate. An accuracy of 1.0 mole% was desired. Tests show that this has been achieved.

#### 2.0 LITERATURE REVIEW

Before the two water meters were developed, a literature search was done to evaluate different methods of water measurement. These methods were evaluated for their possible use as a reference and/or practical method for measuring the stack gas water concentrations. The following features were desirable:

- Range of about 0 to 40 mole %.
- Capability of operating at temperatures of at least 70°C.
- Resistance to contamination from organics and particulates.
- electrical output.
- real-time measurement.

A brief description of some of the methods of water vapor measurement is given below. The first subsection gives a summary of three standard methods of  $[H_2O]$  measurement in flue gases. The next subsection examines different methods of water vapor measurement available with emphasis on their

suitability for measurement of  $[H_2O]$  in stack gases. A table at the end of the discussion summarizes the different methods with respect to their suitability. Several of the methods surveyed seemed suitable for use but were not evaluated further because of the development of the differential flow water meter. A more detailed description of these methods can be found in the ASHRAE brochure on psychrometry (5).

2.1 EXISTING METHODS FOR MEASURING THE [H<sub>2</sub>O] IN FLUE GASES

2.1.1 WHA STANDARD (1)

The theoretical water vapor concentration history is found assuming uniform burning as shown below.

From chemical analysis, we know that the composition of the dry wood sample by mass is approximately 49.3% C, 5.8% H and balance O.

> Assume the composition of wood to be  $C_x H_y O_z . (H_2 O)_w$ Then,

A  $C_x H_y O_z \cdot (H_2 O)_w + B(O_2 + 3.76 N_2)$ D  $CO_2 + E CO + G O_2 + H N_2 + J H_2 O + K(CH_4)$ 

If we have 100 moles of dry products, then  $D = mole\% CO_2$  in stack gas E = mole% CO in stack gas  $G = mole\% O_2$  in stack gas Performing an atom balance,

Ax = D + E + K Ay + 2Aw = 2J + 4K Aw/2 + Az/2 + B = D + E/2 + G + J/2 B = H/3.76 D + E + G + H + K = 100

We have 5 linear equations and 5 unknowns A,B,J,H,K.

The molecular weight of  $C_x H_y O_z$  is assumed to be 1000. Solving this set of equations, we get

J = 31.45 - 0.3652\*D - 1.4972\*G + 0.2259\*E

The concentration of  $[H_2O]$  in the stack gas assuming uniform burning (ie. there is no preferential evolution of water vapor) is

$$[H_2O] = J/(100 + J)*100$$

The dry basis concentrations of  $O_2$ ,  $CO_2$  and CO and the elemental composition of the fuel are known. The concentration of  $H_2O$  can then be calculated.

2.1.2 OREGON SOURCE SAMPLING METHOD 7 (2)

This is a gravimetric method for the measurement of the water vapor concentration in the stack gas. The sample gas is withdrawn isokinetically from the stack and passed through a series of impingers. The volume increase of the impingers is noted. The moisture content is determined as follows:

Volume of gas sampled:

 $Qd = 17.65*Qm (Po + \Delta H/13.6)/Tm$ where

Qm = volume of gas through the meter, CF Po = barometric pressure, abs., in Hg AH = average pressure-drop across the orifice,

#### in $H_2O$

Tm = average dry gas meter temperature, R
The moisture content

 $m_{v} = Qv / (Qd + Qv)$ Qv = 0.0474\*Vv

where

Qv = volume occupied by water vapor, SCF Vv = volume of water condensed in the impinger, ml

Kowalczyk et.al. (7) have used this method for determining the moisture content of wood stove stack gases.

2.1.3 OREGON SOURCE SAMPLING METHOD 4 (2)

This is a less accurate method for water vapor measurement. It is recommended for use only to set the nomograph for isokinetic sampling in the Oregon Method 7. The dry and wet bulb temperatures are measured by thermocouples or

thermometers in the conventional way. The water vapor content is then determined using high temperature psychrometric charts. Tiegs (4) has used this method.

2.2 GENERAL METHODS OF WATER VAPOR MEASUREMENT

In general, the water measurement devices can be broadly classified as

1. Relative humidity type

2. Absolute humidity type

A brief description of some of the sensors under each category is given below.

#### 2.2.1 RELATIVE HUMIDITY TYPE SENSORS

These sensors utilize materials having a property which changes in a measurable way as a function of the relative humidity in the environment. Some of the more common ones in this category are:

 ELECTRICAL RESISTANCE TYPE : The change in resistance of a hygrometer base material is a function of the change in relative humidity.

- DUNMORE TYPE (8,9,10) : This uses a polyvinyl chloride and lithium chloride mixture as electrodes. Its major disadvantages are that it is easily contaminated and the range for a single sensor is low. Howewer, several sensors can be interconnected to give a larger range.
- b. POPE TYPE ION-EXCHANGE HYGROMETER (11,12,13) : The reduction in resistance of a hydrophyllic substance, due to the release of electrostatically held ions, is a function of the change in relative humidity. Range is 10-95 % R.H., and the upper temperature limit is about 25°C.
- c. ALUMINUM OXIDE SENSOR (14,15) : The combined changes in the resistance and capacitance of an anodized  $Al_2O_3$  electrode can be related to the change in humidity. Problems include hysteresis and errors due to the presence of highly polar gases. Its range is from -80°C to 30°C and the instrument is unaffected by standard atmospheric pollutants.
- d. OTHER TYPES : Several other types of sensors have been developed. The most promising for high temperature applications are the ceramic based sensors (16). Though these sensors have a number of favora-

ble properties, they are vulnerable to atmospheric contamination. Protective systems developed to minimize the contamination have not been very successful.

2. CAPACITIVE TYPE RH SENSOR (17) : The change in the dielectric constant of a thin film condenser and the changes in its physical dimensions cause variations in the impedance of the condenser. The change in impedance is a function of the moisture content of the condenser.

One of the sensors developed consists of evaporated gold electrodes on the faces of a thin plastic film. Gold has been used as it is conductive as well as porous.

Its range of operation is 10-100 % RH over a temperature range of -35°C to 80°C. Hysteresis is low and there is little effect due to contamination from common contaminants.

3. DIMENSIONAL CHANGE HYGROMETERS (18,19) : Substances like human hair, nylon and certain other fibres have the property that their dimension changes with a change in the ambient humidity. These changes are measurable and can be correlated with the moisture content.

However the accuracy of the human hair and nylon base sensors is not very good. Using Dacron improves the accuracy to within  $\pm 2\%$  R.H. and the range to 0 to 100 %.

In a carbon element sensor (20) ,the dimensional change in a cellulose-carbon mixture, due to absorption of moisture, causes an increase in the electrical resistance. Its advantages are fast response times, low hysteresis and high resistance to the presence of free moisture. A major problem is that ionic impurities tend to cause significant errors.

- 4. WEIGHT CHANGE HYGROMETERS : These sensors are based on the known relationship between the amount of moisture present and the weight of a sorbing substance. Interferences are mainly due to the absorption of condensible organics.
- 5. PIEZOELECTRIC CRYSTAL (21,22) : These sensors use a piezoelectric crystal with a coating of a hydrophillic substance. The change in resonant frequency is a function of the change in moisture content in the environment. The effect of contaminants can be reduced by selecting suitable coatings. The sensor has a very fast response and high accuracy with a resolution of about 0.1 ppm. But its range is limited to about 3 mole %. H<sub>2</sub>O.

2.2.2 ABSOLUTE HUMIDITY SENSORS

While the previous types of sensors measured the change in moisture content, these sensors measure the total moisture content at a given instant, or the average moisture content over a period of time.

 DEW POINT SENSORS (23,24,25) : These instruments determine the dew point i.e. the temperature at which condensation starts to occur.

They can be either manual or automatic depending on the type of control used to monitor the temperature. The presence of condensate is usually detected by optical means.

Accuracy is between  $\pm$  0.2°C to 2°C and possible range of operation is from -70°C to 80°C. The response time is between a few seconds and a minute. The major limitation of the sensor is that the presence of other condensible gases causes erroneous results.

2. ADIABATIC EXPANSION TYPE : When a gas is expanded suddenly, its temperature drops. Therefore, for a gasvapor mixture, if the temperature drop is just sufficient to cause condensation to begin, then the dew point of the entire mixture can be found from the perfect gas relation. The initial temperature, final pressure and ra-

tio of specific heats of the gas are known. The initial pressure required to produce condensation is found by trial and error. From this the final temperature (dewpoint) is calculated.

- 3. SURFACE CONDUCTIVITY (26) : The surface conductivity of an electrical insulator increases as its temperature approaches the dew point temperature. The conductivity is maintained constant by varying the temperature. The dew point temperature is derived empirically from this temperature.
- 4. LITHIUM CHLORIDE SENSORS (27,28,29) : A lithium chloride solution on a base material such as glass fibre an electrode. This solution is used has as а characterstic vapor pressure which is a function of its temperature. When a salt crystal is exposed to water vapor at a relative humidity below that of its phase transition, the electrical resistance of its surface is very high. As the RH increases to that corresponding to the initiation of a liquid phase on the surface of the crystal, the electrical resistance will decrease rapidly. The decrease in electrical resistance is reversed by heating to reduce the ambient RH. In one version, AC electrical current is furnished to the salt so that it can be brought into phase-transition with the surrounding

air by resistive heating and can be maintained there by a self-regulatory mechanism. The temperature attained is related to the dew-point.

Range and accuracy are about the same as for the dew point sensors. The operation of the sensor is affected because of contamination from salts, ammonia, etc.

- 5. WYLIE SALT CRYSTAL (30,31) : The sensor consists of a potassium chloride crystal with a thin film of its saturated solution, on an electrode. The thickness of the film and the electrical resistance varies with changes in the relative humidity of the sample gas with respect to the equilibrium relative humidity of the salt. The sensor adjusts the ambient temperature so as to maintain a constant film thickness.
- 6. GRAVIMETRIC HYGROMETER (32) : A measured sample of gas is passed through a drying train (either anhydrous magnesium perchlorate, or anhydrous phosphorus pentoxide). The drying train is weighed before and after the test to find the amount of moisture collected. If the drying train is weighed at discrete time intervals, then it is possible to generate average water concentrations for all the time intervals. There may be errors due to the absorption of condensible organics in the drying train.

- 7. COULOMETRIC HYGROMETER (33,34) : A fixed flow rate of the sample gas through an electrolyte cell is maintained. The cell extracts moisture from the gas and electrolyses it. The electrolysing current is proportional to the water vapor concentration. The range is small (approx. 2 mole% H<sub>2</sub>O) due to the limitations of the cell in extracting moisture from the sample and electrolysing it.
- 8. CHEMICAL REACTANT (35) : The sample gas is passed continously over heated calcium carbide which converts the water-vapor present to acetylene. The quantity of acetylene produced is an empirical function of the resultant temperature on burning the gas. The amount of determined then moisture present is from the stoichiometric equation. The range is 0°C to -50°C dew point. Accuracy and response time depend on the purity of the chemical used and the accuracy of calibration. The presence of CO or other combustible products would affect the final temperature.
- 9. CRITICAL FLOW NOZZLES (36,37,38,39,40) : The principle applied here is that the water vapor present in a wet sample is a function of the change in pressure when the moisture present is removed. A pneumatic bridge consisting of four critical flow nozzles is used. The sample gas flows through two parallel arms. In one arm, the sample

is dried out and the change in pressure determined by comparing with the other arm.

10. WET AND DRY BULB PSYCHROMETER (1,41) : The dry bulb thermocouple measures the temperature of the sample gas, while the wet bulb thermocouple measures the wet bulb temperature of the gas. The water content is related to these temperatures.

R.W.Worrall (42) has shown that the wet and dry bulb psychrometer can be used for high temperature applications. Possible errors due to incorrect measurements have been tabulated (42). The following conditions should be maintained to minimize errors:

- Continuous supply of distilled water at temperature slightly below that of the wet bulb.
- b. Radiation shielding on the wet bulb.
- c. The proper high temperature psychrometric charts used to convert the data.
- d. The Lewis number is approximately 1. A Lewis number of 1 indicates adiabatic saturation, and the psychrometric equations based on adiabatic saturation can be used directly. However, if it is not

equal to 1 then the error due to this should be compensated for by the errors due to radiation (41). If the Lewis number is less than 1, the psychrometric equations tend to overpredict the moisture present. Since the effect of radiation is to underestimate the moisture content, these two effects tend to neutralize each other.

11. HEAT OF ADSORPTION SENSORS (43) : A Wheatstone bridge with thermistors imbedded in two small driers is used as the sensor. The heats of adsorption and desorption are used to drive the sensor, the output being electrical. Wet and dry samples are alternately passed through the dryers. The amplitude of the resulting signal is empirically related to the water vapor concentration.

Range of operation is small ( upto 1 mole% H<sub>2</sub>O).

- 12. HEAT OF CONDENSATION SENSORS (44) : The heat given out when the vapor in a fixed sample of gas is condensed out is a function of the water vapor content of the gas. This principle is used in constructing the heat-ofcondensation type sensors.
- 13. GAS CHROMATOGRAPHY (45,46) : The change in thermal conductivity of the sample gas is a function of its composition. This principle is utilized in the thermal

conductivity detectors in gas chromatography for water measurement, among others. A balanced resistance bridge is used.

The sample gas is passed through an adsorbing column which adsorbs the components of interest. When carrier gas is passed through the column, the various components are selectively eluted. The eluted sample is passed over the Wheatstone bridge, and the peaks due to the different components are recorded. The retention time in the column is a property of the particular element and the peak height (or area) indicates its concentration.

