

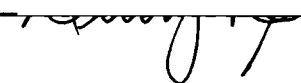
AN ABSTRACT OF THE THESIS OF

Timothy Lee Bauer for the degree of Master of Science in
Mechanical Engineering presented March 29, 1984 .

Title: Investigation of Combustor and Fuel Preparation Requirements
for a Combined-Cycle Wood Fired Power Plant

Redacted for Privacy

Abstract
approved:

 Dwight J. Bushnell

The Pacific Northwest is a particularly good candidate for a power plant fired with wood since the wood products industry is so important in the area. The combined cycle concept for such a plant has increased in popularity due to the generally greater efficiency of the gas turbine part of the cycle. An optional addition to a power plant of this type is a dryer utilizing hot flue-gases to dry the fuel so that less energy would be lost up the stack. The focus of this thesis is an analysis of this dryer option and its effect on the requirements for the combustor and on the overall plant performance.

A base case power plant design was provided by Biomass Energy Corporation for study here at Oregon State University. The components in the cycle were modeled on a computer and linked together with an executive program to simulate the entire plant performance. Among the computer models are programs for the

combustor and dryer performance. These programs simulate the component performance through an energy balance and are not intended to represent one specific size or type of that component. The base-case design incorporates a rotary drum dryer, wood pulverizers, and a suspension burner which requires strict fuel specifications in size and moisture content.

Computer simulations were run to determine the effect of varying the air-fuel ratio and the wood moisture content entering and leaving the dryer. Of particular significance were the results of simulating the plant performance with various amounts of drying. Conflicting conclusions exist in the literature about using a dryer in a wood fired power plant. The results of this analysis however, show that the optimum performance of this power plant occurs when only a moderate amount of drying is done. Performance tends to increase with increasing fuel moisture into the combustor (less drying), however when no drying is done, performance drops, and when only a very small amount of drying is done, problems may occur in the boiler. Also, as expected, performance increases with decreasing fuel moisture as it arrives at the plant location. The effect of increasing the air-fuel ratio into the system while holding the airflow constant is that of increased plant efficiency and decreased power output.

If the choice is made to dry the fuel only a moderate amount, then a different type of combustor from the suspension type must be used. Grate type burners will accept fuel of up to 60% moisture (wet basis) and of large enough particles that pulverizers would not be

required. For optimum performance related to the combustor and fuel preparation arrangement, the best choice seems to be a grate burner with only moderate fuel preparation.

Investigation of Combustor and Fuel Preparation Requirements
for a Combined-Cycle Wood Fired Power Plant

by

Timothy Lee Bauer

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TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
1.1 Description of the Base Case	2
1.2 System Analysis	7
1.3 Thesis Objective	8
2.0 ANALYSIS OF WOOD RESIDUE FUEL	12
2.1 Particle Size	13
2.2 Moisture Content	13
2.3 Ultimate Analysis	16
2.4 Treatment of Dirt	16
2.5 Proximate Analysis	18
2.6 Heating Value	20
3.0 COMBUSTION OF WOOD RESIDUE FUELS	23
3.1 Principles of Combustion	23
3.2 The Equations of Combustion	25
3.3 Concept of the Mole	26
3.4 Excess Air and Air-Fuel Ratio	28
3.5 Combustion Calculations	30
3.6 Energy Balance	34
3.6.1 Combustion Assumptions	35
3.6.2 Stream Calculations	36
3.6.3 Exit Temperature Calculation	49
3.7 Second Law Analysis	51
3.8 The Combustor Program	56
4.0 WOOD DRYING	57
4.1 Principles of Drying Wood	57
4.2 Mass Balance	58
4.3 Energy Balance	58
4.4 Solution Method	63
4.5 Second Law Analysis	63
4.6 The Dryer Program	68
5.0 RESULTS OF SIMULATIONS	69
5.1 System Analysis	70
5.2 Simulations	72
5.3 Summary of System Comparisons	87
5.4 Conclusions	90

REFERENCES	93
------------------	----

APPENDICES

A. Combustor Model Subroutine	96
B. Dryer Model Subroutine	107
C. Sample Overall Simulation	114
D. Gas Properties Function	123

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1.1 Schematic diagram of base-case power plant	3
2.1 Dry basis wood moisture content versus wet basis moisture content	15
3.1 Heat of vaporization and desorption as a function of moisture content	38
5.1 Gross and net power output as a function of "as- burned" moisture content at various air-fuel ratios	74
5.2 Gross and net power output and efficiency as a function of boiler gas exit temperature for system 3	76
5.3 Gross and net efficiency as a function of "as- burned" wood moisture content at various air- fuel ratios	79
5.4 Gross and net power output and efficiency as a function of "as-burned" wood moisture content for system 2 with two pulverizers and an air-fuel ratio of 17	80
5.5 Gross power output as a function of air-fuel ratio	82
5.6 Net power output as a function of air-fuel ratio	83
5.7 Gross plant efficiency as a function of air-fuel ratio	84
5.8 Net plant efficiency as a function of air-fuel ratio	86
5.9 Gross and net power output and efficiency as a function of before drying fuel moisture content for system 2	88

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1.1 Equipment components in base-case design	5
1.2 Approximate states and flow rates for base-case tests	9
2.1 Typical ultimate analysis for moisture free hogged wood and bark fuels	17
2.2 Proximate analysis of wood refuse burned as fuel ...	19
2.3 Typical heating values of wood and bark	21
3.1 Atomic and molecular weights of typical elements and compounds involved in the combustion of hogged fuel	27
3.2 Composition of dry combustion air	28
3.3 Specific heat equations for the gas components	44
3.4 Integrated specific heat equations for the gas components	45

Investigation of Combustor and Fuel Preparation Requirements for a Combined-Cycle Wood Fired Power Plant

1. INTRODUCTION

The last decade has brought about a renewed interest in biomass fuels (particularly wood) due to their availability and also their cost competitiveness with the recent cost inflated fossil fuels. Many efforts have recently been directed toward the acquisition of data in the areas of field testing, pilot plant operation and research activities on ways to utilize biomass fuels effectively. Topics such as gasification, pyrolysis, liquid fuel production, anaerobic digestion and other schemes have been studied for their possibilities for effective energy conversion to a usable fuel. Considerable effort has been spent to design cost effective cogeneration schemes - a process that was routine during the early 1900's. Recently, attention has also been given to the possibility of using biomass fuels to fuel an effective topping cycle.

The topping cycle consists of a high-temperature gas turbine coupled to a generator for the production of electricity with the turbine's high temperature exhaust used for process heat or for use in a waste heat boiler to produce steam for a power generation system. Of particular interest is the method of fueling the gas turbine with biomass fuels. The indirect-fired and the direct-fired approaches have received the most attention with the general consensus being that problems exist when directly firing a gas

turbine with exhaust products from biomass fuels - these being corrosion and erosion of turbine components from the particulate matter in the exhaust gases.

The indirect-fired system offers the advantage of being able to use many types of solid fuels without affecting turbine operation. However, the temperature of the air preheated for the turbine will be limited by the materials in the heat exchanger.

The approach used for indirect firing is to use a conventional metallic heat exchanger and operate the turbine at a derated condition. This type of exchange could be accomplished by diluting combustion gas products such that the temperature is kept below 1600 deg. F.

The overall objective of the study was to perform a thermal analysis of a combined cycle biomass power plant with the primary focus being the generation and use of computer models for each component. The component models were then utilized together such that the overall plant performance could be determined.