14. INFRA RED SENSORS (47,48,49) : Certain wavelengths of IR radiation are selectively absorbed by water vapor. Using the proper windows to isolate this bandwidth, the resulting attenuation in intensity can be related empirically to the water vapor concentration. Usually, a dry reference gas is used as a comparison. The relative amounts of heating caused by the attenuated and the unattenuated beams is a measure of the moisture content of the sample gas. An alternate method is to use a second beam of a nearby wavelength which is not significantly absorbed as the reference, instead of the dry gas cell.

The range of the sensor is at least 40 mole%. Commercially available instruments have a claimed accuracy of about 1 mole%. Interferences are possible due to other

gases which could absorb in the same wavelength regions. The cost of commercially available instruments is also quite high (\$8000 and higher).

#### 2.3 ANALYSIS OF THE SURVEYED METHODS

Of all the methods described above, the following table lists those not suitable for measuring the water-vapor concentration in stack gases and the reasons.

Dunmore	type	-	Small	range,	easily
			contar	ninated	

Pope type ion-exchange - upper temperature limit is hygrometers 25°C which is too low

Carbon element sensor - errors due to ionic impurities

Dimensional change type - poor accuracy

Ceramic based sensor - vulnerable to contamination

Gravimetric hygrometer - absorption of condensible organics

Piezoelectric - range is very small (3 mole%)

- Dew point sensors errors due to the presence of condensible organics
- Adiabatic expansion error in the measurement of dew point due to the presence of condensible hydrocarbons

Lithium chloride sensors - contamination from organics

Coulometric hygrometer - small range of operation

Heat of adsorption sensors - small range ( 1 mole%)

The following types of sensors in particular looked promising:

1. Wet and dry bulb technique

2. Infrared sensors

3. Gas chromatography

4. Gravimetric method

5. Critical flow nozzles

#### 3.0 LAMINAR FLOW WATER METER

A laminar flow water meter was first developed for measuring the water vapor concentrations in the stack gases.

#### 3.1 APPARATUS

The apparatus is shown in Fig.1. The sample line is a 5mm i.d. copper tube of length 1 m approximately. The sample gas is drawn in through a filtering system which contains a pair of 15 cm diameter filters maintained at 74°C. The filters remove the particulates and some of the condensible organics present in the sample.

The gas is then passed through two coils of 5mm i.d. teflon tubing. A drying trap is present between the two coils, which removes all of the moisture from the sample gas. Thus we have dry flow through one coil and wet flow through the other. The two coils are in a box, maintained at  $80^{\circ}$ C. Since the [H<sub>2</sub>O] in the flue gas is less than 40% max., the dew-point of the sample gas is also less than  $80^{\circ}$ C. So, at this temperature there should be no condensation of water vapor. This should also prevent the condensation of some condensible organics i.e. those with dew point less than  $80^{\circ}$ C.


The dry sample gas is then passed through a Horiba MPA-21 oxygen analyzer and an Infrared Industries IR 702 CO/CO<sub>2</sub> analyzer. From this, the dry basis concentrations of O2, CO,  $CO_2$  in mole% are determined. The balance is assumed to be nitrogen. The dry sample gas flow rate is kept constant at 500 cc/min.

The entry length is calculated as shown below.

Assuming a dry flow rate of 540 cc/min and 0.5 cm i.d. teflon coil of length 1 m,

Reynolds number = 600

Therefore,

Entry length = 0.05 Re D

= 15 cm

3.2 BASIC EQUATIONS OF THE LFWM

The assumptions made are laminar flow, symmetrical distribution of velocity with maximum velocity at the center and no velocity (no slip condition) at the walls. The tube is assumed to be long enough for end effects to be negligible.

Then from the Hagen-Poiseuille law (50),

$$\dot{Q} = \frac{\pi (\Delta P) R^4}{8 \mu L}$$
(1)

where  $\dot{Q}$  = volume flow rate,  $m^3/s$  $\Delta P$  = pressure-drop, kPa

- R = radius of tube in m
- = viscosity of the fluid, kg/m-s μ
- length, m L =

Eq. 1 can also be written as

$$\dot{Q} = C \frac{\Delta P}{\mu}$$
,

where  $C = \frac{\pi^4 R}{RT}$ .

The water vapor concentration is

 $[H_20] = \frac{\dot{n}_{G_1} - \dot{n}_{G_2}}{\dot{n}_{G_1}} \times 100 = (1 - \frac{\dot{n}_{G_2}}{\dot{n}_{G_1}}) \times 100$ 

where  $n_{G_1}^{\bullet}$ ,  $n_{G_2}^{\bullet}$  are the wet and dry molar flow rates, respectively.

The molar flow rate is given by the relation

$$\hat{n}_{G} = \hat{Q} \frac{m^{3}}{s} \times \frac{-\rho}{\rho} \frac{kmol}{m^{3}}$$

Therefore, 
$$[H_20] = (1 - \frac{\dot{Q}_2 - \bar{\rho}_2}{\dot{Q}_1 - \bar{\rho}_1}) \times 100$$

$$= (1 - C \frac{\Delta P_2}{\Delta P_1} \frac{\mu_1}{\mu_2} \frac{\overline{\rho_2}}{\overline{\rho_1}}) \times 100$$
 (2)

The density,  $\rho,$  is calculated from the ideal gas law as given below

$$\rho = (P - \delta P - \Delta P/2) * M/RT$$

The following parameters are measured:

- 1.  $\Delta P_1, \Delta P_2$ : The pressure drops across the two resistances respectively, in.  $H_2O$ .
- 2.  $\delta P_1, \delta P_2$ : Vacuum at inlet to the resistances, in.  $H_2O$  vacuum.
- 3. The concentrations of  $O_2$ ,  $CO_1$ ,  $CO_2$  in the sample gas

4. Dry sample gas flow rate, cc/min.

The viscosities of the dry and wet samples are calculated and the constant C is known from calibration data. The effects of curvature on the Hagen-Poiseuille law are accounted for by the constant C.

# 3.3 VISCOSITY CALCULATION

The viscosity of either the wet or dry gas mixture is calculated from the equation (50)

$$\mu_{\min \mathbf{x}} = \sum_{\substack{i=1\\i \in I}}^{n} \frac{\mathbf{x}_{i} \, \mu_{i}}{\sum_{i \in I} \mathbf{x}_{i} \, \phi_{ij}}$$

,

where constant  $\phi$  is given by

$$\phi_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{\mu_i}{\mu_j}\right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4}\right]^2$$

and n = number of chemical species in the mixture x = mole fraction µ = viscosity at the system temperature and pressure, kg/m-s µ = viscosity of the gas mixture kg/m-s and the i and j subscripts indicate different

species.

The equation is useful for computing viscosities of nonpolar gas mixtures. For polar gases such as  $H_2O$ , because of highly angle-dependent force fields between molecules, this equation may be incorrect (49).

The components of the stack gas are assumed to be  $O_2$ ,  $N_2$ ,  $H_2O$ ,  $CO_2$  and CO only. Table 1 shows how the values of  $\Phi$ 

can be determined. A sample calculation for  $\Phi_{i,j}$ , i=1, j=1..5 is shown in Table 2.

The viscosity of the dry mixture  $\mu$  can be calculated directly as all of the dry basis concentrations and the viscosities are known. However, the mole fraction of water being unknown, the viscosity of the wet mixture cannot be directly calculated. Therefore, for calculating the water vapor concentration, a trial and error method is used. An initial value for  $[H_2O]$  is assumed and the new concentration calculated. If the difference between the assumed and the calculated concentrations is less than 0.1 mole%, the process is stopped and the assumed concentration is the required water vapor concentration.

A FORTRAN (Appendix B) program has been written, which does all of these calculations. The constants are read in from an external file.

#### 3.4 CALIBRATION

Calibration is necessary in order to determine the constant C in eqn.[1]. The constant depends on the internal radius and the effective length of the tube. C is determined by passing dry air through the instrument. The values of  $\Delta P_1$ ,  $\Delta P_2$ ,  $\delta P_1$  and  $\delta P_2$  are measured. The temperature T in the two resistances is the same. Since the concentration of wa-

ter vapor is zero, the value of C can be determined as shown below.

From Eqn.1, with  $[H_2O] = O$ ,

$$0 = (1 - \frac{\Delta P_2}{\Delta P_1} \frac{\mu_1}{\mu_2} \frac{\rho_2}{\rho_1} C)$$

Since 
$$\mu_1 = \mu_2$$

and

.

$$\rho = \frac{P}{RT} = \frac{P_o - \delta P - \frac{\Delta P}{2}}{RT}$$

where  $P_0$  = barometric pressure.

The constant C is then

.

$$\therefore C = \frac{\Delta P_1}{\Delta P_2} \frac{(P_0 - \delta P_1 - \frac{\Delta P_1}{2})}{(P_0 - \delta P_2 - \frac{\Delta P_2}{2})}$$

Table 1.	Constants used : of a gas mixture	for determinati e	ion of the	e viscosity
species	dry basis mole fraction	wet basis mole fraction	Mol. wt M kg/kmol	viscosity µ kg/m-s @350K
CO₂ O₂ N₂ CO H₂O	X <sub>1</sub> X <sub>2</sub> X <sub>3</sub> X <sub>4</sub>	x <sub>1</sub> (1-y) x <sub>2</sub> (1-y) x <sub>3</sub> (1-y) x <sub>4</sub> (1-y) y	44 32 28 28 18	17.205 23.16 20.0 20.1 11.615

mole fraction of  $H_2O = y$ 

The dry basis mole fractions of all the components in the sample and the wet basis mole fraction of  $\rm H_2O$  are known.

Table 2. Sample calculation for constant ∮ used for calculation of viscosity of a gas mixture.

i	j	M <sub>i</sub> /M <sub>j</sub>	μ <sub>i</sub> /u <sub>j</sub>	₽ <sub>ij</sub>	
1	1	1.000	1.000	1.000	
	2	1.375	0.743	0.740	
	3	1.571	0.860	0.737	
	4	1.571	0.856	0.735	
	5	2.444	1.482	0.742	
	M;/M;	- rat	io of mole	ecular wei	a

## 3.5 TESTING AND EVALUATION

The accuracy of the system was tested by passing gas mixtures with known water vapor concentrations through the system. Measured volumes of propane and bottled air were passed through a catalyst heated to about 500°C. The volume flow rates of propane and air were measured by a bubble flowmeter. Since complete combustion was achieved, the concentrations of the components in the product, can be estimated theoretically from stoichiometric considerations.

For complete combustion,

 $C_3 H_8^+ x(O_2^+ 3.76N_2^-) = -> 3CO_2^+ 4H_2^- O_2^+ (x-5)H_2^- O_2^+ 3.76xN_2^$ where x = (air/propane)/4.76

= oxygen/propane volumetric ratio

Therefore,

 $[CO_2] = 3/(4.76x - 2)$ 

 $[H_2O] = 4/(4.76x + 2)$ 

Table 3 gives the calibration data taken before and after the test, with dry air. Table 4 gives the values of the various parameters measured. Table 5 gives the comparison between the theoretical and experimental values for  $CO_2$  and  $H_2O$ . Table 3. Data used for calibration of LFWM.

TIME	$\Delta P_1$	ΔP <sub>2</sub>	δP <sub>1</sub>	δP <sub>2</sub>
	in.H <sub>2</sub> O	in.H <sub>2</sub> O	in.H <sub>2</sub> O	in.H₂O
Beginning	0.590	0.980	1.2	3.9
End	0.560	0.920		4.7

The pressure drops were measured using a water manometer.

Air flow cc/min	C <sub>3</sub> H <sub>8</sub> cc/min	CO2 mole%	CO <sub>2</sub> mole%	ΔP <sub>1</sub> in. H <sub>2</sub> O	ΔP <sub>2</sub> in. H <sub>2</sub> O	δP <sub>1</sub> in. H <sub>2</sub> O	δP <sub>2</sub> in. H <sub>2</sub> O
		<u>IR 702</u>	<u>CalC</u>				
2400	44.37	3.6	3.4	0.600	0.960 0.965	1.3	4.0
	57.36	4.7	4.4	0.595 0.600	0.600 0.940	1.3	4.0
	72.03	6.1	5.6	0.595 0.600	0.920 0.925	1.3	4.0
	97.08	7.9	7.7	0.610 0.610	0.920 0.910	1.3	4.0
	106.56	9.1	8.4	0.605	0.900 0.910	1.3	4.1
	123.59	10.7	10.03	0.620	0.910	1.3	4.3
	135.71	11.7	10.92	0.620 0.615	0.900	1.4	4.7
	164.79	14.2	13.47	0.640 0.630	0.900 0.890	1.4	4.8

Table 4. Test data for checking the accuracy of the LFWM

Air flow is kept nearly constant at about 2400 cc/min for the test.  $[CO_2]$  is estimated by an IR 702  $CO_2$  analyzer and is also calculated from theoretical considerations.

[H <sub>2</sub> O] mole %	[H <sub>2</sub> O] mole % measured
4.34	4.23
5.58	4.77 7.19
6.95	7.66 9.66
9.26	10.10 13.22
10.12	14.79 15.15
11.80	14.76 16.88
12.71	18.37
15.22	22.08 21.55

Table 5. Comparison of the measured and calculated [ $H_2O$ ] (using the LFWM)

 $[H_2O]$  is from stoichiometric considerations. pred

#### 3.5.1 EXPERIMENTAL SET-UP

The experimental set-up for testing the accuracy of the instrument is shown in Fig.2. Measured volumes of propane and air are passed through the catalyst . The catalyst is in a catalyst holder, electrically heated to 500°C and controlled by a temperature controller. A part of the product mixture is drawn through the instrument by a pump. The dry sample gas from the instrument is then passed through an IR702  $CO/CO_2$  analyzer. A zero CO reading indicates complete combustion.

Before each test a leak test is done to ensure that there is no leakage of room air into the system when it is under a vacuum of about 4.4 kPa.

### 3.6 DISCUSSION

The measured value of the water vapor concentration is higher than the stoichiometric value as shown in Fig.3. The difference ranges from 1 mole% at the lower end to 6 mole% at the upper end. Figure 4 shows a plot of the theoretical concentration of  $CO_2$  versus the experimental values.

A comparison of the  $CO_2$  concentrations from the IR702 analyzer and from stoichiometric considerations shows good agreement within the accuracy limits of the IR702 analyzer. The main reason for the inaccuracies in the measured [H<sub>2</sub>O]





Figure 3. Comparison of the measured and predicted  $[H_2O]$ .: Measured  $[H_2O]$  from the LFWM and predicted  $[H_2O]$  from stoichiometry.



Figure 4. Comparison of the measured and predicted  $[CO_2]$ : Measured  $[CO_2]$  from the IR 702  $CO_2$  analyzer and predicted  $[CO_2]$  from stoichiometry.

could be the equation used for calculating the viscosity of the wet mixture. This equation is suitable only for non polar gases (50). The presence of water vapor, a highly polar gas, may have caused the calculated viscosity to be lower than the actual value (Fig.5). The actual value is estimated from eqn.[1], the  $[H_2O]$  being the stoichiometric values from the calibration experiment.

Figure 6 shows the relation between the viscosity of a wet mixture and the  $[H_2O]$ . The viscosity of the mixture is calculated for different  $[H_2O]$ , assuming that the dry basis concentrations of  $O_2$ , CO, CO<sub>2</sub> and N<sub>2</sub> remain the same.

The flow is laminar and the entry length is 15 cm for the coil which is of length 1 meter. The end effects can be ignored however, as the constant C takes care of this.

An alternate method is to plot of the viscosity of the wet mixture against the theoretical  $[H_2O]$  (Fig.11). The theoretical concentration is derived from stoichiometry and the viscosity is calculated from eqn.[1]. Then a curve fit can be used to give an empirical relation between the viscosity of the wet mixture and the actual concentration of water vapor. This relation can be used instead of eqn.[1] for calculating the viscosity of the wet sample gas. This should give more accurate water vapor concentrations as the errors due to incorrect calculation of the viscosity can be eliminated.



Figure 5. Comparison of the actual and calculated viscosities of the wet mixture. : The actual viscosity is calculated from equation [2], the  $[H_2O]$  being known from stoichiometry. The calculated viscosity is from the Wilkes relation (50).



Figure 6. Relation between calculated viscosity of the wet sample and  $[H_20]$ . The dry basis concentrations of  $O_2$ ,  $CO_2$ , CO and  $N_2$  are assumed constant and for different  $[H_20]$ , the viscosity is calculated using Wilkes semi-empirical relation.

#### 4.0 DIFFERENTIAL FLOW WATER METER

## 4.1 INTRODUCTION

Because of the problems associated with calculating the viscosity of the wet mixture in the LFWM, the differential flow water meter was developed. In this sensor there is negligible effect due to viscosity.

## 4.2 APPARATUS

Figure 7 shows the schematic for this instrument. The filtering system is the same as in the LFWM. The two resistances in the LFWM are replaced by a pair of sharp-edge orifices.

The diameters of the two orifices are 0.0813 cm and 0.0940 cm respectively. The pressure-drops across these orifices are measured by Schaevitz P3061 pressure transducers. A water manometer is used to measure the pressure at the inlet to either orifice, using a valve to switch the manometer between the two. The moisture trap consists of an ice bath followed by a column of drierite ( $CaSO_4$ ). The two orifices are maintained at  $80^{\circ}C$ .



The sample gas is drawn in through the instrument by means of a pump. A pressure regulator and a needle valve are used to maintain a nearly constant dry flow.

4.3 BASIC EQUATIONS OF THE DFWM

The following parameters are measured by the instrument:

- 1.  $\Delta P_1$ ,  $\Delta P_2$ ; ie. the pressure drops across the two orifices (in.  $H_2O$ );
- 2.  $\delta P_1$ ,  $\delta P_2$ ; i.e. vacuum at inlet to the orifices (in.  $H_2O$ ).

The following values are also known:

- Discharge coefficients from calibration data (see section 4.4)
- Dry sample gas flow rate (maintained constant throughout the test) , cc/min
- 3. Dry basis concentrations of  $O_2$ , CO,  $CO_2$  in the sample gas, mole %

The concentration of water vapor is

$$[H_20] = \frac{\dot{n}_{G_1} - \dot{n}_{G_2}}{\dot{n}_{G_1}} \times 100$$
$$= (1 - \frac{\dot{n}_{G_2}}{\dot{n}_{G_1}}) \times 100$$

where  $n_{G_2}^{\circ}$  = molar dry gas flow rate, kmol/min, and  $n_{G_1}^{\circ}$  = molar wet gas flow rate, kmol/min.

$$n = \frac{\rho V}{M}$$
,

where

 $\rho$  = density, kg/m<sup>3</sup> V = volumetric flow rate, m<sup>3</sup>/min M = molecular weight, kg/kmol.

The volumetric flow rate is

$$\mathbf{\dot{v}} = \mathbf{C}_{\mathbf{D}} \checkmark \frac{\overline{2\Delta \mathbf{P}}}{\rho} \mathbf{A}$$

where A is the cross-sectional area of the orifice and density

$$\rho = \frac{P}{RT} = \frac{PM}{RT}$$

$$\cdot \cdot [H_2 0] = \left[1 - \frac{C_{D_2}}{C_{D_1}} \frac{A_2}{A_1} \left(\frac{\Delta P_2}{\Delta_{P_1}} \frac{M_1}{M_2} \frac{P_{bar} - \delta P_1}{P_{bar} - \delta P_2}\right)^{1/2}\right] \times 100$$

#### 4.4 CALIBRATION

 $C_{D_1}$  and  $C_{D_2}$  are determined by running dry air through the system. The general procedure is as follows:

- 1. The dry gas flow rate is adjusted so that  $\Delta P_2$  reads 3.93 Volts (0.39 kPa). The 3.93 Volts corresponds to a dry flow rate of 550 cc/min. The data acquisition system used has an upper limit of 4.095 Volts. Therefore 3.93 Volts would ensure a high flow rate and simultaneously allow for some fluctuation. The response time of the instrument is better at higher flow rates. The values of  $\Delta P_1$ ,  $\delta P_1$ ,  $\delta P_2$  are noted. The dry gas flow rate is determined at the outlet using a bubble flowmeter, corrected for wet flow.
- 2. The dry gas flow is then increased to give values of  $\Delta P_1$  from 2.00 to 3.90 volts, in steps of 0.5 volts (i.e. 0.2 kPa to 0.39 kPa), and the values of  $\delta P_1$  and the dry flow rate are noted.
- 3. The discharge coefficients are then calculated as follows:

$$C_{\rm D} = \frac{\dot{v}}{A \sqrt{\frac{2\Delta P}{\rho_{\rm inlet}}}} ,$$

where

A = 
$$\frac{A_2}{\sqrt{1 - \frac{A_2^2}{A_1^2}}}$$
 and  $\rho_{\text{inlet}}$  = density at inlet to orfice.

If 
$$\dot{Q} = dry$$
 flow rate, cc/min  
and  $\dot{Q}' = wet$  flow rate, cc/min,

then 
$$\vec{Q} = \frac{\vec{Q}' (P_{amb} - P_{sat})}{P_{amb}}$$

The volumetric flow rate is therefore,

 $\overset{\bullet}{V}$  =  $\frac{10^{-6}}{60} \overset{\bullet}{Q} \frac{m^3}{s} \cdot \frac{T_{box}}{T_{amb}} \frac{P_{amb}}{P_{inlet}}$ 

$$\rho_{\text{inlet}} = \frac{PM}{RT} = (P_{amb} - \delta P_1) \frac{M}{RT}$$

$$\therefore C_{\rm D} = \frac{\frac{10^{-6}}{60} \circ \frac{T_{\rm box}}{T_{\rm amb}} \frac{P_{\rm amb}}{P_{\rm inlet}}}{A \sqrt{\frac{2\Delta P}{(P_{\rm amb} - \delta P} \frac{RT}{M}}}$$
(3)

The discharge coefficient for each orifice can be determined from (3).

The molecular weight of the dry mixture is given by  $M_2 = 32.0x_1 + 28.0x_2 + 44.0x_3 + 28.0x_4$ where  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$  are dry basis concentrations of  $O_2$ , CO, CO<sub>2</sub> and N<sub>2</sub> respectively.

For the wet mixture,

 $M_1 = M_2 * (1-y) + 18.0*y$ 

where y = wet basis mole fraction of  $H_2O$ 

# 4.5 TESTING AND EVALUATION

Testing of the instrument was needed to check its accuracy, especially as no calibration gases containing  $H_2O$  are used to get the instrument ready to measure. Gas mixtures with known water vapor concentrations are generated by burning different mixtures of hydrogen and air. The product gas is then passed through the system. The measured water vapor concentration is then compared with the theoretical concentration.

The experimental set up is similar to the one used for testing the LFWM. Measured volumes of  $H_2$  and air are mixed

and passed through a heated catalyst, maintained at 500°C (H<sub>2</sub> is used instead of propane as higher water vapor concentrations can be generated with H<sub>2</sub>). Complete combustion occurs and the H<sub>2</sub> is converted to H<sub>2</sub>O. The products are then passed through a heated line (at approx.72°C) to the instrument. The dry flow rate is maintained constant such that  $\Delta P_2$  is 3.93 volts (0.39 kPa). The values of  $\Delta P_1$ ,  $\delta P_1$ ,  $\delta P_2$  are noted. The process is repeated for different concentrations of water vapor.

The theoretical  $[H_2O]$  and  $[O_2]$  are computed from stoichiometry as shown below:

Assuming complete combustion, the chemical reaction is

$$H_2 + x (O_2 + 3.76 N_2) \rightarrow H_2O + (x - \frac{1}{2}) O_2 + 3.76 x N_2$$

where

$$x \equiv (Air/H_{2})/4.76$$

$$[H_20]_{\text{theoretical}} = \frac{1}{4.76 \text{ x} + 0.5}$$

$$[0_2]_{\text{dry basis}} = \frac{(x - 0.5)}{4.76 \ x - 0.5}$$

Figure 8 shows a graph of  $C_{D_1}$  vs the pressure-drop  $\Delta P_1$ . The discharge coefficient  $C_D$  is a function of the Reynolds number. However, the dimensions of the tube remain the same



Figure 8. Variation of  $C_D$  with pressure-drop  $\Delta P_1$  (1/1/1985) 1

and viscosity and density are nearly constant at a particular flow rate (assuming that any differences are negligible). Therefore,  $C_{0}$ , is proportional to the flow rate and hence to the pressure-drop. For more accurate results, it is recommended that  $C_{p}$  as a function of Re be used. The values used for determining the discharge coefficients  $C_{p}$ , and the curve fit used are tabulated in Table 6.

Table 7 shows the data from the test, while Table 8 gives the results as compared with the theoretical values. A graph of  $[H_2O]$  vs  $[H_2O]$  is shown in Fig.9.

As seen from Fig.9, there is good agreement between the experimental and theoretical values of  $[H_2O]$ . The difference ranged from 0.2 mole% to 0.6 mole%. This was well within the desired accuracy range of 1 mole%.





Table 6. DFWM calibration data taken on 1/1/1985

ΔP1	ΔP2	δP <sub>1</sub>	δΡ <sub>2</sub>	wet flow rate	c <sub>D1</sub>	c <sub>D2</sub>
volts	volts	in.H <sub>2</sub> O	in.H <sub>2</sub> O	cc/min		
2.012 2.488	3.938	1.6 1.8	2.6	540.1 603.5	0.7056 0.7119	0.6766
2.974		2.0		661.3	0.7136	
3.947		2.5		762.9	0.7152	

T  $ambox{$\stackrel{=}{_{_{_{_{}}}}}} 301K$ P  $bax \\ Dry air, M = 29 kg/kmol$ 

Since the dry flow rate in the DFWM is maintained constant, C is to be calculated for this flow rate only. Therefore  $\Delta P_2$  and  $\delta P_2$  are measured only once.

Curve fit used was : for  $\Delta P_1 < 3.0 \text{ V}$ (Figure 8) for  $\Delta P_1 = 0.00939734 \text{*} \Delta P_1 + 0.66498243$ for  $\Delta P_1 > 3.0 \text{ V}$  $C_{D_1} = 0.6390$ 

#	$\Delta P_1$	$\Delta P_2$	δP <sub>1</sub>	δP2	air flow rate	H flow rate
	volts	volts	in. H O	in. H O	cc/min	cc/min
1	2.018	3.930	1.7	2.7	543.8	->(dry air)
2	2.167	3.916	1.7	2.7	1465.6	77.3
3	2.367	3.934	1.9	2.9	1465.6	153.9
4	2.503	3.933	1.9	2.9	1497.4	213.9
5	2.732	3.936	2.3	3.3	1497.4	295.7
6	3.195	3.976	2.3	3.5	1460.7	401.5

Table 7. Test data for checking the accuracy of DFWM (1/1/1985)

Room temperature = 301K Barometric pressure = 94.96 kPa

Note : Data for reading 6 was taken on 1/2/1985 at  $T_{am\overline{b}} = 300 \text{ K}$ P  $\overline{bar} = 94.96 \text{ kPa}$ 

Pressure-drop in volts can be converted to kPa by multiplying with 0.6229.

	Table	8.	Results	of	the	test	done	on	1/1	/1985
--	-------	----	---------	----	-----	------	------	----	-----	-------

#	[H <sub>2</sub> O] mole %	[H <sub>2</sub> O] mole %
1	0.0	0.33
2	5.14	4.92
3	9.98	9.78
4	13.33	12.94
5	17.97	17.53
6	24.17	24.76

Comparison of measured [H<sub>2</sub>O] from DFWM and predicted [H<sub>2</sub>O] from stoichiometry.