1.1 Description of the Base Case

A base case was specified and is shown in figure (1.1). The system consists of two parallel streams which contain fuel preparation equipment, fuel storage capabilities, combustors, heat exchangers and gas turbines. The combustion exhaust streams from each combustor pass through heat exchangers and then are combined prior to entering the waste heat boiler. When the combustion gases

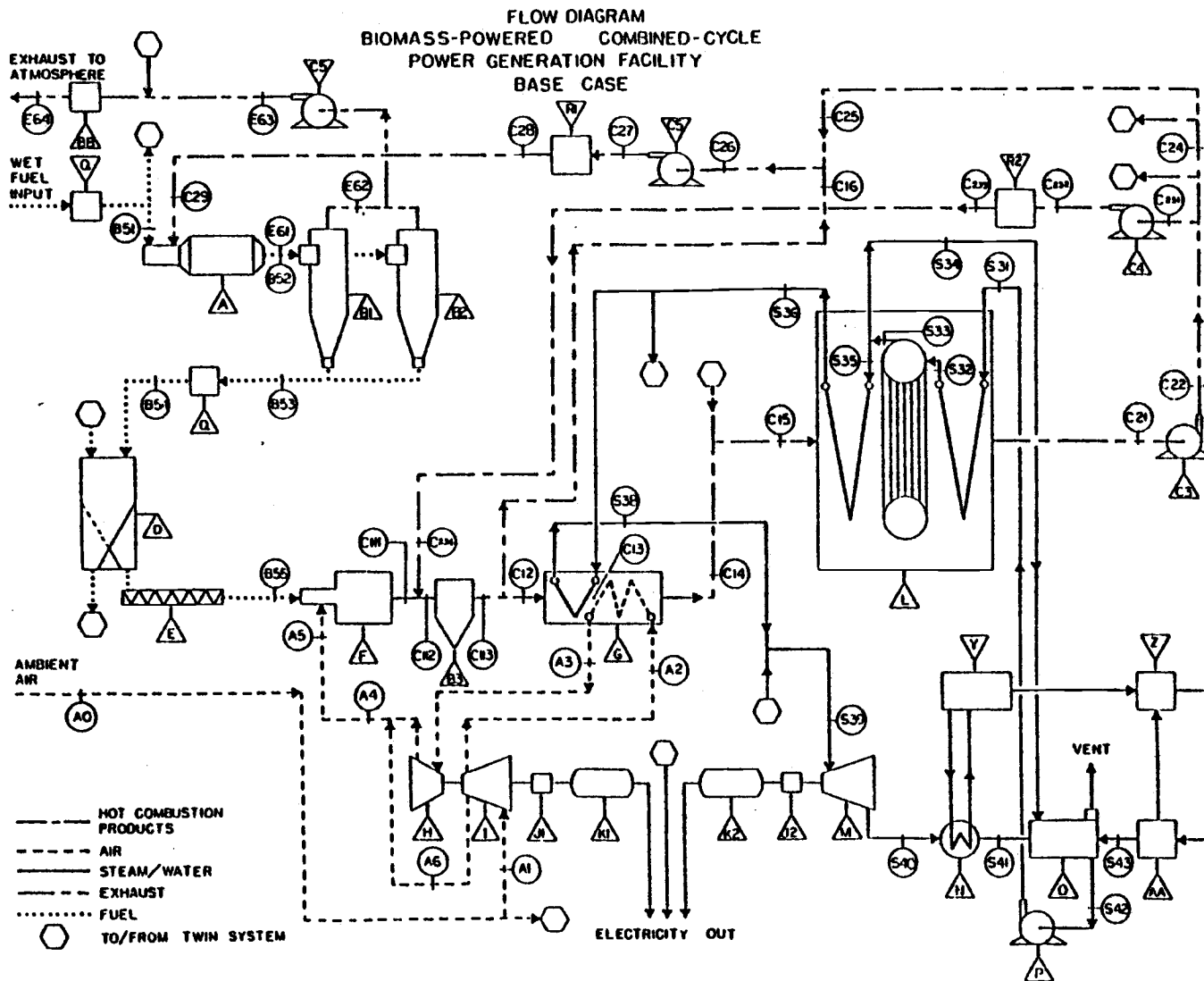


Figure 1.1 Schematic diagram of base case power plant

exit the waste heat boiler they are divided, directed through pollution removal equipment, returned to fuel dryers and then exited to a final clean-up stage prior to venting to the atmosphere.

The base case, as illustrated in figure (1.1), has the major components specified in table (1.1).

A. Air Compressor and Air Turbine

The air compressor and air turbine are both components from a single gas turbine system. The specific system investigated initially was the Solar Centaur GS 4000 unit with the combustion chamber replaced with a heat exchanger and thus operating in the indirect-fired mode as prescribed for the present system. The unit has a nominal compression ratio of 9 to 1. The base case specifies an inlet temperature for the turbine of 1450 deg. F, and at this temperature the power output from the unit with typical inlet and exit pressure losses is about 2090 kW.

The compressor of the gas turbine unit determines the flow rate of air to be used in the system. This flow rate of air varies with the ambient air conditions, and for the standard conditions of 59 deg. F and 14.696 psia the flow rate of dry air is 38.75 lbm per second under the condition of zero inlet ducting loss.

B. Flue Gas-To-Air Heat Exchanger

The flue gas-to-air heat exchanger is to be of the crossflow type with the high pressure air inside tubes and the combustion gases flowing over the outside of the tubes. The design of the heat

TABLE 1.1 EQUIPMENT COMPONENTS IN BASE-CASE DESIGN
(Letters are identified on figure 1.1)

Dryer - A

Cyclones - B1, B2 and B3

Fans - C1, C2, C3, C4 and C5

Storage Bins - D

Screw Feeders - E

Combustor - F

Heat Exchanger (steam/flue gas and air/flue gas) - G

Gas Turbines - H

Compressor - I

Gearboxes - J1 and J2

Generators - K1 and K2

Waste Heat Boiler - L

Steam Turbine - M

Condenser - N

Deaerator - O

Pump - P

Hammer Mill - Q

Air Pollution Control Devices - R

exchanger is crucial in several aspects: (i) the pressure drop both on the air side and the combustion gas side must be kept to a reasonably low value (industry indicates that pressure drops of the order of 5% of the inlet pressure have seemed to be about optimum); (ii) the metal temperature must be kept below the range where the material will very rapidly be destroyed (maximum metal temperature must be less than approximately 1500 deg. F for a reasonable lifetime); (iii) the design must allow for the thermal expansion that will occur in such a high temperature unit. It is particularly critical that the expansion of the tube and the shell be compatible.

The general design concept used for this study was a commercially available unit that consists of bundles of tubes in u-shape that are oriented perpendicular to the flow of the flue gas. The heat exchanger has four sets of u-tube bundles with the first set used as a steam superheater and the remaining three bundles acting as combustor gas to air heaters.

C. Steam System

The steam system would be a conventional intermediate size (50,000 lb/hr) steam system. The heat recovery boiler will deliver steam that is slightly superheated at a pressure of about 640 psia to the superheater that is located in the hot combustion gas stream just behind the combustion unit and ahead of the flue gas-to-air heat exchanger. In the superheater, the steam will be additionally superheated to a temperature of about 850 deg. F, with the exact

temperature being a variable in order to control the air temperature into the air turbine unit closely at its design value.

The steam turbine would be a condensing unit, with the design exit pressure being at 1.5 psia.

D. Air Pollution Equipment

The air pollution control equipment consists of standard cyclones, multicyclones, and baghouses.

E. Remaining Components

The remaining components of the system are the combustor, the dryer, and the fuel preparation equipment. These components make up the focus of this thesis work (particularly the combustor and dryer). The combustor used in the initial study is a suspension burner fired with a substantial amount of excess air. Because this type of burner is used, the fuel must be prepared to quite specific conditions as will be explained later. A hammer hog is used to break the fuel down to 1/2-inch and minus. It then is dried and processed in a second mill to further reduce the material to the desired dimensions required for the combustor. The dryer specified is a triple-pass rotary drum dryer. A 12 foot diameter dryer that is 40 feet long is necessary for drying the fuel for each combustor stream for the base case conditions.

1.2 System Analysis

The base case models consist of the models for the overall

system and the models for the individual components. To determine the power output and the corresponding plant efficiency for a given plant size and specific operating conditions, various state point properties, flow rates and losses need to be specified. State point conditions and flow rates for an initial test are presented in table 1.2. Each component includes a pressure effect term representative of that particular component. For example the combustor is represented by a 16 inch of water drop in pressure and the dryer by a 9 inch drop. The model for the overall system results from the setting up and running of the executive program which couples all of the individual component models together and iteratively evaluates how they will operate together in the system.

1.3 Thesis Objective

The objective of the work done for this thesis is to analyze the effects of parameter changes on the performance of the overall system. Because of the way in which the cycle is designed, changing parameters in one place will affect the entire process. The parameter variations to be studied involve mostly changes in the input to the combustor and dryer models, however the results of these changes will influence the performance of the entire cycle.