Since the results of this test confirmed the accuracy of the differential flow water meter, it was decided to do some testing on a wood stove. A total of 5 tests under different firing conditions were run. After 3 tests, the accuracy of the sensor was checked again by passing gases with known water vapor concentrations through the instrument. Calibration was also done and the C calculated were found to be different from the previous value. This may have been because of deposition of organics in the tube. A new correlation between C and  $\Delta P_1$  was thus needed.

Figure 10 is a plot of the new discharge coefficient C  $$^{\rm D}_{\rm l}$$  vs  $\Delta P_{\rm 1}$  .

The calibration data used to determine the discharge coefficients is shown in Table 9. The data from the accuracy test are shown in Table 10 and the corresponding results are in Table 11. The results again show excellent agreement between the measured and predicted values of  $[H_2O]$ , the difference being 0.5 mole% at the worst case. Fig.ll is a plot of the measured  $[H_2O]$  versus the predicted concentration.

(In Table 10, #3 is for a methane-air mixture heated to 500°C, the methane being 2.83% of the mixture).



Figure 10. Variation of  $C_{D_1}$  with pressure-drop  $\Delta P_1$ (3/26/1985).:  $\Delta P_1$  is a function of the flow rate through the orifice.





Comparison of predicted and measured [ $H_20$ ]

- $[H_20]$  measured from DFWM
- $[H_20]$  predicted from stoichiometry
| ΔP <sub>1</sub>                           | ΔP <sub>2</sub>          | δP <sub>1</sub><br>in H <sub>2</sub> O | δP <sub>2</sub><br>in H <sub>2</sub> O | Rate of<br>wet flow                       | $c_{D_1}$                                      | c <sub>D2</sub> |
|---|--------------------------|--|--|---|--|-----------------|
|   |                          | 111.1120                               |  |   |  |                 |
| 2.045<br>2.544<br>3.024<br>3.507<br>3.833 | 3.926                    |  | 0.8                                    | 517.8<br>581.1<br>637.9<br>686.3<br>719.3 | 0.6842<br>0.6887<br>0.6934<br>0.6928<br>0.6947 | 0.6611          |
|   | Room<br>Barome<br>Dry a: | temperatu<br>etric pre<br>ir, M = 2    | ire = 298<br>ssure =<br>9 kg/kmc       | 8 K<br>95.26 kPa<br>ol is used            |  |                 |
| Cn <sub>a</sub> h                         | as to be                 | measured                               | l onlv or                              | nce as drv                                | flow ra  | ate is con      |

Table 9. DFWM calibration data taken on 3/26/1985

 $C_{D_2}\,has$  to be measured only once as dry flow rate is constant.  $\delta P_2\,\,is$  0 because of a slight back pressure from the gas cylinder.

Curve fit :	For	$\Delta P_1 < 3.0 Volts$		
(Figure 10)		$C_{D_1} = 0.00831601 * \Delta P_1$	+	0.68886819
	else	for $\Delta P_1 > 3.0$ Volts		
		$C_{D_1} = 0.7150$		
		T		

#	$\Delta P_1$ volts	∆P <sub>2</sub> volts	$\delta P_1$ in.H <sub>2</sub> O	δΡ <sub>2</sub> in.H <sub>2</sub> O	air flow cc/min	fuel flow cc/min
1 2 3	2.016 3.000 2.193	3.922 3.939 3.950	$\begin{array}{c} 0.4\\ 0.4\\ 0.4\\ 0.4 \end{array}$	1.4 1.4 1.4	(dry air) 1678.3	433.4

3 2.193 3.950 0.4 1.4 #3 is for a methane-air mixture, heated to 500C, the methane

Table 10. Data for checking accuracy of the DFWM

(taken on 4/2/1985)

being 2.83% of the mixture.

Room temperature = 299 K Barometric pressure = 94.9 kPa

#	[H <sub>2</sub> O] <sub>pred</sub>	[H <sub>2</sub> O] measured
1 2 3	0 22.87 5.66	0.5 23.2 5.68
	[H <sub>2</sub> O]measured [H <sub>2</sub> O]pred	from DFWM from stoichiometry

Table 11. Comparison of measured and predicted  $[H_2O]$ 

### 5.0 TESTS, RESULTS AND DISCUSSION

## 5.1 INTRODUCTION

The moisture concentration of the stack gases during a complete wood stove burn cycle was measured in 5 tests using the DFWM. The wood stove used has primary and secondary air inlets, the primary air entering through a thermostatically controlled damper mounted on the door. The damper is preset by the manufacturer, so that primary air flow will never be completely stopped. The top half of the door has two 1.3 cm diameter holes which act as the secondary inlet. A manually adjustable plate is used to control the air flow through this inlet. The stove has a false bottom with a grate in the center. Air enters through the damper and comes up through the grate and past the fuel. The secondary air is intended to facilitate the combustion of volatiles by providing extra oxygen to the region above the charge.

## 5.2 EXPERIMENTAL SET-UP

A schematic of the experimental set-up using the DFWM is shown in Fig.12.

The sample gas is drawn from the stack through a probe, at a height of about 1.3 m above the floor, at a rate of about 540



cc/min. A heated line at approx. 72°C connects the instrument to the stack.

A second line feeds the gas analyzers. The sample gas in each of the two lines is first filtered to remove the particulates present. Any condensible organics present are removed using an ice bath. The dry gas sample is then passed through the Horiba MPA-21  $O_2$  analyzer and the Horiba PIR 2000 CO and CO<sub>2</sub> analyzers, all of which are in parallel.

A data acquisition system reads the output from the two pressure transducers and the three gas analyzers. The data acquisition system is driven by a TRS80 Model III microcomputer. A BASIC program takes digital outputs from the A/D card every 30 seconds and converts the voltage signals from the gas analyzers to mole percent concentrations on a dry basis. The results are stored on a floppy disk.

A wet and dry bulb sensor was also set up, to compare the results obtained from the DFWM to that of the Oregon Source Sampling Method 4 (2), which is a wet and dry bulb type method. The wet and dry bulb readings were taken at a height of about 6 m to reduce the dry bulb temperature and hence the radiation errors.

The dry and wet bulb temperatures are measured by two Type K Chromel-Alumel thermocouples. A sock wetted with water is tied around the junction of the wet bulb thermocouple. The sock was kept wet for the entire test.

### 5.3 TEST PROCEDURE

The procedure followed for each test is:

- The filters in the DFWM and in the gas analysis part are replaced before each test.
- Using dry air as the zero gas, the discharge coefficients are checked. (see section 4.4)
- The coil and trap in the ice bath and the drierite tube are weighed.
- 4. A fuel sample (cut and split cordwood) of weight about 10-12 kgs is prepared. The moisture content of this sample is determined by taking small pieces and drying them in an oven. The difference in weight before and after drying determines the moisture content of the wood sample.
- 5. The gas analyzers are zeroed and spanned, and the pressure transducers zeroed.
- The DFWM is allowed to warm up at least 30 minutes before the test is started.

- 7. The thermostat is set for the desired firing condition before the test and is not adjusted during the test.
- About 5-6 kgs of kindling are used to start the fire and to build a good coal bed.
- 9. The pumps are switched on and the values adjusted to maintain the required dry gas flow rate in both the instrument and the gas analysis sections. The data acquisition system is also turned on.
- 10. Once the weight of the kindling is down to about 20% of the main charge, the main load is added.
- 11. The readings of  $\Delta P_1$  and  $\Delta P_2$  are taken every 30 seconds.
- 12. The wet and dry bulb readings are also taken at 10-15 minute intervals.
- 13. The test continues till the weight of the charge comes down to about 20% of the main load.
- 14. After the test, the instrument is allowed to cool down. Then the trap,coil and the drierite tube are weighed again to determine the amount of moisture collected during the test.

Five tests were run under different firing conditions. The above procedure was essentially repeated for each of the tests. Table 12 shows the mass of kindling and the main load used for each test.

Test #	m <sub>main</sub> load kg	<sup>m</sup> kindling kg	Burn rate kg/hr
1	12.08	2.40	2.90
2	12.62	2.52	2.50
3	12.14	2.43	2.95
4	12.40	2.48	2.81
5	10.58	2.15	3.10

Table 12. Weight of fuel used per test

# 5.4 RESULTS AND DISCUSSION

The data was transferred from the floppy disk to the mainframe computer (IBM 3084). Using a Fortran program (Appendix B), the water vapor concentrations were generated. The data and results for Test 1 are given in Appendix B.

The water vapor concentrations from the wet bulb-dry bulb technique are generated from the test data, using high temperature psychrometric charts (1). The water vapor concentrations from the DFWM, the wet and dry bulb methods, and theoretical considerations (WHA standard) are all drawn on the same graph. Figures 13,14,15,16,17 show these plots.

A further check on the accuracy of the DFWM was made by comparing the measured condensate catch in the moisture trap with the predicted catch from the DFWM readings. A sample calculation for test#1 is given below

Measured catch = 16.2 gms To find the predicted catch,

Let

R = 
$$\frac{{}^{n}_{H_20}}{{}^{n}_{gas wb}}$$
 = 0.1495

The number of moles of water vapor present is given by

$$n_{H_20} = n_{gas db} \frac{R}{1 - R}$$



Figure 13. Water vapor concentration history (test# 1): Burn rate = 2.90 kg/hr. The abrupt increase in  $[H_2O]$  at time = 170 minutes is due to unknown reasons.



Figure 14. Water vapor concentration history (test# 2): Burn rate = 2.50 kg/hr



Figure 15. Water vapor concentration history (test# 3): Burn rate = 2.95 kg/hr



Figure 16. Water vapor concentration history (test# 4): Burn rate = 2.81 kg/hr



Figure 17. Water vapor concentration history (test# 5): Burn rate = 3.10 kg/hr

The mass of water vapor present is

$$m_{H_20} = n_{H_20 \text{ db}} t 18 \text{ gms}$$
  
=  $n_{gas \text{ db}} \frac{R}{1-R} - 18 \frac{kg}{kmol} - 1000 \frac{g}{kg}$ ,

where dry gas flow rate = 540 cc/min and t = 250 minutes.

The molar dry gas flow rate is

$$\hat{n}_{gas \ db} = 540 \ cc/min \ x \ 10^{-6} \ \frac{m^3}{cc} \ x \ \overline{\rho}$$

$$= 540 \ x \ 10^{-6} \ x \ \frac{P}{RT} = 1.99 \ x \ 10^{-5} \ kmol/min$$

$$m_{H_20} = 1.99 \ x \ 10^{-5} \ x \ \frac{0.1495}{1 - 0.1495} \ x \ 250 \ x \ 18 \ x \ 1000 \ gms$$

$$= 15.77 \ gms$$

$$D = \frac{16.2 - 15.77}{16.2} \ x \ 100 \ = + 2.7\%.$$

where D is the difference between measured and predicted values.

The difference is probably due to the condensation of hydrocarbons and other organics. The molecular weight of these organics being much higher than that of water, the weight of the measured catch is also higher. The same procedure was repeated for the other tests. The results are shown in Table 13. The difference in predicted and measured values is less than 5% for tests 1,2,4 and 5. Howewer, the agreement is not very good for test 3. This could be because the discharge coefficients (Table 6) used may have become inaccurate because of deposition of particulates or other organics in the tube or orifice plate.

Table 13. Comparison of the predicted and measured  $\rm H_2O$  catch

Test #	Thermal energy	diff%	Average [CO]
	Btu/hr	(m - p)/p*100	mole %
1	35000	+2.7%	1.90
2	21000	+4.1%	2.14
3	35000	+14%	1.99
4	24000	+0.4%	2.42
5	17000	+1.5%	1.47

The predicted catch (p) is calculated from the average  $[H_2O]$  from the DFWM. The measured catch is denoted by m.

The thermal energy released is calculated assuming that the heating value of fuel is 7500 Btus/lb and efficiency of 50%. (The thermal energy released is used to classify the firing condition as hi or low fire).

From the figures (Fig.13 etc) it can be seen that the WB/DB method overpredicts the water vapor concentration as compared to the DFWM for the most part. The difference varies from 1 to 3 mole % generally. However, the shape of these two curves are similar. This means that for the conditions of these tests, a constant correction factor can be applied to the WB/DB readings so as to get more accurate results from the WB/DB data.

The theoretical method underpredicts the water vapor concentration in the first part of the burn cycle and overpredicts in the second part. This can be expected as the composition of the fuel is not the same for the entire burn cycle.

# 5.5 CONCLUSIONS

Two methods of water vapor measurement were developed

1. LAMINAR FLOW WATER METER: This was a simple, easy to construct instrument. However, the lack of a suitably accurate equation for calculating the viscosity of the wet gas sample caused inaccuracies in the measured value of  $[H_2O]$ . An empirical curve fit for the viscosity could have been used, but the development of the DFWM eliminated the need for viscosity calculations. Therefore

further work on the LFWM was postponed and the DFWM was used instead.

2. DIFFERENTIAL FLOW WATER METER: In this sensor, there is negligible effect due to viscosity. Calibration tests showed that the accuracy of the instrument is within 1 mole%. The measured  $[H_2O]$  is sensitive to the correct calculation of the discharge coefficient and hence extreme care is needed while finding a curve fit for the variation of  $C_{D_1}$  vs  $\Delta P_1$ .

The following measurements are required for the DFWM:

- The pressure-drops across the two orifice plates and the pressure at the inlet to the orifices
- The dry basis concentrations of O<sub>2</sub>, CO<sub>2</sub> and CO.