Because the flue-gas temperature into the heat exchanger must be limited to under about 1675 deg. F and the air flow rate and temperature are fixed, one area of analysis involves the best way to keep the temperature in the correct range. One possibility is to

TABLE 1.2 APPROXIMATE STATES AND FLOW RATES FOR BASE CASE TESTS

Type	Stream No.	Temperature °F	Pressure psia	Pressure in. H ₂ O gauge	Flow Rate lbm/s	Humidity or Moisture Content*
Air	A0	59	14.696		38.4	0.007
	A1	59		-4	38.4	0.007
	A2	598	132		36.8	0.007
	A3	1450	125		36.8	0.007
	A4	720		28	38.4	0.007
	A5	720		26	38.4	0.007
	A6	598	132		1.5	0.007
Fuel	B51	59			4.49	50%
	B52	190			2.55	12%
	B53				2.55	12%
	B54	59			2.55	12%
	B55	59			2.55	12%
Combustion Gas	C113	1675		10	54.5	0.044
	C12	1675		10	51.4	0.044
	C13	1625		8	51.4	0.044
	C14	1058		4	51.4	0.044
	C15	1058		4	5.4	0.044
	C16	-		-	0	-
	C21	350		-6	102.8	0.044
	C22	350		5.5	102.8	0.044
	C231	350		5		
	C232	350		20	13.7	0.044
	C233 & C234	350		15		
	C24	350		~ 5	75.4	0.044
	C25	350		~ 5	37.7	0.044
	C26	458		~ 5	40.8	0.044
	C27	458		14"	40.8	0.044
	C28	458		9"	40.8	0.044
	C29	458		9"	40.8	0.044
Exhaust Gas	E61	190		~ 0	42.7	0.0453
	E62	190		-2.5	42.7	0.0453
	E63	190		3.2	42.7	0.0453
Steam	S31	118	650		15.4	NA
	S36	701	650		15.4	NA
	S38	852	600		7.7	NA
	S39	852	600		15.4	NA
	S40	(quality = 0.93)	1.5		15.4	NA

*For gas streams, humidity is specified as W, lb_v/lb_{dry air}; for fuel streams, moisture content is specified as % on a wet basis.

simply dilute the combustion process with enough air so that the gas temperature is correct. Another option is to mix cooler flue-gases with the hot ones to reach the right temperature. Another option is to burn higher moisture content wood allowing the water to absorb the necessary amount of energy. The last option mentioned received the most study because of the opportunities presented for system design changes.

The possibilities for design changes include changing the type of combustor and deleting the dryer as well as most of the other fuel preparation equipment; leaving only that preparation equipment necessary for compatibility with the selected combustor.

The present design utilizes a suspension burner which burns fuel as it blows through the unit with a large amount of combustion air. Because of the nature of combustion in these burners the fuel preparation requirements are quite stringent. The fuel moisture content can be no greater than approximately 15% and the size of fuel particles must be 1/8-inch minus with about half of this passing through a 40-mesh screen. This combustor type is one of the primary reasons for the dryer and other fuel preparation equipment. Problems with this system include substantial auxiliary power requirements and fire hazards due to the fine, dry fuel which may require spark detection and fire prevention equipment.

A possible option to this system is to use a grate-type burner such as the Lamb-Cargate "Wet-Cell" burner. This type of combustor burns the fuel in a pile which is on a grate and burns the fuel at a

significantly slower rate than the suspension burner. Because of the slower burning rate, these burners can accept fuel with up to 60% moisture and sizes up to more than three inches with little or no advantage for smaller or dryer fuel. With high air-fuel ratios, some modifications in the combustion air inlets may be required to accomodate the large air flows, however this should not be a major problem. This option opens up many possibilities for altering the fuel preparation system ranging from that of not using any fuel preparation to anywhere up to the present system design. This is the chief area of investigation for this report.

Another possibility is the use of a fluidized bed combustor. These burners offer about the same advantages in fuel preparation range as the grate-type burners do but the applicability to this system is uncertain. Because of the similarity in fuel preparation requirements to the grate burners, the fluidized bed burner is simply considered to be a different option in the same classification as grate burners.

Because the study involves the combustor and dryer models to a great extent, detailed descriptions of these models are provided in the following chapters with sufficient background and explanation of the terms involved.

2. ANALYSIS OF WOOD RESIDUE FUEL

To use wood residue as a fuel in a power plant it must first go through one or several preparation processes so that it can be handled easily and burned properly. In combustion, the most common method of releasing energy and the method used in this analysis, the wood residue must be broken down into relatively small particles. Several other methods of wood energy conversion are also available such as pyrolysis, gasification, and liquefaction. Commonly, wood waste will be "hogged" on site before it is transported anywhere.

Hogged wood residue consists principally of wood and bark particles with varying amounts of soil, rocks, leaves and sometimes paper, glass, etc. mixed in. Moisture content and size of the particles vary considerably. Chemical composition of the wood is fairly consistent for most fuels.

Fuel particle size and makeup determine the type of combustion unit that can be used to burn the fuel. Further preparation of fuel is sometimes done using a pulverizer which besides producing very fine particles, also helps to dry the particles. Finally, many power plants are now incorporating a particle dryer to greatly reduce the moisture content of the fuel. Dry, fine particles are burned most efficiently in a suspension burner or a fluidized bed burner. Coarse, wet particles are burned most efficiently in a grate type burner.

2.1 Particle Size

Hogged fuel particles may range in size from extremely fine sawdust size particles with dimensions as small as 1/100 inch to pieces with lengths of up to six inches and occasionally more. Generally bark particles are more coarse than wood particles because they are softer and do not break up as easily.

Pulverized fuel generally consists of very small particles in the sawdust size range. The major drawback to incorporating pulverizers however, is their high power consumption. The power used also increases greatly with increasing moisture content of the fuel.

2.2 Moisture Content

The amount of water contained in the fuel is a very important characteristic. Higher moisture content means more water must be vaporized and the heat required in doing this is all lost up the stack. If the moisture level is sufficiently high, the fuel will not be able to support combustion at all.

The forest products industry defines moisture content in two different ways. Wet basis moisture content refers to the mass of water in one pound of wet, clean fuel. This is often put on a percentage basis by multiplying by 100. The equation is as follows:

$$XH_{2O_{wet}} = M_{wat} / M_{c wd}$$

where

$XH2O_{wet}$ = fractional wet basis moisture content
 M_{wat} = mass of water in wood sample
 M_{cwf} = mass of wet clean wood in sample

Dry basis moisture content is the ratio of water to dry, clean wood:

$$XH2O_{dry} = M_{wat} / M_{dcf}$$

where

$XH2O_{dry}$ = fractional dry basis moisture content
 M_{dcf} = mass of dry, clean wood in sample

Converting from one basis to the other is done using the following equations:

$$XH2O_{wet} = XH2O_{dry} / (1 + XH2O_{dry})$$

and

$$XH2O_{dry} = XH2O_{wet} / (1 - XH2O_{wet})$$

The relationship between dry basis and wet basis moisture content is illustrated in figure 2.1 for the typical range of wood fuels.

In this report, moisture content will always be referred to on a wet basis.

Hogged fuel moisture content varies widely and is dependent on many factors such as species, log handling, location and season of the year. The range for typical Pacific Northwest hogged fuels is generally between 30% and 65% but may vary considerably beyond this range under adverse conditions (Oswald, Junge 1980). In any given