Using a single pressure transducer and a valve to switch between the two orifice plates, we can measure the inlet pressure to both orifice plates. If the filter system works, then the inlet pressure does not change much over a burn cycle. So the pressure need only be measured once during the test. However to ensure safe operation, the inlet pressure readings should be monitored continuosly. A decrease in the inlet pressure (by about 5 kPa) indicates that the filter system has failed.

(This is because there is a vacuum in the system caused by the clogged filters.)

Thus at least three pressure transducers are required including two needed for measuring the pressure-drops across the orifices. The instrument gives real-time  $[H_2O]$  as the time interval between two consecutive readings depends only on the rate at which the data acquisition system samples data.

The major problem in maintenance is that after a few tests, the system may have particulate deposition in the sample lines and the orifices, which must be cleaned out. The presence of particulates in the nozzle may cause the discharge coefficient to drift and the instrument may have to be recalibrated.

The instrument has an accuracy of 0.5 mole %. A comparison with the dry and wet bulb method showed that the latter overpredicted the water vapor concentration by about 1 to 3 mole%. The WHA method underpredicted the  $[H_2O]$  in the early part of the burn cycle and overpredicted in the latter part as compared to the DFWM.

Based on the results of the tests performed on the wood stove, and the calibration tests, we can use this instrument both as a reference and as a practical method for measuring the  $[H_2O]$  in stack gases. The dry and wet bulb method can be used to get a rough estimate of the  $[H_2O]$  in the stack gases.

It can be used to give more accurate results, if calibrated against the DFWM.

APPENDIX A. SENSITIVITY ANALYSIS OF LFWM AND DFWM

A complete sensitivity analysis was performed to analyze the effect of errors in the various parameters involved in the measured water vapor concentration. These parameters are measured directly or calculated from measured quantities. The approach used was to consider each parameter separately and to vary it by a fixed percentage each time. The corresponding change in the  $[H_2O]$  is then noted. Tables 14 and 15 show the initial values and the results for the LFWM.

From the results, we can see that the calculated  $[H_2O]$  is very sensitive to errors in the measurement of the pressuredrops  $\Delta P_1$ ,  $\Delta P_2$  and the calculation of viscosity of the wet mixture. The errors in  $\Delta P_1$  and  $\Delta P_2$  being in opposite directions, (one being positive and the other negative) tend to compensate for each other. Since the transducers are zeroed before each test, and the errors are mainly due to noise the two errors are likely to occur together. However, the semi-empirical equation used for calculating the viscosity of the wet mixture is valid only for non-polar gases. This error would cause significant errors in the measured  $[H_2O]$ .

A similar analysis was carried out for the DFWM. The initial values used are in Table 16, while the results are shown in Table 17. The accuracy of the measured  $[H_2O]$  is highly dependent on the errors in measuring  $\Delta P_1$ ,  $\Delta P_2$  and the

Appendix A. Sensitivity analysis of LFWM and DFWM

calculated values of the discharge coefficients. Since the pressure transducers are zeroed before each test, the errors in  $\Delta P_1$ ,  $\Delta P_2$  are small and compensate for each other. The correct calculation of the discharge coefficient is thus critical for the accuracy of the measured values of [H<sub>2</sub>O] and proper care must be taken while finding a curve-fit for  $C_D$ .

Table 14. Base values used for sensitivity analysis of LFWM

	P <sub>bar</sub>	ΔP <sub>1</sub>	ΔP <sub>2</sub>	δP <sub>1</sub>	$\delta P_2$
	in.	in.	in.	in.	in.
	H₂O	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O
Calibration	382.0	0.590	0.980	1.2	3.9
Test		0.620	0.900	1.3	4.7

Calibration refers to the initial (base) values used to find the sensitivity of the constant C to changes in  $P_{\rm bar}, \Delta P_1, \ \Delta P_2, \ \delta P_1$  and  $\delta P_2$ Test refers to the initial values used to find the sensitivity of [H<sub>2</sub>O] to changes in the various  $\Delta P$  and C.

Variable	Percent c	hange in	given	parameters
	+10	+5	+1	-5
$\Delta P_1$	8.2	4.1	0.87	-4.7
$\Delta P_2$	-8.8	-4.4	-0.86	+4.4
$\delta P_1$ $\delta P_2$	0 0.1	0	0 0	0
[CO <sub>2</sub> ] [O <sub>2</sub> ]	-0.17 0.13 -8.84	-0.09 0.06 -4.42	0 0 -0.89	0.09 -0.06 +4.4

Table 15. Variation in  $[H_2O]$  with changes in the parameters of interest (LFWM)

Base value of  $[H_2O]$  is 18.4 mole %. Sensitivity is expressed as a percentage of the base value.

Table 16. Initial values used for sensitivity analysis of DFWM.

Parameter	Value
$P$ $T$ $CO_{2}$ $O_{2}$ $CO$ $\Delta P_{1}$ $\Delta P_{2}$ $\delta P_{1}$	94.9 kPa 299 K 10 mole% 11 mole% 0 mole% 0.51 kPa 0.98 kPa 0.10 kPa
δP <sub>2</sub>	0.35 kPa

Base case is  $[H_2O] = 4.5 \text{ mole}\%$ 

Appendix A. Sensitivity analysis of LFWM and DFWM

Table 17. Percent variation in  $[H_2O]$  due to errors in various parameters (for DFWM)

	+10%	+5%	+1%	-5%
c	+9.5	+5	+1.1	-5.6
С	-10.8	-5.3	-1.1	+5.3
$\Delta P_1$	+5.1	+2.6	+0.55	-2.9
$\Delta P_2$	-5.2	-2.6	-0.53	-2.7
$\delta P_1$	-0.01	0	0	0
$\delta P_2$	+0.02	0	0	0
02	+0.01	0	0	0
CO2	0	0	0	0

Variation in  $[H_2O]$  is expressed as a percent of the base case.

APPENDIX B. PROGRAM LISTINGS FOR THE LFWM AND DFWM.

PROGRAM USED BY THE LFWM

```
INTEGER CTR
      DIMENSION S(10),X(10),Z(10),P(40),PHI(8,8)
      CTR=0
С
CS(1) ETC ARE THE VISCOSITIES OF CO2,02,N2,CO RESPECTIVELY IN KG/M-SE
С
      S(1)=17.205E-06
      S(2)=23.160E-06
      S(3)=20.0E-06
      S(4)=20.1E-06
      S(5)=11.3E-06
C
CTHE VALUES OF PHI READ IN ARE USED IN CALCULATING THE VISCOSITY OF TH
C MIXTURE LATER.
C
      READ(5,*)((PHI(I,J),J=1,5),I=1,5)
      READ(4,*) P0,P1,P2,CP1,CP2
С
      C=P1/P2*(P0-CP1)/(P0-CP2)
C THE CONCS OF CO2,02,N2,CO,THE AMBIENT PRESSURE PO, AND THE CONSTANT
CFOR ALL THE DATA SETS ARE READ IN. (ONE COMMON VALUE FOR ALL DATA SETS
      WRITE (6,200)C
С
C READ THE DATA
С
   10 READ (9,*,END=100) P1,P2,CP1,CP2
      READ (7,*) (X(I),I=1,4)
С
C CONVERT MOLE PERCENT TO MOLE FRACTIONS.
C
С
С
  INITIALIZE Y
C
      X(5)=3.00
C
C
С
С
C CALCULATE THE HOLAR DENSITIES R1 & R2 OF THE MIXTURE.
С
      R2=(P0-CP2)/2851.82*0.2483
      R1=(P0-CP1)/2851.82*0.2483
С
C THE NEXT SECTION CALCULATES THE VISCOSITY OF THE MIXTURE.
C (REF: TRANSPORT PHENOMENA BY BIRD, STEWART AND LIGHTFOOT. )
C
С
C THE FIRST SUBSECTION CALCULATES THE VISCOSITY OF THE MIXTURE IN
C RESISTANCE 2 (THE DRY MIXTURE)
C
          SUR12=0.0
          DO 30 I=1,4
          T=X(I)*S(I)
          SUM1=0.0
            DO 20 J=1,4
```

```
T2=X(J)*PHI(I,J)
             SUH1=SUH1+T2
   20
             CONTINUE
           T3=T/SUH1
           SUM2=SUM2+T3
   30
           CONTINUE
           VIS2=SUH2
      N=0
С
      DO 80 L=1,1000
С
C INITIALIZE THE VALUES OF SUM2, SUM3, T, T2, T3 WHERE
С
              SUM2 = VISCOSITY IN RESISTANCE 2
C
              SUM3 = VISCOSITY IN RESISTANCE 1
Ċ
              T,T2,T3 ARE TEMPORARY LOCATIONS FOR STORING INTERMEDIATE
С
              CALCULATIONS.
č
      SUM3=0.0
      T=0.0
      T2=0.0
      T3=0.0
С
   THIS SUBSECTION CALCULATES THE VISCOSITY IN THE HET SAMPLE.
С
С
   Z(I) = MOLE FRACTIONS ON HET BASIS.
Ċ
           DO 35 J=1,4
           Z(J)=X(J)*(1-X(5)/100.)
   35
           CONTINUE
           Z(5)=X(5)
            DO 60 I=1,5
            T=Z(1)*S(1)
      SUM1=0.0
              DO 45 J=1,5
              T2=Z(J)*PHI(I,J)
              SUM1=SUM1+T2
   45
              CONTINUE
            T3=T/SUM1
            SUN3=SUM3+T3
   60
           CONTINUE
            VIS1=SUM3
С
CHE CALCULATE THE VALUE OF Y1 AND COMPARE WITH Y. IF THE DIFFERENCE I
C LESS THAN 1% THIS VALUE OF Y IS CORRECT; ELSE INCREMENT Y AND REPEAT
      Y=X(5)
      VIS1=(-0.06408706*Y+20.33540508)*1E-06
.
      Y1=(1-(F2/F1 ++(R2/R1 ++C#VIS1/VIS2 ++100
      N=N+1
       V=ABS(Y1-X(5))*10
      IFIV.LE.1 GO TO 70
С
      X(5)=Y1
       V=(Y1-X(5))*10
      IF(V.GT.2) V=2.
      IF (V.LT.-2) V=-2.
```

X(5)=X(5)+V/10

```
С
      IF (P1.LE.3) THEN
      CD1=0.00436590*P1+0.5475158
      ELSE
      CD1=0.5617
      ENDIF
      CD2=0.5323
      P1=P1*2/5
      P2=P2+2/5
C
С
     Input constants
С
      A2=6.6064E-07
      A1=8.8322E-07
С
С
      Initialize Y to start calculations
C
      Y=0.03
С
C
      Calculate the concentration of N2
C
      X(4)=1-(X(1)+X(2)+X(3))
С
C
      Calculate the molecular weight of the dry mixture
С
      M2=32.0*X(1)+28.0*X(2)+44.0*X(3)+28.0*X(4)
С
С
      Find the water concentration and the molecular weight of the wat
C
      mixture, by trial and error
С
          DO 80 I=1,5000
          M1=(1-Y)*(M2+Y/(1-Y)*18.0)
          H2O=(1-CD2/CD1*A2/A1*SQRT(P2/P1*(PBAR-DELP2)/(PBAR-DELP1)
     1
              #M1/M2))
С
С
      Compare the difference between the assumed and calculated values
С
          V=(H20-Y)+1000
          V= ABS(V)
          IF (V.LE.1)GO TO 70
          Y=Y+0.0001
С
          Y=H20
   80
          CONTINUE
С
С
      Convert concentration to mole percent and print
С
   70 H20=H20×100.0
      WRITE(6,90) TIME,H20
   90 FORMAT (F6.1,3X,F5.2)
      GO TO 10
  100 CONTINUE
      STOP
      END
```

```
C
С
   This program calculates the water concentration from the data
С
   generated by the DIFFERENTIAL FLOW WATER METER .
С
C
С
      The first READ statement gets the barometric pressure, and the
      values for deltaP1, deltaP2 for the test.
С
С
      The second READ statement inputs the data from the test, one
С
      line for each set.
С
      The following variables have been declared :
С
С
          PBAR : barometric pressure
          Pl :pressure drop across the first nozzle
P2 :pressure drop across the second nozzle
С
С
C
          DELP1 : drop in pressure at inlet to nozzle 1 from pbar
C
          DELP2 : drop in pressure at inlet to nozzle 2
C
          X(1),X(2),X(3),X(4) are respectively the concentrations of
C
C
                02,C0,C02,N2
          H2O :The concentration of water
C
C
          Al,A2 are respectively the areas of the two nozzles (larger)
          CD1, CD2 are the discharge coefficients respectively
C
          M1 is the molecular weight of the wet mixture
С
          M2 is the molecular weight of the dry mixture
С
С
С
       The units of the different variables read in are :
С
          PBAR : inches of water
С
          P1 :volts
С
          P2 :volts
С
          DELP1, DELP2 : inches of water
          X(1) etc : mole percent
С
C
C
     REAL P1,P2,DELP1,DELP2,PBAR,H20,CD1,CD2,X(6),M1,M2,Y
        ,TIME
    $
С
     READ(5,*)PBAR, DELP1, DELP2
 10 READ(5,*,END=100)CNT,X(1),X(2),X(3),P1,P2
C Convert counter to time in minutes
С
     TIME = CNT * 0.5
С
С
   Convert to mole fractions
C
     DO 12 I=1,4
     X(I)=X(I)/100.0
 12 CONTINUE
C
C
   Convert volts to pressure
```

```
80 CONTINUE

70 WRITE(6,90)Y1

90 FORMAT(1F8.4)

CTR =CTR+1

GO TO 10

100 CONTINUE

200 FORMAT ('WATER CONCENTRATION IN % ',//)

WRITE (6,240)

240 FORMAT ('THE CORRECT OUTPUT IS ',//)

DO 220 I=1,CTR

READ (8,*,END=250) W

WRITE (6,230) W

230 FORMAT (1X,F6.2)

220 CONTINUE

250 STOP

END
```