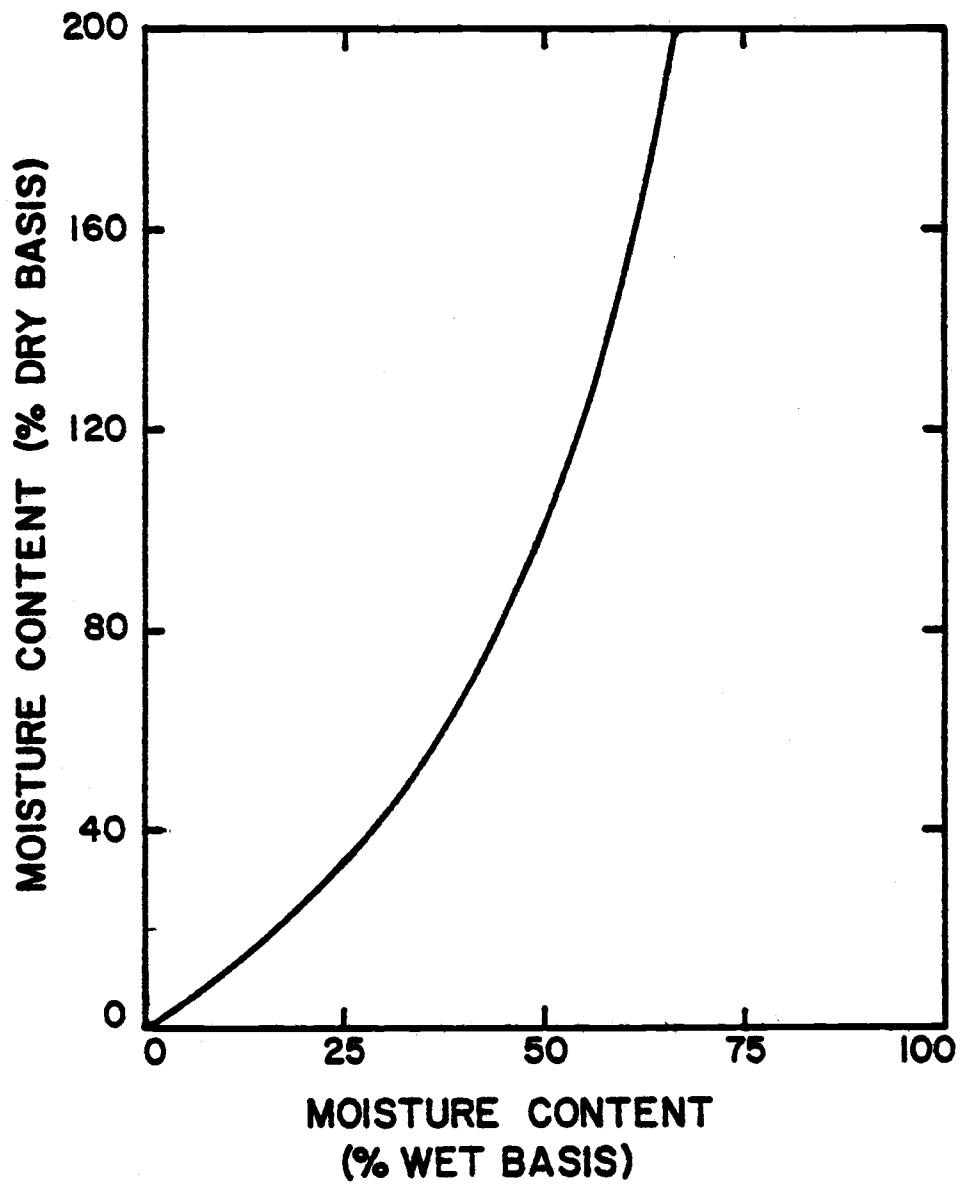


Figure 2.1 Dry basis wood moisture content versus wet basis moisture content (Oswald, Junge 1980)

sample of wood waste, the moisture content may vary considerably depending on size, shape, and type of fuel.

2.3 Ultimate Analysis

The ultimate analysis of a fuel is a breakdown into elements or compounds of the dry, clean fuel. It is usually given on a percent mass basis. Ultimate analysis is used in calculating combustion parameters such as excess air and flue-gas composition. Table 2.1 lists some various hogged fuels and their dry compositions (Oswald, Junge 1980).

Note that the sulfur content of most hogged fuels is negligible which eliminates air pollution and corrosion problems from sulfur compounds. This is one of the advantages of wood fuel over coal and many heavy fuel oils.

Ash is an inert noncombustible present in all wood and most other fuels as well. It must either stay in the furnace or leave with the flue-gas as most of it will. The ash that leaves with the hot gases tends to corrode surfaces in heat exchangers and boilers and also is an undesirable particulate emission in the exiting gases. The ash content of most wood is less than one percent while that of bark is anywhere from one to ten percent depending on the species.

2.4 Treatment of Dirt

In the handling of the fuel, some dirt, sand, and rocks are

TABLE 2.1 TYPICAL ULTIMATE ANALYSIS FOR MOISTURE FREE HOGGED WOOD
AND BARK FUELS (Oswald, Junge, 1980)

WOOD

<u>Wood Type</u>	<u>Hydrogen</u> Mass%	<u>Carbon</u> Mass%	<u>Nitrogen</u> Mass%	<u>Oxygen</u> Mass%	<u>Sulfur</u> Mass%	<u>Ash</u> Mass%
<u>Softwoods</u>						
White Cedar	6.37	48.80	--	44.46	--	0.37
Douglas Fir	6.3	52.3	0.1	40.5	--	0.8
W. Hemlock	5.8	50.4	0.1	41.4	0.1	2.2
Pitch Pine	7.19	59.0	--	32.68	--	1.13
White Pine	6.08	52.55	--	41.25	--	0.12
Redwood	5.9	53.5	0.1	40.3	--	0.2
<u>Hardwoods</u>						
White Ash	6.93	49.73	--	43.04	--	0.3
Beech	6.26	51.64	--	41.45	--	0.65
White Birch	6.49	49.77	--	43.45	--	0.29
Maple	6.02	50.64	0.25	41.74	--	1.35
Black Oak	6.09	48.78	--	44.98	--	0.15

BARK

<u>Species</u>	<u>Hydrogen</u> Mass%	<u>Carbon</u> Mass%	<u>Oxygen, Nitrogen</u> Mass%	<u>Sulfur</u> Mass%	<u>Ash</u> Mass%
<u>Softwoods</u>					
Douglas Fir	6.2	53.0	39.3	--	1.5
Jack Pine	5.9	53.4	38.7	--	2.0
Scots Pine	5.9	54.4	38.0	--	1.7
Redwood	5.1	51.9	42.6	--	0.4
<u>Hardwoods</u>					
Red Maple	5.9	50.1	41.0	--	3.0
Oak	5.4	49.7	39.5	0.1	5.3
Yellow Birch	6.4	54.5	36.8	--	2.3
American Elm	5.3	46.9	39.7	--	8.1

usually caught in the rough surfaces of the wood or bark. Most of this is separated from the exhaust gases either inside the burner or in a separation unit immediately following the burner. A small amount is always entrained in the exhaust gases with the ash causing the same problems as the ash.

2.5 Proximate Analysis

The proximate analysis of solid fuels separates the fuel up into proportions by mass of volatile matter, fixed carbon, and ash (see table 2.2).

Volatile matter is that part of the fuel that, when heated, vaporizes and burns as a gas. This generally constitutes about 80% of woods by mass and 10% to 15% less for barks. Fixed carbon is that part of the fuel that remains and burns as solid carbon. This normally constitutes only about 20% of the fuel by mass. Ash makes up the small amount of fuel not included as either volatile matter or fixed carbon.

The large ratio of volatile matter to fixed carbon helps to explain how wood based fuels must be burned. In most cases, wood fuels are burned with two separate streams of air; one flowing through the carbon and the other into the gaseous products. The proximate analysis aids the designer in determining the relative amounts of air for each stream.

TABLE 2.2 PROXIMATE ANALYSIS OF WOOD REFUSE BURNED AS FUEL
(Mingle and Boubel, 1968)

Percent Dry Basis by Mass				
<u>Species</u>	<u>Type</u>	<u>Volatile Matter</u>	<u>Fixed Carbon</u>	<u>Ash</u>
Hemlock	Sawdust	84.8	15.0	0.2
Hemlock	Bark	74.3	24.0	1.7
Douglas Fir	Sawdust	86.2	13.7	0.1
Douglas Fir	Old Growth	70.6	27.2	2.2
	Bark			
Douglas Fir	Second Growth	73.0	25.8	1.2
	Bark			
Grand Fir	Bark	74.9	22.6	2.5
White Fir	Sawdust	84.4	15.1	0.5
White Fir	Bark	73.4	24.0	2.6
Ponderosa	Sawdust	87.0	12.8	0.2
Pine				
Ponderosa	Bark	73.4	25.9	0.7
Pine				
Redwood	Sawdust	83.5	16.1	0.4
Redwood	Bark	71.3	27.9	0.8
Cedar	Sawdust	77.0	21.0	2.0
Cedar	(Red) Bark	86.7	13.1	0.2

2.6 Heating Value

Two common terms associated with most fuels are higher heating value and lower heating value. Heating value in general is the energy released in burning a specified amount of fuel to completion. The difference between the terms has to do with the water formed in combustion. Higher heating value is the most common term used in burning wood based fuels and is the term that will be used throughout this report. The higher heating value includes the heat released in the combustion of dry, clean fuel plus the heat released by condensing the water formed in combustion and cooling it to 77 degrees Fahrenheit at one atmosphere pressure (Combustion Engineering, 1981).

Several definitions exist for the lower heating value of a fuel. The first and most common definition is the same as that for the higher heating value except that the water formed in combustion is assumed to remain as vapor. Mathematically, it is the higher heating value minus the heat released in condensing the water formed in combustion at 77 degrees F. Another definition of lower heating value takes the previous definition but on a wet fuel basis (Btu/lb of "as burned" fuel) and subtracts out the heat required to vaporize the water that was initially in the fuel. Other definitions simply involve slightly different treatment of the energy required for the water in the fuel.

Higher heating values for some common wood fuels are listed in table 2.3. Although the ultimate analysis of most wood is quite

TABLE 2.3 TYPICAL HEATING VALUES OF WOOD AND BARK
(Oswald, Junge 1980)

WOOD

<u>Species</u>	<u>Higher Heating Value (Btu/lb)</u>
<u>Softwoods</u>	
Western Red Cedar	9,700
White Cedar	8,400
Douglas Fir	9,050
Western Hemlock	8,620
Pitch Pine	11,320
Ponderosa Pine	9,100
Redwood	9,040
<u>Hardwoods</u>	
White Ash	8,920
Beech	8,760
Elm	8,810
Maple	8,580
Black Oak	8,180

BARK

<u>Softwoods</u>	
Douglas Fir	9,800-10,100
Western Hemlock	9,400-9,800
Jack Pine	8,930-9,380
Ponderosa Pine	9,100
Scots Pine	8,595
Western Redcedar	8,700
<u>Hardwoods</u>	
Red Alder	7,947-8,760
American Elm	6,921-7,600
Hard Maple	8,230
Red Maple	8,100
Black Oak	8,340
Sycamore	7,403-7,909

similar, the heating values tend to vary somewhat. The reason for this is the difference in resin (sap) content of wood fuels. This resin has a heating value around 17,000 Btu per pound so a small difference in resin content can make a significant difference in the total heating value of the fuel. Bark has a greater heating value than wood as a rule, probably again due to the resin content.

3. COMBUSTION OF WOOD RESIDUE FUELS

Combustion of a fuel is a method commonly used to release stored energy in the form of heat. A combustible fuel has chemical energy stored in the molecular and atomic bonds that determine the makeup of the fuel. When these bonds are broken and the atoms are rearranged to make new molecules, energy is released (Combustion Engineering, 1981). This is the principle of combustion of fuels. The objective in producing power from combustion is to release the theoretical maximum quantity of this energy possible while meeting safety and air-emission regulations.

3.1 Principles of Combustion

Technically, combustion is defined as an oxidation process. In other words, elements in the fuel combine chemically with oxygen to form new compounds. Not all of the elements in a fuel are combustible. The principal combustible ones are carbon, hydrogen, and sulfur. Combustion can also be defined as an exothermic process, meaning that heat is released. Also, combustion is a rapid process. These last two properties set a combustion reaction apart from any other oxidation reaction (Oswald, Junge 1980).

Another property of combustion reactions is that they generally occur in the gaseous phase. Many fuels exist naturally in the liquid or solid phase but combustion actually occurs only as the fuel vaporizes. The reason for this is that for the combustible

elements in a fuel to burn, they must come into direct contact with oxygen molecules. This can happen much more easily for a fuel in the gas phase than in the solid or liquid phase. This is accomplished by a destructive distillation process occurring as the fuel is exposed to heat (Tuttle, Junge 1979). This distillation process is endothermic (absorbs energy).

The burning of wood takes place in three steps.

1. The moisture in the wood is heated and vaporized to allow the wood temperature to continue increasing beyond the boiling point of water. The energy required to vaporize the water is approximately 1200 Btu/lb of water.

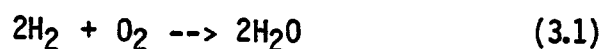
2. The temperature of the wood continues to rise as the volatile matter is distilled from the wood. The volatile matter burns overfire as it is mixed with air. The greatest percentage of the wood's energy is released in this step.

3. Finally, the fixed carbon or charcoal burns. Most grate type burners provide separate air streams for the volatile matter and the charcoal because the charcoal burns much slower and burns on the grate in the solid phase.

As mentioned, for burning to take place, oxygen must come in direct contact with the combustible elements. This requires a large amount of mixing or turbulence. Also the temperature must be sufficiently high to ignite the components. Finally, time in the combustion chamber must be adequate to allow the components to burn completely.

3.2 The Equations of Combustion

The burning of wood fuel is an extremely complex process physically, but it can be modeled fairly simply using chemical equations. In perfect combustion, the process can be described by two simple equations. The first of these is the combination of the hydrogen (H_2) in the fuel, with oxygen (O_2) either from the fuel or the air.



The equation is interpreted to mean that every two molecules of hydrogen combine with one molecule (or two atoms) of oxygen to form two molecules of water.

The second reaction is the combination of carbon (C) in the fuel, with oxygen.



One atom of carbon combines with one molecule of oxygen to form one molecule of carbon dioxide.

These equations are used as the basis for most combustion calculations. Using these two equations alone however, assumes that all of the carbon combines to form carbon dioxide. In reality, some of the carbon combines with only one atom of oxygen to form carbon monoxide (CO)



This is generally termed "incomplete combustion". Also, some of the

carbon does not come into contact with any oxygen and leaves as unburned carbon.

The reactions described will be used to determine the products of combustion and their relative proportions.

3.3 Concept of the Mole

The term pound-mole, or simply mole for this purpose, represents a common bookkeeping technique used in combustion calculations. A mole of a substance is the mass of that substance that is numerically equal to its molecular weight (Babcock and Wilcox, 1978). For example, oxygen (O_2) has a molecular weight of 32, therefore a mole of oxygen weighs 32 pounds. Table 3.1 lists the elements and compounds involved in this combustion analysis and their corresponding atomic and molecular symbols and weights. A characteristic of gases is that a mole of gas has a specific volume governed by temperature and pressure but not by species. In other words, mole ratios in a gas are the same as volume ratios. The mole concept simplifies the bookkeeping in combustion reactions. For example, equation 3.1:



Using moles, this equation is interpreted the same way as with molecules. Two moles of hydrogen combine with one mole of oxygen to form two moles of water. The difference is that with moles, the numbers can be translated into weights so that mass ratios can be

TABLE 3.1 ATOMIC AND MOLECULAR WEIGHTS OF TYPICAL ELEMENTS AND COMPOUNDS INVOLVED IN THE COMBUSTION OF HOGGED FUEL

<u>ELEMENT</u>	<u>ATOMIC SYMBOL</u>	<u>ATOMIC WEIGHT</u>	<u>MOLECULAR SYMBOL</u>	<u>MOLECULAR WEIGHT</u>
Carbon	C	12	C	12
Oxygen	O	16	O ₂	32
Nitrogen	N	14	N ₂	28
Hydrogen	H	1	H ₂	2
Argon	Ar	40	Ar	40
Carbon Dioxide	--	--	CO ₂	44
Carbon Monoxide	--	--	CO	28

obtained. Two moles of hydrogen weigh four pounds; one mole of oxygen weighs 32 pounds, and two moles of water weigh 36 pounds. Since many properties such as enthalpy, entropy, and specific heat are defined on a per pound basis, the advantages of the mole concept are apparent.

3.4 Excess Air and Air-Fuel Ratio

In nearly all combustion processes, the oxygen required is supplied by air. Air consists of mostly nitrogen and oxygen with small amounts of other gases intermixed (see Table 3.2). Only the oxygen in the air reacts, the other elements pass through unchanged. The amount of oxygen required from the air for perfect combustion is termed theoretical oxygen and the quantity of air containing this oxygen is commonly called theoretical air (Combustion Engineering, 1981). This quantity is usually referred to as a percentage i.e. 100% theoretical air.

TABLE 3.2 COMPOSITION OF DRY COMBUSTION AIR
(Combustion Engineering, 1981)

Constituent	Volume/Mole %	Mass %
Nitrogen	78.09	75.52
Oxygen	20.95	23.14
Argon	0.93	1.28
Carbon Dioxide	0.03	0.05

Note: Neon, helium, krypton, hydrogen, xenon, ozone, radon, and carbon monoxide combined are less than 0.003%

All combustion reactions require greater than 100% theoretical air (stoichiometric quantity) for efficient burning. Some of the oxygen molecules simply do not come into contact with combustible elements. The term excess air is used to represent that portion above 100%. For example, if a fuel is burned with 150% theoretical air, the common terminology is to say that the fuel is burned with 50% excess air. Excess air required for complete combustion of wood fuels depends on fuel particle size, moisture and inert matter content, and on the specific furnace design.

Varying the level of excess air can serve several purposes. Increasing the rate of air introduced helps to dry the fuel before it is burned, thus allowing the fuel to burn more easily. Adjusting the excess air level also effects the volumetric flow rate directly and the combustion temperature inversely. It can be seen that the rate of air intake has an impact on several important combustion parameters.