### TEST#1 DATA

Count	0 <sub>2</sub>	ср	co <sub>2</sub>	ΔP <sub>1</sub>	ΔP2
	mole 7	% mole %	mole %	mole %	mole%
1	12.575	.0408405	6.63757	2.482	3.961
3	1.725	4.93812	18.2233	3.145	3.985
4	1.325	6.68416	18.6094	3.072	3.978
5	. 75	7.5095 <del>9</del> 7.98752	18.8588	3.195 2.992	5.777
7	. 975	7.67595	18.5386	3.166	3.973
8	1.3	7.11429	18.1885	3.148	3.995
7 10	1.25	0.0/530 6.52412	17.573	3.102	3.98
11	1.225	5.90618	17.6405	3.067	3.986
12	1.675	6.05238	16.813	3.006	3.996
15	2.1	5.3/471 4.66809	16.7483	2.929	3.983
15	2.3	4.34671	16.3961	2.829	3.919
16	2.6	4.72694	15.8442	2.789	3.912
17	2.85 3.15	9.12275 3.66172	15.5581	2./19 2.688	3.904
19	3.325	3.28732	15.4673	2.805	4.095
20	3.875	3.40461	14.6402	2.56	3.804
21	4.45	3.00835	14.4106	Z.595 2.541	3.924
23	5.1	2.47079	13.7665	2.53	3.903
24	5.65	2.41327	13.0922	2.488	3.894
25	5.825	2.3399	13.1717	Z.63 2 510	4.095
27	6.45	2.15006	12.4687	2.484	3.935
28	6.675	2.05145	12.3923	2.466	3.93
29	7.075	1.88228	12.0157	2.449	3.933
30	7.525	1.86778	11.5746	2.416	3.901
32	7.875	1.73567	11.2158	2.423	3.9
33	8.125	1.64023	11.0509	2.406	3.905
35	8.675	1.50705	10.4982	2.345	3.881
36	8.975	1.43295	10.2287	2.33	3.866
37	9.4	1.3467	9.78944	2.314	3.874
38 39	9.55	1.31052	7.83770	2.299	3.845
40	9.925	1.23952	9.3408	2.274	3.835
41	10.125	1.19317	9.06928	2.261	3.825
42	10.4	1.17517	8.84311	2.357	4.026
44	10.575	1.16269	8.62014	2.266	3.873
<b>45</b>	10.9	1.13629	8.34084	2.35	4.03
47	11.125	1.00085	8.06641	2.271	3.911
48	11.375	1.00085	7.96956	2.267	3.908
49 50	13.2	. 745949	5.64193	2.175	3.908
51	11.65	. 3177/3	7.64466	2.327	3.984
52	11.8	.885577	7.51281	2.284	3.961
53	11.975	.861766	7.45664	2.305	3.986
	76.73	.0314/4	7.47740	6.699	3.725
Baron	netric	Pressure was	379.5	in. $H_2^0$	•

TIME (minutes) = count/2.

 $\Delta P$  is in volts, 1 volt = 0.63 kPa.

 ${}^{\mathrm{SP}}{}_1$ ,  ${}^{\mathrm{SP}}{}_2$  remains constant for entire test.

 $\delta P_1$ ,  $\delta P_2$  are 0.7 and 2.0 in.  $H_2^0$ , respectively.

# TEST#1 DATA (Continued)

Count	02	CO	co <sub>2</sub>	$^{\Delta P}$ 1	<sup>∆</sup> Р2
	mole %	mole %	mole %	mole %	mole %
55	12.3	.821456	7.16046	2.277	3.963
56	12.45	.771954	6.96005	2.275	3.962
57	12.725	.758917	6.79797	2.263	3.955
58	12.975	.76217	6.53155	2.251	3.946
59	13.05	. 733048	6.37386	2.238	3.93
60	13.025	.73949	6.49637	2.262	3.942
61	13.1	.720215	6.40877	2.257	3.943
62	13.25	./10654	6.33704	2.25/	3.949
63 44	13.365	./1/01/	<b>0.10327</b>	2.240	3.73
65	13.575	707449	6.01204	2 237	3.947
66	13.625	. 68527	5.89333	2.232	3.946
67	13.75	.691586	5.84272	2.233	3.932
68	13.875	.688426	5.742	2.233	3.94
69	13.95	. 68527	5.62532	2.216	3.922
70	14.125	.697919	5.4766	2.22	3.934
71	14.175	.691586	5.36192	2.218	3.931
72	14.25	.682118	5.36192	2.208	3.93
73	14.375	.688426	5.23191	2.21	3.933
74	14.625	.710634	4.92753	2.2	3.922
75	14.8	.73949	4.81692	2.201	3.919
76	14.725	.742717	4./8540	2.191	3.907
70	14.725	./33040	4.00002 E 16772	2.202	3.700
70 79	14.43	.0/2000	5.10/3C	2 201	3.761
7 7 80	15 025	. 710634	4.62918	2.198	3.918
81	15.45	. 752424	4.15493	2.168	3,915
82	15.65	. 794933	3.96055	2.156	3.911
83	15.75	.80816	3.84223	2.16	3.897
84	15.775	. 794933	3.7395	2.147	3.896
85	15.9	.811477	3.72489	2.163	3.896
86	15.95	.794933	3.62301	2.144	3.883
87	16.05	. 785059	3.56512	2.143	3.891
88	16.075	.811477	3.52186	2.137	3.883
89	16.075	.788346	3.42146	2.136	3.883
90	16.175	.791638	3.40717	2.163	3.953
91	17.525	.425571	1.92587	2.11	5.754
76	14.73	.0/306/	4.2/300 5 70227	2.249	3.720 Z 928
73 94	12.275	1 36293	7.08728	2.492	3.963
95	11.875	1.47917	7.51281	2.545	3.97
96	11.375	1.55643	7.91173	2.625	3.969
97	10.925	1.6944	8.60002	2.7	3.99
<b>98</b>	10.375	1.72185	9.11075	2.755	3.992
<b>99</b>	10.425	1.83422	9.23581	2.806	4.002
100	9.9	1.97071	9.63848	2.874	4.024
101	9.15	2.1448	10.2065	2.974	4.009
102	7.4	Z.17652	10.5209	3.022	<b>4.03Z</b>
103	9.775	Z.U7196	10.0296	Z.981	4.04/
104	7.143	6.1723	10.5207	3.U4 7 079	7.JJ 6 047
105	G.83 A 175	6.1/161 9 18874	10.7346	3.030	4.047
107	7.113	2 1184	10.3854	3.025	4.046
108	9.763	2.1100	10.0957	3.045	4.059
109	9.65	2.07711	10,1399	3.019	4.043
Count	02	CO	co <sub>2</sub>	$\Delta P_1$	$\Delta P_2$
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	mole %	mole %	mole %	mole %	mole %
110 111	9.45 9.575	1.98069 1.9558	10.453 10.251	3.039 3.005	4.052 4.04
112	9.675 9.7	2.01082	10.1621	3.002	4.049
114	9.775	2.01082	10.0957	2.965	4
115	9.775	2.05657	10.1399	2.973	4.005
110	7.7 9.675	Z.026 1.96573	9.87814 10.0736	2.915	3.986
118	9	1.99572	10.8415	2.977	3.969
119	9.275	2.12382	10.7262	2.981	3.974
120	7.35 9.225	2.1448	10.604	3.016	3.97
122	9.2	2.22469	10.8878	3.022	3.97
123	9.15	2.16591	10.8415	3.016	3.981
124	9.45	2.15554	10.7033	3.027	3.978
126	9.425	2.10298	10.453	3.004	3.986
127	9.375	2.05145	10.5436	3.005	3.977
128	9.1	2.07196	10.7722	Z.998 3.012	3.975
130	8.525	2.08227	11.1921	3.046	3.988
131	8.45	2.10817	11.5263	3.051	3.978
132	8.3	2.13954	11.5504	3.05	3.988
134	8.05	2.11338	11.7692	3.068	4
135	8.175	2.07196	11.6959	3.051	4.003
136	7.925	2.12382	12.0157	3.065	4.011
138	8 7.9	2.07/11 2.08763	12.0903	3.104	4.008
139	7.775	2.07196	12.1403	3.089	3.998
140	7.525	2.0926	12.3416	3.089	4.005
141	7.4	2.1186	12.4178	2.986	3.869
142	7.225	2.13429	12.0402	3.033	3.926
144	6.625	2.27358	13.1187	3.08	3.946
145	6.275	2.25721	13.5208	3.108	3.936
146	6.5	2.17121	13.4666	3.096	3.947 7 957
148	6.85	2.08743	13.013	3.031	3.953
149	6.625	2.16591	13.1983	3.048	3.956
150	6.15	2.35109	13.7941	3.126	3.957
151	6.325	2.30106	13.6842	3.082	3.952
153	6.7	2.1186	13.1717	3.074	3.944
154	6.925	2.04634	13.0922	3.047	3.953
155	7.15	1.9907	12.8036	3.038	3.957 z gz7
157	7.5	1.92127	12.4687	3.008	3.951
158	7.7	1.92618	12.1403	2.972	3.933
159	7.8	1.91148	12.1653	2.982	3.946
160	7.9 8 15	1.90172	11.9661 11.94 <i>9</i> 7	2.9/2	5.753 3.921
162	8.275	1.84856	11.623	2.934	3.929
163	8.5	1.87744	11.3822	2.913	3.919
164	8.825	1.84856	11.1449	2.914	3.937

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Count	0 <sub>2</sub>	СО	co <sub>2</sub>	$^{\Delta P}$ 1	ΔP <sub>2</sub>
	mole %	mole %	mole %	mole %	mole %
165	8.875	1.84377	10.9808	2.88	3.918
167	9.175	1.82945	10.711	2.871	3.967
168	9.125	1.80574	10.7722	2.876	3.92
169	9.15	1.8247	10.7492	2.872	3.913
170	9.175	1.7963	10.6346	2.833	3.907
171	9.325	1.7916	10.6118	2.871	3.923
178	7.35	1.62793	10.507	2.85	3.911
174	9.45	1.80102	10.4304	2.823	3.898
175	9.4	1.77284	10.2957	2.804	3.894
176	9.325	1.76817	10.5663	2.832	3.91
177	9.275	1.75885	10.5663	2.842	3.91
179	9.225	1./542	10.0118	2.839	5.915
180	9.25	1.72645	10.5436	2.828	3.902
181	9.375	1.73567	10.4756	2.803	3.911
182	9.5	1.71726	10.2733	2.782	3.905
183	9.725	1.74956	10.0296	2.771	3.903
184	9.9	1.75885	9.94183	2.765	3.911
185	10 225	1.73567	7./US 9./3868	2./4 2 822	3.872 7 991
187	10.225	1.71267	9.48894	2.756	3.918
188	10.375	1.7542	9.46769	2.736	3.903
189	10.4	1.74029	9.40412	2.756	3.924
190	10.45	1.70809	9.31974	2.78	3.929
191	10.35	1.72645	9.40412	2.753	3.916
192	10.373	1.77284	9.51022	2.736	3.913
194	10.35	1.6944	9.38298	2.71	3.905
195	10.3	1.71726	9.40412	2.71	3.897
196	10.325	1.71726	9.40412	2.745	3.917
197	10.25	1.6853	9.38298	2.716	3.918
178	10.3	1.72185	7.33133	2./30	3.700
200	10.125	1.6853	9.57422	2.73	3.92
201	10.2	1.71267	9.48894	2.726	3.915
202	10.225	1.68076	9.42528	2.704	3.919
203	10.275	1.73567	9.48894	2.714	3.913
204	10.3	1.6744	7.4041Z	2.708	3.907 7 417
205	10.375	1.68985	9.29872	2.71	3.929
207	10.475	1.66268	9.17316	2.691	3.903
208	10.475	1.68985	9.27772	2.722	3.93
209	10.475	1.6944	9.29872	2.713	3.915
210	10.5	1.6944	9.27772	2.669	3.899
212	10.55	1.8/843	7.20670	6.073 2.677	3.904
213	10.275	1.6944	9.55286	2.685	3.901
214	10.2	1.71726	9.57422	2.733	3.917
215	10.25	1.70352	9.55286	2.711	3.925
216	10.45	1.72185	9.36187	2.691	3.919
217	10.25	1.64919	9.48894	Z.701	5.918 1 477
218	10.5	1.00/19	7.470/2	2.642	3.733
647	au . 7/3	~ ~ 쓰러 소리			