Air-Fuel ratio is a term strongly related to excess air. It is simply the ratio of dry air to dry fuel burned, without reference to any "theoretical" amount. Air-fuel ratio varies directly with excess air and therefore they are simply two different terms commonly used in combustion practice for essentially the same purpose. In this particular analysis, air-fuel ratio is the term used.

3.5 Combustion Calculations

Several different methods exist for calculating combustion products. The method chosen for this analysis is called the mole method because it is based on molar ratios explained earlier. Essentially all that is done is to calculate a mass balance based on the restrictions imposed by the combustion equations

The dry compositions of the wood fuel and air are known. The remaining constituent parameters required are the moisture content of the fuel and either the relative humidity or the humidity ratio of the air. Finally, the air-fuel ratio or the excess air level for combustion must be specified. Knowing these and the governing equations of combustion, a mass balance can be performed and assuming perfect combustion, all of the products and their ratios can be determined. However, to be more accurate, it must be assumed that a small amount of carbon passes through unburned entirely and a small amount is incompletely burned to carbon monoxide. These amounts of carbon depend on such factors as type of combustor, air-fuel ratio, moisture in the fuel, and size of fuel particles.

To avoid confusion, quantities of constituents are related to a base quantity. In this report, the base quantity is one pound of "as-burned" fuel. For example, oxygen entering from the air would be expressed as moles or pounds per pound of fuel input.

From the ultimate analysis of wood fuel (table 2.1), it is apparent that the quantities of components in the wood must be converted from pounds per pound of dry, clean fuel to pounds per

pound of wet, dirty fuel. Similarly, the moisture content and dirt content are also related to one pound of as-burned fuel. In this way, one pound of fuel can be broken down into the masses of each individual constituent.

As an example, take the following case:

Species Douglas Fir

Ultimate Analysis:

Component	LB/LB (dry, clean wood)
Carbon	0.523
Oxygen	0.405
Hydrogen	0.063
Nitrogen	0.001
Ash	0.008

Moisture Content - 0.15 lb H₂O/lb wet, cleanfuel

Dirt etc. Content - 0.035 lb/lb dry, clean fuel

For easy application, these figures are broken down to a per pound of wet, dirty (as-burned) fuel as shown below. The reacting elements are most simply manipulated on a mole basis. For brevity, wet, dirty fuel will be abbreviated as wdf.

Constituent	lb/lb wdf	moles/lb wdf
carbon	.4317	.0360
oxygen	.3343	.0104
hydrogen	.0520	.0260
nitrogen	.0008	negligible
ash	.0066	-----
water	.1457	.0081
dirt etc.	.0298	-----

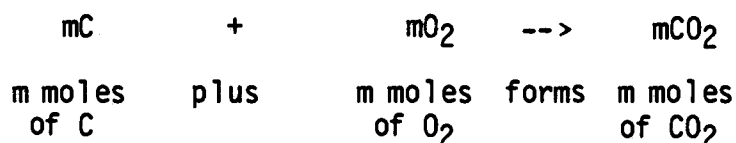
Using the known, or desired, air-fuel ratio and the known composition of air, the air can be broken down into components in

the same manner as the fuel (on a per pound of wet, dirty fuel basis). From the previous example, one pound of as-burned fuel contains .8254 pounds of clean, dry fuel. The air-fuel ratio is then used to calculate the mass of air required:

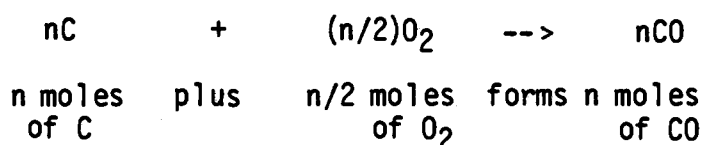
$$A/F * .8254 = \text{pounds of air per pound of fuel}$$

Finally, from the combustion equations and the estimates for unburned carbon and carbon burned to CO, the exiting gas composition is calculated on the same basis. For example, let m be the number of moles of carbon burned to completion and n be the number of moles of carbon burned to CO ($n+m$ = total no. of moles of C/lb of fuel).

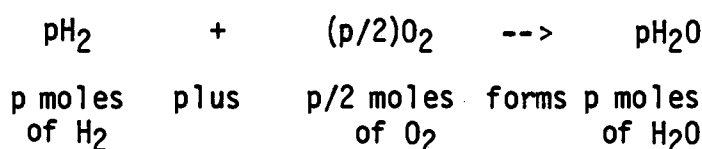
From equation 3.2:



From equation 3.3:



Finally, from equation 3.1:



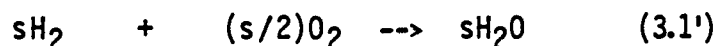
All desired quantities can be calculated from this point. The total number of moles of CO₂, CO, and H₂O formed per pound of fuel

burned are m , n , and p respectively. Since nitrogen and argon pass through unchanged, the exiting quantities are equal to the total input quantities in the air and the fuel. The amount of oxygen exiting the burner is the quantity coming in from the air plus that in the fuel minus the quantity used in combustion ($m + n/2 + p/2$).

The calculation of excess air is a simple matter also. Remember that excess air is based on complete combustion so that only equations (3.1) and (3.2) are applied.



and



The quantity of oxygen required for complete combustion is $r + s/2$ moles. If f is the number of moles of oxygen in the fuel (per pound), then the "theoretical oxygen" is $r + s/2 - f$ moles. Letting g represent the number of moles of oxygen in the air per pound of fuel, the percentage of excess air (excess oxygen) is determined as follows:

$$g / (r + s/2 - f) - 1 * 100$$

Total air, g , divided by theoretical air gives a fraction of theoretical air provided, and subtracting one converts this number to excess air.

3.6 Energy Balance

A power plant generally represents a steady state, steady flow process. From a thermodynamic standpoint, the best way to model a system of this nature is with the control volume. Each individual component of the cycle is also steady state, steady flow so the control volume is chosen to model the combustor also. An energy balance of this control volume refers directly to the first law of thermodynamics for a steady state, steady flow process. The equation is written as follows:

$$Q_{cv} + M(H_i + V_i^2/2 + gZ_i) = M(H_e + V_e^2/2 + gZ_e) + W_{cv}$$

where

Q = heat rate gain by the control volume.

W = work rate done by the control volume.

M = mass flow rate through the control volume.

H = enthalpy per unit mass.

V = velocity.

g = gravitational constant.

Z = elevation.

Subscript i represents the inlet stream.

Subscript e represents the exit stream.

Subscript cv represents control volume.

To simplify the equation, it is first recognized that no work is done by a combustor mechanism. Next it can easily be shown that in general, the velocity and elevation components are orders of magnitude below the enthalpy terms and thus can be neglected. The simplified first law equation then becomes:

$$Q_{cv} + M \cdot H_i = M \cdot H_e$$

The burner has two inlet streams so when these are separated and the mass balance is incorporated, the equation becomes:

$$Q_{cv} + M_{i1} \cdot H_{i1} + M_{i2} \cdot H_{i2} = (M_{i1} + M_{i2}) \cdot H_e$$

The control volume analysis is a simple way to see the energy balance but in a combustion process, details of what happens on the inside of the unit must be known or assumed.

3.6.1 Combustion Assumptions

As in computing the mass balance and products of combustion, the energy balance is most easily carried out by breaking the streams down into individual components and considering them separately. They need not be broken down into single elements or compounds but are separated by energy considerations. The streams are as follows:

- 1) Dry, Clean Fuel
- 2) Water in the Fuel
- 3) Water in the Air
- 4) Water Formed in Combustion
- 5) Dry Air
- 6) Dry Exhaust Gases
- 7) Dirt and other Non-Combustibles (excluding ash)
- 8) Ash and Unburned Carbon

Combustion is a very complex process. Exact analysis is impossible at this time, so simplifying assumptions must be made to

model the system. In actual combustion as was detailed earlier, the fuel is heated and pyrolysis takes place and finally burning. This all takes place over a wide temperature range. To simplify calculations, the entire process is assumed to take place at one temperature. 25 deg. C is often used, however in this model, the ambient air temperature is used. This provides a basis from which to make energy calculations. The following section details how each stream is treated.

3.6.2 Stream Calculations

A. Dry, Clean Fuel:

Dry, clean fuel is the basis for higher heating value. The rate of dry, clean fuel determines the major part of the heat available to the exhaust gases. Since combustion is assumed to take place at ambient temperature, no heating of the wood itself is considered. The heat released by the dry, clean fuel is determined by:

$$Q_{rel} = M_{dcf} * HHV$$

where

Q_{rel} = heat rate released by the fuel (Btu/lbdcf)
 M_{dcf} = mass rate of dry, clean fuel.
 HHV = higher heating value of the fuel.

B. Water in the Fuel

This water enters the burner as liquid at ambient temperature. It must be heated to boiling, evaporated, and further heated to the

final exhaust gas temperature. The process of heating the liquid water to boiling is treated the same as any standard heating of water. Boiling temperature is considered to be 212 deg. F because the pressure during burning is very near atmospheric. Therefore, the first part of this component is modeled with the equation:

$$Q_{wf1} = M_{wf} * C_{pw} * (212 - T_{amb})$$

where

Q_{wf1} = heat required to raise the water in the wood to boiling.
 M_{wf} = mass rate of water in the fuel.
 C_{pw} = specific heat of liquid water at atmospheric pressure
 (=1 Btu/lb deg. F).
 T_{amb} = ambient air temperature.

Next, the water must be driven from the wood and vaporized. The standard heat of vaporization of water is not adequate in this case. Moisture in wood is found in two forms: Bound water and free water. Bound water is adsorbed into the cell walls. The limit to which water can be held in this manner is called the fiber saturation point (FSP) and can range between 25% and 32% moisture content. Any excess water beyond the FSP is called free water.

Free water requires simply the standard heat of vaporization to evaporate. This value is approximately 971 Btu/lb. Bound water however, requires this energy plus an additional amount to break the bonds of adsorption. The additional energy requirement varies from about zero at the FSP to approximately 368 at zero moisture content (Oswald, Junge 1980). Figure 3.1 shows the relationship between moisture content and the energy requirement to vaporize the water.

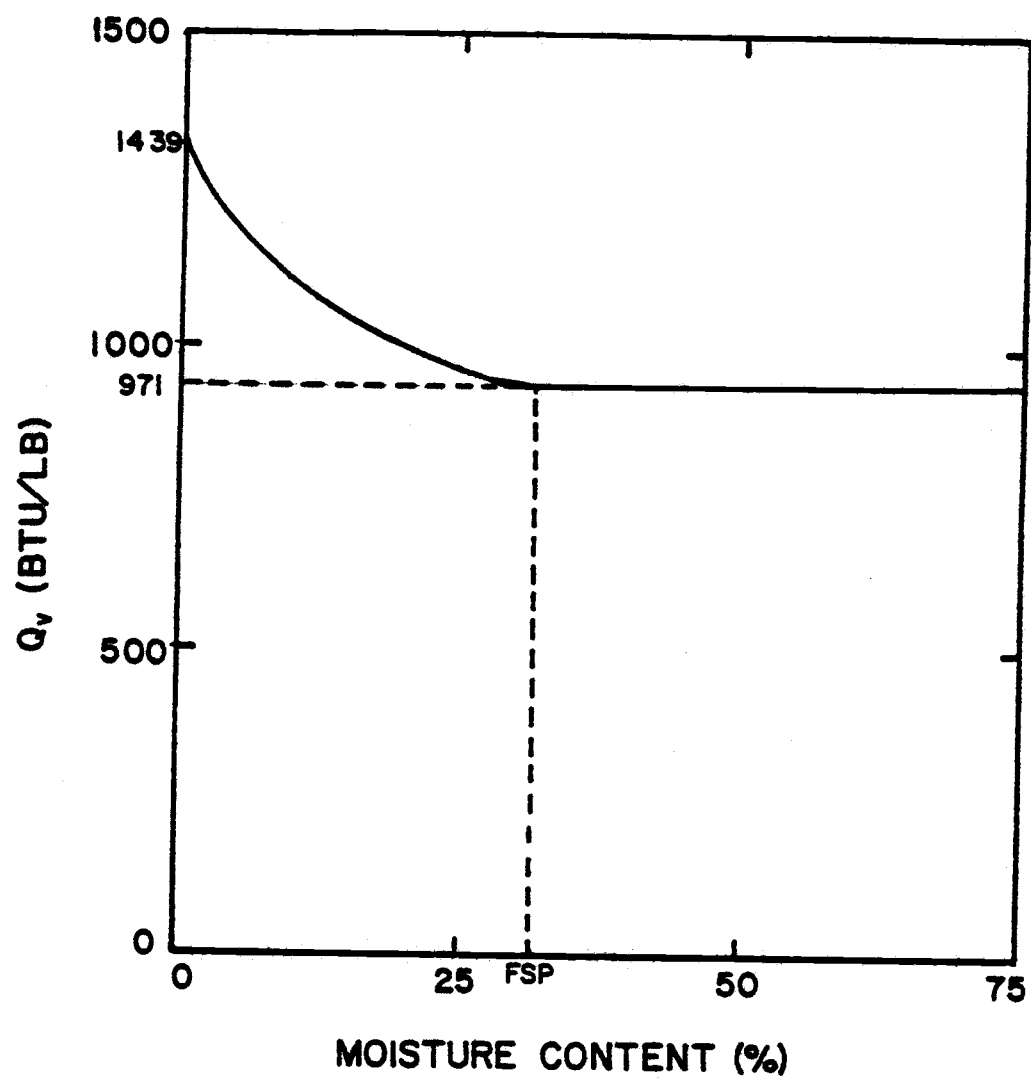


Figure 3.1 Heat of vaporization and desorption as a function of moisture content (Oswald, Junge 1980)

This part of the equation is written as:

$$Q_{wf2} = M_{wf} * Q_v$$

where

Q_{wf2} = heat required to vaporize the water in the wood (Btu).

Q_v = average heat required to vaporize water over a given moisture content range (Btu/lb).

To simplify the calculation of Q_v , the curved part of the figure is modeled as a straight line and from that point, determining the average heat of vaporization and desorption over a given range of moisture content is a trivial matter.

Finally, the water vapor must be raised to exhaust gas temperature. The temperature range associated with combustion reactions is very great and a constant specific heat would not be accurate for a calculation of this nature. Instead, the specific heat of water vapor is a function of temperature and must be integrated in the desired temperature range to produce enthalpy changes.

$$Q_{wf3} = M_{wf} / MW_w * \int_{212}^{T_{ex}} C_{pw}(T) dT$$

where

Q_{wf3} = heat required to raise water vapor from fuel from 212 deg. F to exit temperature.

T_{ex} = exit (exhaust gas) temperature (deg. F).

$C_{pw}(T)$ = specific heat of water vapor as a function of temperature (Btu/lbmole deg F).

MW_w = molecular weight of water.

The specific heat of water vapor as a function of temperature (at constant pressure) is given by (Van Wylen and Sonntag, 1978)

$$C_{p_w} = 34.190 - 43.868G \cdot 25 + 19.778G \cdot 5 - 0.88407G$$

where

$$G = \text{temperature (deg R)}/180$$

The accurate range of this equation is from 540 deg. R (80 deg. F) to 6300 deg. R (5840 deg. F) with a maximum error in this temperature range of 0.43 percent. Integration of this equation yields:

$$\int_{212}^{T_{ex}} C_p(T) dT = \Delta H = (34.190(G_e - G_b) + 35.094(G_e^{1.25} - G_b^{1.25}) + 13.185(G_e^{1.5} - G_b^{1.5}) + 0.4420(G_e^2 - G_b^2)) \cdot 180$$

where

$$\begin{aligned} \Delta H &= \text{enthalpy change (Btu/lbmole) from 212 to } T_{ex} \\ G_e &= T_{ex}(\text{in deg. R})/180 \\ G_b &= (\text{Boiling Temp. in deg. R})/180 \end{aligned}$$

Problems arise however, due to the fact that the exit temperature is unknown. As a result, the solution is an iterative one involving this component. The details of the solution method are presented in a later section.

C. Water in the Air

The water in the air enters as a gas at the incoming air temperature (T_{air}) and exits as gas at the exhaust gas temperature (T_{ex}). No chemical or state change takes place so it can be modeled simply as a gas temperature change the same as the last part of the last section. The only differences are the flow rate and the starting temperature.

$$Q_{wa} = M_{wa} / MW_w * \int_{T_{air}}^{T_{ex}} C_{pw}(T) dT$$

where

Q_{wa} = heat required to raise the water in the air from T_{air} to T_{ex} .
 M_{wa} = flow rate of the water in the air.

The same problem of an unknown exit temperature arises again and the final iterative solution method is described later.