Count	0 <sub>2</sub>	CO	со <sub>2</sub>	$\Delta P_1$	<sup>∆₽</sup> 2
	mole %	mole %	mole %	mole %	mole %
220 221 222	10.1 9.875 9.85	1.74029 1.7963 1.7822	9.59561 9.87634 9.94183	2.681 2.689 2.738	3.907 3.923 3.938
223	9.6	1.8152	10.2287	2.708	3.918
224	7.1/5 9.2	1.80102	10.3629	2.718 2.745	3.92 3.92
226	9.225	1.83899	10.5209	2.741	3.943
227	9	1.84856	10.5663	2.743	3.926
228	8.825	1.83422	10.8189	2.782	3.939
230	8.425	1.87261	11.3583	2.758	3.943
231	8.125	1.89685	11.4781	2.777	3.946
232	7.9 7.825	1.93602	11.7937	2.801	3.949
234	7.675	1.94589	12.0405	2.801	3.947
235	7.625	1.91148	12.2155	2.829	3.969
236	7.325	1.94589	12.2658	2.822	3.952
238	7.175	1.9558	12.4942	2.844	3.75/
239	7.125	1.96076	12.6482	2.851	3.982
240	7	2.00075	12.7516	2.845	3.98
291 262	6.7	1.95069	12.8270	Z.861 2 872	3.97 3.975
243	6.8	2.01587	13.0394	2.87	3.987
244	6.55	2.10817	13.0922	2.861	3.975
245	6.525	2.16062	13.225	2.902	3.996
246 247	5.4/5	2.35667	13.6842	2.912	3.994
248	5.6	2.85665	13.6296	2.936	3.987
249	5.425	2.95489	13.8769	2.938	3.975
250	5.1	3.08311	14.2686	2.962	3.98
252	3.025 4.875	3.20862	14.4677	2.975	3.984
253	5	3.20862	14.5825	3.004	3.995
254	4.925	3.15933	14.4106	3.007	4.018
255	4.7	3.13144	14.9901	2.955	3.942
257	4.3	3.22201	15.3668	2.98	3.951
258	4.15	3.15933	15.4673	2.988	3.965
259	3.65	3.2729	15.8333	2.985	3.958
260	3.825	3.36024	15.6189	2.976	3.959
262	3.85	3.2727	15.6799	3.016	3.972
263	3.775	3.15933	15.7411	3.023	3.985
264	3.8	3.15933	15.6799	2.988	3.969
265	3.8	3.1245	15.6499	3.004	3.9/2 3 981
267	4.15	2.89564	15.6189	2.969	3.969
268	4.025	2.91529	15.6799	2.991	3.982
269	4.2	2.83089	15.3769	2.968	3.978
270	4.15 4.17F	Z.84375 2 71712	15.5581	2.95 2.961	5.975 3.068
272	4.3	2,73584	15.257	2.94	3.974
273	4.25	2.59481	15.257	2.927	3.976
274	4.425	2.4766	15.3769	2.945	3.976

Count	02	CO	co <sub>2</sub>	$\Delta P_1$	<sup>∆</sup> ₽2
	mole %	mole %	mole %	mole %	mole %
275	4.475	2.50578	15.3468	2.918	3.977
279	4.6/3	2.27004	15.1474	2.070	3.7/7 3 968
278	4.85	2.29554	14.7852	2.877	3.966
279	4.975	2.28455	14.8727	2.911	3.967
280	5	2.24633	14.7852	2.874	3.966
281	5.1	2.21931	14.5825	2.878	3.967
282	5.25	2.21931	14.5825	Z.849	3.966
283	5.4	2.65921	14.3253	2.01/ 2.823	3.745
285	5.175	2.54112	14.3537	2.814	3.946
286	5.275	2.45343	14.2686	2.851	3.962
287	5.4	2.55298	14.1839	2.832	3.951
288	5.325	2.47079	14.0437	2.802	3.938
287	5.425	2.51104	14.077/	2.821 2 798	3.753 7 974
291	5.65	2.43616	13.8216	2.822	3.958
292	6	2.37921	13.6569	2.804	3.947
293	5.975	2.39619	13.4937	2.789	3.934
294	6.25	2.34549	13.2784	2.769	3.938
295	6.475	2.36231	13.1187	2.756	3.935
296	0.05 4 775	2.30100	12.8270	2.75	3.717
298	6.925	2.26811	12.7257	2.755	3.917
299	6.9	2.24633	12.6224	2.7	3.914
300	7.1	2.20856	12.5198	2.704	3.918
301	7.2	2.21931	12.1653	2.678	3.914
302	7.1	2.19785	12.3163	2.693	3.917
303 704	7.525	2.20050	12.2000	2./15	3.71/
305	7.6	2.12382	11.892	2.673	3.913
306	7.675	2.08743	11.9413	2.656	3.916
307	7.725	2.07711	11.892	2.645	3.905
308	7.875	2.026	11.6959	2.666	3.912
309	7.8	2.01082	11.6473	Z.644	3.91
211	7.8/3	1.775/6	11.6737	2.677	3.740
312	8	1,98569	11.6716	2.628	3,905
313	8.05	1.88228	11.3583	2.619	3.905
314	8.225	1.91637	11.2394	2.621	3.899
315	8.275	1.81994	11.2631	2.569	3.882
316	8.1	1.94095	11.4301	Z.601	3.905
51/ 718	8.US 8.275	1.07005	11.1685	2.566	3.074
319	8.3	1.83899	11.2394	2.58	3.899
320	8.025	1.94589	11.4062	2.553	3.888
321	8.075	1.90659	11.4062	2.581	3.885
322	7.725	2.00075	11.7447	Z.607	3.902
323	7.875	1.87178	11 5744	2.357 7 Egg	2.070
264 325	1.7 7.925	1.00440	11.4062	2,589	3,906
326	7.9	1.83422	11.2869	2.578	3.901
327	8.05	1.84856	11.4541	2.593	3.907
328	8.1	1.7822	11.3107	2.543	3.899
329	7.9	1.83899	11.3345	2.55	3.907

Count	0,	CO	CO2	∆P <sub>1</sub>	$\Delta P_2$
	mole %	mole %	mole %	mole %	mole %
) 330 331	8.1 8.475	1.7869 1.76817	11.3583	2.561	<b>3.902</b>
332	8.275	1.69896	11.1449	2.546	3.899
333	8.4	1.68985	11.0979	2.537	3.891
335	8.4	1.6313	10.9808	Z.531 2.531	3.892
336	8.75	1.65818	10.8415	2.518	3.898
337	8.9	1.58703	10.6118	2.503	3.896
538 339	8.875	1.60966	10.5436	Z.588 2 545	3.989
340	8.85	1.58703	10.7262	2.577	3.976
341	8.875	1.59142	10.7033	2.558	3.98
342 363	8.875	1.57387	10.5663	<b>2.543</b>	3.966
344	8.775	1.49616	10.6804	2.557	3.987
345	8.825	1.57387	10.7033	2.568	3.981
346	8.625	1.58703	10.8646	2.569	3.981
348	0.32 8.325	1.55208	11.2869	2.557	3.917
349	7.975	1.54774	11.4541	2.528	3.913
350	7.925	1.54341	11.5746	2.554	3.924
351	7.875	1.50897	11.7692	Z.54 2.549	3.927 3.935
353	7.675	1.60908	11.8673	2.536	3.929
354	5.725	2.13954	13.3857	2.594	3.931
355	6.025	1.91148	13.1187	2.575	3.935
357	6.65	1.85816	12.6482	2.612	3.973
358	6.675	1.88713	12.3416	2.54	3.955
359	6.725	1.97071	12.2407	2.557	3.935
360	6.9 7.05	1.89685	12.3163	2.576	3.942 3.927
362	7.175	1.77752	11,9661	2.545	3.94
363	7.2	1.70352	11.9166	2.557	3.941
364	7.35	1.66719	11.7692	2.528	3.927
505 366	7.5	1.04717	11.7692	2.524	3.935
367	7.525	1.89198	11.623	2.496	3.931
368	7.225	1.91148	11.7937	2.52	3.935
369	7.275	1.86297		2.509 2.535	3.929
370	7.075	1.96573	11.9909	2.526	3.937
372	6.75	1.9907	12.2155	2.549	3.951
373	6.75	1.98569	12.2155	2.511	3.938
374	6.825 6.875	1.92618	12.1033	2.502	2.72 3.934
376	6.775	1.94095	12.1403	2.515	3.94
377	6.925	1.91148	12.0654	2.527	3.934
378	6.95 6.95	1.88713	12.2911	<b>Z.541</b> 2 E24	3.957 z 04.2
3/7 380	9.03 7.025	1.07201	12.1904	2.525	3.946
381	6.85	1.80102	12.1653	2.54	3.945
382	6.7	1.7869	12.4432	2.525	3.942
383	6.875	1.74492	12.4432	Z.541	3.95Z
584	0.075	1.07070	16.3765	6.310	3.740

Count	0 <sub>2</sub>	CO	co <sub>2</sub>	$\Delta P_1$	$\Delta P_2$
	mole %	mole %	mole_%	mole_%	mole %
385 386 387	6.725 6.925 6.9	1.74956 1.73106 1.66719	12.3923 12.2155 12.3416	2.542 2.513 2.53	3.95 3.948 3.948
388	6.95	1.6853	12.3923	2.536	3.955
389	7.1	1.60908	12.0903	2.496	3.941
391	7.275	1.55643	11.892	2.523	3.934
392	7.375	1.54774	11.9413	2.501	3.943
393	7.525	1.47071	11.6959	2.491	3.934
395	7.85	1.3467	11.5263	2.507	3.955
396	7.9	1.32253	11.4062	2.452	3.939
397	8.025	1.31852	11.2394	2.471	3.942
370 399	0.2/3 8.35	1.32253	10.9808	2.437	3.925
400	8.3	1.34266	10.8646	2.428	3.924
401	8.375	1.27875	10.7492	2.422	3.931
40Z 403	8.6 A.75	1.29657	10.6604	2.417	5.929 3.915
404	8.925	1.35075	10.4079	2.392	3.909
405	8.95	1.35887	10.251	2.402	3.908
406	8.975	1.38335	10.0516	2.414	3.921
408	9.075	1.39979	9.98564	2.376	3.91
409	9.175	1.36293	9.91997	2.385	3.913
410	9.25	1.35075	9.98564	2.352	3.9
411 412	9.575	1.35451	7.55155	2.3/2	3.91 3.899
413	9.6	1.38335	9.59561	2.373	3.905
414	9.75	1.40391	9.42528	2.381	3.904
415	9.75	1.47071	9.57422	2.362	3.899
417	7.75	1.46649	9.3408	2.332	3.882
418	9.675	1.42878	9.23581	2.352	3.885
419	9.75	1.49191	9.3408	2.346	3.889
420	9.625	1.47917	9.31974	2.342	3.881
422	7.73 9.5	1.50043	9.53153	2.385	3.954
423	9.925	1.47071	9.17316	2.381	3.961
424	9.875	1.45807	9.11075	2.388	3.954
425	9.875	1.47071	9.15233	2.37 2 398	3.994 7.94
427	9.975	1.45387	9.09	2.388	3.959
428	10.075	1.4413	8.98666	2.385	3.955
429	9.85	1.47071	9.19402	2.373	3.963
431	9.8	1.46228	9.19402	2.379	3.97
432	9.7	1.50043	9.2149	2.37	3.958
433	9.5	1.35481	9.42528	2.386	3.95
434	9.6	1.31052	7.42528 8 4446	Z.386 2 774	5.965 2 04
436	7.23 9.475	1.330/3	9.57422	2.381	3.964
437	9.4	1.36293	9.51022	2.382	3.96
438	9.25	1.3467	9.65996	2.386	3.962
439	9.4	1.33057	9.51022	2.374	3.964

.

Count	°2	CO	CO2	ΔP	$\Delta P_2$
	mole %	mole %	mole %	mole %	mole %
440	9.65	1.2748	9.19402	2.355	3.974
441	9.575	1.31452	9.3408	2.363	3.96
442	7.73	1.30335	7.U2/71 A AA399	2.334	3.704 3.945
444	10.05	1.42462	8.92498	2.328	3.964
445	9.975	1.48766	8.78198	2.313	3.959
446	10.025	1.48341	8.80233	2.318	3.961
447	10.15	1.49616	8.66044	2.324	3.96
448	10.225	1.47717	8.62014	2.295	3.954 7 864
450	10.4	1.44967	8.26194	2.286	3.959
451	10.575	1.47071	8.26194	2.287	3.949
452	10.475	1.47917	8.34084	2.26	3.915
453	10.5	1.43295	8.22264	2.275	3.942
454	10.525	1.41632	8.24228	2.278	3.951
455	10.5/5	1.42047	8.1638/	2.267	3.74/
457	10.625	1.39979	8.16387	2.271	3.962
458	10.575	1.39567	8.08584	2.261	3.942
459	10.625	1.42878	8.18344	2.272	3.961
460	10.575	1.43712	8.12482	2.263	3.949
461	10.55	1.39979	8.22264	Z.25Z	3.95
402 442	10.2/5	1.42462	8.47703 8.44007	2.20	3.709
464	10.425	1.43712	8.42013	2.252	3.96
465	10.475	1.42047	8.12482	2.245	3.962
466	7.825	1.60466	10.8415	2.329	3.966
467	7.15	1.67623	11.2869	2.373	3.985
468	6.85	1.63576	11.3107	Z.363	3.987
487 470	0.//S 6 775	1.50/05	11.1447	2.401	3.773 4 013
471	6.5	1.62239	11.4541	2.401	4.008
472	6.375	1.64471	11.4301	2.392	4.013
473	6.3	1.70809	11.5504	2.385	4.025
474	6.375	1.6313	11.5263	2.38	4.023
475	6.55	1.5047	11.5263	2.377	<b>9.021</b>
4/8	9.9 4 T	1.47171	11.3700	2.357	4.025
478	6.55	1.6853	11.5022	2.35	4.031
479	6.725	1.72185	11.4301	2.337	4.031
480	6.775	1.69896	11.4062	2.303	4.021
481	6.975	1.72185	11.3583	2.298	4.029
482	7.125	1.67623	11.0744	Z.236	3.934
405	7.375	1.69896	10.9808	2.204	3.928
485	7.4	1.72645	10.8184	2.215	3.919
486	7.6	1.73106	10.7262	2.201	3.92
487	7.675	1.70809	10.6575	2.183	3.919
488	7.95	1.68076	10.4982	2.179	3.92
489	/.775 8 175	1 71947	10.3101	6.1/1 9 1/1	3.721 3.617
470	8.475	1.76351	9,91997	2,168	3.925
492	8.525	1.70352	9.78944	2.158	3.912
493	8.65	1.74029	9.74616	2.157	3.92
494	8.7	1.74956	9.65996	2.138	3.907

Count	0 <sub>2</sub>	CO	co <sub>2</sub>	$^{\Delta P}$ 1	$\Delta P_2$
	mole %	mole %	mole %	mole %	mole %
4 <b>75</b> 494	8.85	1.75885	9.48894 9.53153	2.152	3.91
497	8.975	1.7542	9.29872	2.141	3.904
498	9.15	1.74956	9.2149	2.144	3.904
499	9.15	1.71726	9.15233	2.12	3.905
500	9.275	1.72185	9.11075	2.136	3.903

#### TEST#1 RESULTS

Time	[H <sub>2</sub> , <sup>0</sup> ] <sub>DFWM</sub>	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
0.5 1.0 1.5	11.% 25.05 24.45	9.27 18.69 18.92
2.0	23.40	19.47
3.0	24.63	20.09
3.5	24.91 24.37	19.97 19.66
4.5	23.07	19.78
5.0 5.5	23.81 23.19	19.86 19.69
6.0	22.06	19.47
6.5 7.0	21.72 20.92	19.21 18.86
7.5	19.94	18.70
8.0 8.5	19.28 18.06	18.59 18.33
9.0	17.49	17.95
10.0 10.5	16.18 15.30	17.41 16.81
11.0	14.21	16.37
11.5 12.0	14.19 13.38	16.21 15.80
13.0	13.29	15.33
13.5 14.0	12.72 12.38	15.06 14.82
14.5	11.95	14.46
15.0 15.5	11.82	14.24 14.08
16.0	11.79	13.76
16.5	11.32	13.51
17.5	10.19	13.02
18.0	10.04	12.74
19.0	9.31	12.22
19.5 20.0	9.43 9.07	12.12
20.5	8.88	11.70
21.0 21.5	8.76 8.42	11.70 11.45
22.0	8.30	11.30
22.5 23.0	8.19 8.29	10.99 10.77
23.5	7.87	10.78
29.0 24.5	7. <b>51</b> 5.32	10.51 8.92
25.0	7.97	10.26
25.5 26.0	8.25 7.48	10.25 10.11
26.5	7.66	9.91
27.0	7.11	9.77

Time	[H <sub>2</sub> 0] <sub>DFWM</sub>	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
27.5	7.27	9.59
28.5	7.02	9.17
29.0	6.83	8.94
29.5	6.72 7 18	8.87
30.5	7.03	8.81
31.0	6.94	8.64
31.5	6.64	8.60
32.5	6.42	8.34
33.0	6.30	8.30
33.5	6.55	8.16
34.5	6.22	7.98
35.0	6.15	7.80
35.5	6.14	7.77
36.U 36.5	5.87	7.56
37.0	5.79	7.34
37.5	5.86	7.15
38.0 Ta e	5.76	7.26
39.0	6.26	7.48
39.5	5.86	7.36
40.0 40 E	5.79	6.91
41.0	4.73	6.33
41.5	5.05	6.24
42.0	4.70	6.23
42.5 43.0	5.15	6.06
43.5	4.67	5.93
44.0	4.62	5.91
44.5 45 0	4.57	5.81
45.5	2.78	4.40
46.0	6.94	7.12
46.5	10.19	8.80
47.5	13.51	10.12
48.0	15.20	10.62
48.5	16.45	10.98
47.0	18.33	11.42
50.0	19.30	11.94
50.5	21.21	12.67
51.0 51.5	21.75	12.30
52.0	21.83	12.62
52.5	21.89	12.82
53.0	21.96	12.54
33.3 54.0	61.80 21.80	12.17
54.5	21.56	12.11

Time	[H20] DFWM	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
55.0 55.5	21.79	12.23
54.0	21.21	12.06
56.5	21.05	12.05
57.0	21.17	11.96
57.5	21.25	11.96
58.0	20.88	11.87
59.0	21.44	12.00
59.5	21.76	12.38
60.0	22.31	12.31
60.5	22.36	12.47
61.0	22.49	12.44
61.5	22.26	12.50
42.5	22.31	12.26
63.0	21.99	12.28
63.5	22.12	12.30
64.0	22.03	12.56
64.5	22.22	12.65
65.U 45 5	22.0/ 22 88	13.10
66.0	22.74	13.26
66.5	22.95	13.34
67.0	22.90	13.48
67.5	22.59	13.35
68.0 (* 5	22.73	13.56
60.3 49.0	22.00	13.54
69.5	23.26	13.68
70.0	23.19	13.91
70.5	23.14	14.03
71.0	23.71	14.17
71.5	23.22 27.75	14.15
72.5	24.31	14.99
73.0	24.00	14.74
73.5	23.41	14.68
74.0	22.89	14.47
74.5	23.13	14.65
/5.0 75 5	24.30	16.90
76.0	23.73	14.89
76.5	23.68	14.60
77.0	23.15	14.36
77.5	22.95	14.18
/8.U 78.5	22.40	13.75
79.0	22.14	13.74
79.5	22.15	13.62
80.0	22.14	13.56
80.5	21.82	13.31
81.0	Z1.54	13.ZZ
51.5 87 0	21.5U 21 De	12.72
	54. U7	****

Time	[H2 <sup>0]</sup> DFWM	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
82.5 83.0	20.73	12.72
83.5	20.75	12.44
84.0	20.63	12.48
84.5	20.65	12.47
as.u 85.5	20.05	12.30
86.0	20.28	12.28
86.5	20.33	12.20
87.0	19.96	12.21
88.0	17.00	12.30
88.5	20.15	12.36
89.0	20.06	12.41
89.5	19.83	12.41
90.0	20.00	12.37
91.0	19.12	12.18
91.5	18.94	11.99
92.0	18.72	11.82
72.5	18.47	11.70
93.5	18.46	11.56
94.0	18.27	11.39
94.5	18.38	11.38
75.U 95.E	18.76	11.59
96.0	17.85	11.42
96.5	18.14	11.53
97.0	17.75	11.44
77.5 98.0	17.85	11.47
<b>98.5</b>	17.69	11.55
99.0	18.25	11.46
99.5	18.05	11.57
100.0	17.99	11.69
101.0	17.45	11.57
101.5	17.72	11.50
102.0	17.68	11.49
102.5	17.65	11.37
103.5	17.40	11.34
104.0	17.66	11.32
104.5	17.67	11.31
105.0	17.05	11.27
106.0	17.12	11.40
106.5	17.32	11.48
107.0	18.04	11.56
107.5	17.51	11.33
108.5	17.41	11.52
109.0	16.73	11.28
109.5	16.68	11.32

Time	[H <sub>2</sub> 0] <sub>DFWM</sub>	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
110.0	17.16	11.68
111.0	17.87	11.88
111.5	17.56	12.09
112.0	17.73	12.54
112.5	10.19 17 AR	12.95
113.5	18.13	12.69
114.0	18.71	12.82
114.5	18.44	13.10
115.0	18.ZZ 18.54	13.13
116.0	18.95	13.61
116.5	19.07	13.54
117.0	18.98	13.80
117.5	19.23	13.80
118.5	19.51	14.12
119.0	19.61	14.23
119.5	19.47	14.24
120.0	19.39	14.36
120.5	19.96	14.43
121.5	19.76	14.51
122.0	19.75	14.78
122.5	20.22	14.78
123.0	20.61	15.77
124.0	20.92	15.78
124.5	21.10	15.92
125.0	21.46	16.18
125.5	Z1.51 21.54	16.26
126.5	21.99	16.23
127.0	21.76	16.34
127.5	21.82	16.42
128.0	21.96	16.5Z
129.0	22.17	16.88
129.5	22.15	17.32
130.0	21.98	17.21
130.5	21.95	17.29
131.0	22.47	17.20
132.0	22.06	17.19
132.5	22.29	17.19
133.0	21.85	17.12
133.5 134 0	21.75 21.44	10.30 16.92
134.5	21.62	16.80
135.0	21.38	16.81
135.5	21.45	16.78
136.0	21.19	16.71
150.5	20.74	10./4 16.51
	la de o la de	

Time	[H20] <sub>DFWM</sub>	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
137.5	20.78	16.47
138.0	20.36	16.30
130.5	20.64	16.37
139.5	20.77	16.03
140.0	20.13	16.02
140.5	20.18	15.96
141.0	19.68	15.80
141.5	19.35	15.64
142.0	17.29	15.99
143.0	19.76	15.90
143.5	19.55	15.80
144.0	19.16	15.90
144.5	19.32	15.79
145.0	19.13	15.61
145.5	17.27	15.01
146.5	18.96	15.34
147.0	18.53	15.09
147.5	18.32	14.90
148.0	18.41	14.77
148.5	17.66	14.63
147.0	10.54	14.47
150.0	17.53	14.35
150.5	17.07	14.33
151.0	17.33	14.40
151.5	17.75	14.17
152.0	16.95	14.00
152.5	10.70	13.75
153.5	16.53	13.80
154.0	16.85	13.68
154.5	16.43	13.78
155.0	16.36	13.68
155.5	16.28	13.45
154.5	15.99	13.55
157.0	16.11	13.40
157.5	15.26	13.32
158.0	15.62	13.49
158.5	15.33	13.57
159.5	15.26	13.30
160.0	14.84	13.58
160.5	15.47	13.52
161.0	15.79	13.83
161.5	19.89	13.67
102.U 142 E	13.37	13.00
163.0	15.19	13.73
163.5	15.43	13.52
164.0	14.48	13.49
164.5	14.52	13.72

Time	[H2 <sup>0]</sup> DFWM	[H20] WHA
minutes	mole %	mole %
165.0 165.5	14.82 14.85	13.4 <b>8</b> 13.11
166.0	14.54	13.33
166.5	14.46	13.20
167.0	14.32	13.02
168.0	13.95	12.87
168.5	13.64	12.75
167.0	14.25	12.80
170.0	14.17	12.77
170.5	13.71	12.75
171.0	13.57	12.79
172.0	13.60	12.86
172.5	13.91	12.81
173.0	13.94	12.99
173.5	13.90	13.22
174.5	13.97	13.55
175.0	14.39	13.58
175.5	14.05	13.57
176.5	13.94	13.79
177.0	15.17	15.60
177.5	14.71	15.31
178.5	14.98	19.33
179.0	13.68	14.81
179.5	14.31	14.79
180.0	14.63	14.57
181.0	13.99	14.34
181.5	14.23	14.32
182.0	13.79	14.18
182.5	13.63	14.15
183.5	13.03	14.07
184.0	13.51	14.36
184.5	13.34	14.31
185.5	13.61	14.48
186.0	13.93	14.78
186.5	13.28	14.77
187.5	13.16	14.61
188.0	13.34	14.76
188.5	13.68	14.61
189.0 180 5	15.65 13.54	14.52 16-64
190.0	13.48	14.47
190.5	13.81	14.65
191.0	13.53	14.74
191.5	15.75	14.54
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Time	[H <sub>2</sub> 0] DFWM	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
192.5	13.79	14.72
193.5	13.56	14.52
194.0	13.60	14.46
194.5	12.90	14.36
195.0	13.50	14.17
173.3	12.10	14.21
196.5	12.88	13.98
197.0	12.10	13.78
197.5	12.95	13.64
198.0	11.93	13.61
175.5	12.51	13.52
199.5	11.14	13.23
200.0	11.57	13.32
200.5	11.33	13.25
201.0	11.24	13.02
201.5	11.22	12.90
202.0	10.75	12.75
203.0	11.27	12.78
203.5	10.61	12.77
204.0	10.53	12.69
204.5	10.70	12.59
205.0	10.09	12.45
205.5	10.44	12.40
206.5	10.52	12.20
207.0	10.72	12.07
207.5	10.34	12.04
208.0	10.33	12.09
208.5	7.89	12.25
209.5	10.09	12.11
210.0	10.10	12.26
210.5	10.45	12.10
211.0	10.12	12.35
211.5	9.92	11.95
212.0	10.18	12.05
213.0	10.36	12.18
213.5	10.12	11.92
214.0	10.10	11.83
214.5	9.70	12.03
215.0	7.47	12.08
216.0	9.70	12.21
216.5	10.20	12.35
217.0	9.95	12.23
217.5	9.77	12.29
218.0	9.88	12.35
218.5	7.70	12.45
219.5	9.71	12.44
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Time	[H <sub>2</sub> 0] <sub>DFWM</sub>	[H <sub>2</sub> 0] <sub>WHA</sub>
minutes	mole %	mole %
220.0 220.5	9.10 9.50	12.23
221.0	8.75	11.95
221.5	8.71	12.14
222.0	8.57	11.87
222.5	8.26	12.01
223.5	8.53	11.84
224.0	7.83	11.76
224.5	8.10	11.71
225.0	7.57	11.66
226.0	7.53	11.55
226.5	7.53	11.55
227.0	7.48	11.51
227.5	7.30	11.47
228.0	7.08	11.37
229.0	7.14	11.49
229.5	7.18	11.41
230.0	7.12	11.49
230.5	6.81	11.48
231.0	6.81	11.73
232.0	6.62	11.58
232.5	6.43	11.60
233.0	8.59	13.90
233.5	9.42	14.53
234.0	9.14	14.85
234.3	7.73	14.98
235.5	9.77	15.19
236.0	9.49	15.33
236.5	9.15	15.39
237.0	9.06	15.30
238.0	7.UL 8.39	15.07
238.5	8.40	15.33
239.0	8.20	15.13
239.5	7.88	14.97
240.0 240 E	7.15	14.71
241.0	6.65	14.62
241.5	6.19	14.53
242.0	5.85	14.37
242.5	6.28	14.39
243.5	3.07 5.41	14.13
244.0	5.28	13.87
244.5	5.04	13.90
245.0	4.88	13.74
245.5	<b>4.90</b>	15.45
240.U 246.E	7.3L 6.44	13.46
247.0	4.32	13.27

Time	[H20] DFWM	[H20] WHA
minutes	mole %	mole %
247.5 248.0 248.5 249.0 249.5 250.0	4.67 4.44 4.45 4.53 3.83 4.32	13.15 13.13 13.06 12.88 12.89 12.76

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