D. Water Formed in Combustion

As previously described, the higher heating value includes the energy released by condensing the water formed in combustion to a liquid and further cooling it to 77 deg. F or simply condensing it at 77 deg. F. Since this water leaves in the gas phase, the energy value for condensing at 77 deg. F must be subtracted from the heating value. The latent heat of vaporization of water at 77 deg. F is 1060 Btu/lb. The equation for this quantity of energy is

$$Q_{lh} = M_{wc} * 1060$$

where

Q_{lh} = latent heat requirement for water formed.
 M_{wc} = flow rate of combustion water.

Under the assumption that combustion takes place at ambient temperature (T_{amb}), the water vapor formed must be heated from ambient to the final exhaust gas temperature. This quantity of energy is calculated in the same way as that for the water in the air

but using ambient temperature for the base instead of the incoming air temperature.

$$Q_{wc} = M_{wc} / MW_w * \int_{T_{amb}}^{T_{ex}} C_{pw}(T) dT$$

where

Q_{wc} = heat required to raise the combustion water temperature from T_{amb} to T_{ex} .

The solution again involves iteration on the exit temperature.

E. Dry Air

The dry air enters the furnace at an elevated temperature and is involved in the burning process which is assumed to take place at ambient temperature. To do this, the air must be cooled to ambient temperature which frees energy to be absorbed by the exhaust gases. The amount of energy released is the same as would be needed to raise the temperature from ambient to the inlet temperature. It is modeled with variable specific heat equations for each individual element or compound involved. Table 3.3 lists the specific heat equations for all of the gas constituents involved in the analysis, and specifies their accurate range and their maximum error within that range. Table 3.4 lists the integrated forms of these equations which are used to determine enthalpy changes of the gas in Btu/lbmole. The form of the equation used to evaluate the energy released by the air is

$$Q_{air} = M_{air} * \sum_i (y_i * \Delta H_i) / MW_{air}$$

where

Q_{air} = heat released in cooling the air to combustion temperature.
 M_{air} = flow rate of air.
 y_i = mole fraction of substance i.
 ΔH_i = enthalpy change (Btu/mole) of substance i in given temperature range.
 MW_{air} = molecular weight of air.

This quantity of energy is combined with the heat released in combustion to make up the total available heat for the exhaust gases.

F. Dry Exhaust Gases

All of the water involved in the process has been dealt with already, so the only remaining gas constituents to consider are the dry exhaust gases. The composition of this gas is known from earlier calculations. The exhaust gas takes it's final form and composition at combustion and must then absorb energy to raise the temperature to the final exiting temperature. The equation for the energy to do this is the same as that for cooling the air except that the temperature range is different and the composition is different.

$$Q_{gas} = M_{gas} * \sum_i (y_i * \Delta H_i) / MW_{gas}$$

where

Q_{gas} = heat required to raise the flue-gas from ambient to final temperature.
 M_{gas} = flow rate of dry gas.
 y_i = mole fraction of substance i.
 ΔH_i = enthalpy change (Btu/mole) of substance i in given temperature range.
 MW_{gas} = molecular weight of flue-gas.

TABLE 3.3 SPECIFIC HEAT EQUATIONS FOR THE GAS COMPONENTS
(Van Wylen, Sonntag, 1978)

<u>GAS</u>	<u>SPECIFIC HEAT EQUATION (Btu/mole deg. R)</u>	<u>MAX. ERROR</u>
Nitrogen	$9.3355 - 122.56(G^{-1.5}) + 256.38(G^{-2}) - 196.08(G^{-3})$	0.43
Oxygen	$8.9465 + .004804(G^{1.5}) - 42.679(G^{-1.5}) + 56.615(G^{-2})$	0.30
Carbon Monoxide	$16.526 - 0.16841(G^{0.75}) - 47.985(G^{-0.5}) + 42.246(G^{-0.75})$	0.42
Water Gas	$34.190 - 43.868(G^{0.25}) + 19.778(G^{0.5}) - 0.88407$	0.43
Carbon Dioxide	$-0.89286 + 7.2967(G^{0.5}) - 0.98074(G) + .0057835(G^2)$	0.19
Argon	Constant 5.005	

Where:

$$G = T / 180 \quad \text{and } T \text{ is gas temperature given in degrees R.}$$

Note: All of the equations are accurate for the range 540-6300 degrees R.

TABLE 3.4 INTEGRATED SPECIFIC HEAT EQUATIONS FOR THE GAS COMPONENTS (Van Wylen, Sonntag, 1978)

<u>GAS</u>	<u>INTEGRATED SPECIFIC HEAT EQUATION (Btu/mole)</u>
Nitrogen	$(9.3355(G-G_r) - 245.12(G^{-.5}-G_r^{-.5}) - 256.38(1/G - 1/G_r) - 98.04(G^{-2}-G_r^{-2})) * 180$
Oxygen	$(8.9465(G-G_r) + 0.001922(G^{2.5}-G_r^{2.5}) - 85.358(G^{-.5}-G_r^{-.5}) - 56.615(1/G - 1/G_r)) * 180$
Carbon Monoxide	$(16.526(G-G_r) + 0.09623(G^{1.75}-G_r^{1.75}) + 95.97(G^{.5}-G_r^{.5}) + 168.984(G^{.25}-G_r^{.25})) * 180$
Water Gas	$(34.190(G-G_r) + 35.0944(G^{1.25}-G_r^{1.25}) + 13.1853(G^{1.5}-G_r^{1.5}) + 0.44203(G^2-G_r^2)) * 180$
Carbon Dioxide	$(-0.89286(G-G_r) + 4.8645(G^{1.5}-G_r^{1.5}) + 0.49037(G^2-G_r^2) + 1.92783(G^3-G_r^3)) * 180$
Argon	$(5.005 * (G-G_r)) * 180$

where: $G = T / 180$ and T is gas temp. in degrees R.

$G_r = T_r / 180$ and T_r is reference gas temp. in degrees R.

Since this quantity involves a variable specific heat and the unknown exit temperature, it must be included in the iteration discussed earlier.

G. Dirt

Dirt and other noncombustibles that enter the furnace and are not part of the fuel are assumed to be separated from the gases before they enter another piece of equipment. The method of accomplishing this varies with the type of burner used. Some types of burners have a simple collection device at the bottom of the unit where the noncombustibles can simply drop into the collector and be disposed of later. Others use a cyclone separator just after the burner where the noncombustibles drop out the bottom and the gases flow out the top. Whatever the method used, the noncombustibles absorb energy in the burner and are then disposed of. The energy is then lost to the environment. For this purpose it will be assumed that all of the external noncombustibles (ash is not included) are separated from the gases and that they leave the furnace at the exiting gas temperature. These constituents are assumed to have a constant specific heat of 0.20 Btu/lb. The equation for the heat loss in the noncombustibles is

$$Q_{\text{dirt}} = M_{\text{dirt}} * .20 * (T_{\text{exit}} - T_{\text{amb}})$$

where

Q_{dirt} = heat loss to external noncombustibles.
 M_{dirt} = flow rate of external noncombustibles.

This component of the energy balance is also unknown because it involves the unknown exit temperature. It must be part of the iteration routine.

H. Unburned Carbon and Carbon Monoxide

As was mentioned earlier, the higher heating value represents the heat released by complete burning of the combustible elements in the fuel. Included in this value is the heat of combustion of carbon in the formation of CO_2 . This value is 14,100 Btu/lb of carbon (Babcock and Wilcox, 1978). Not all of the carbon burns to carbon dioxide however, as the higher heating value assumes. Carbon burned incompletely to carbon monoxide releases only 3960 Btu/lb of carbon and unburned carbon of course, releases no energy. Thus, every pound of carbon burned to CO represents a loss of 10,140 Btu and every pound of carbon passing through unburned represents a loss of 14,100 Btu. The equations for these heat losses are

$$Q_{\text{CO}} = M_{\text{C-CO}} * 10140$$

where

$$\begin{aligned} Q_{\text{CO}} &= \text{heat loss due to formation of CO.} \\ M_{\text{C-CO}} &= \text{rate of carbon burned to CO.} \end{aligned}$$

and

$$Q_{\text{unbc}} = M_{\text{unbc}} * 14,100$$

where

$$\begin{aligned} Q_{\text{unbc}} &= \text{heat loss due to unburned carbon.} \\ M_{\text{unbc}} &= \text{rate of unburned carbon.} \end{aligned}$$

These values are considered losses because they were already included into the heating value.

J. Other Losses

Since the type of combustor is variable, the remaining loss values must be estimated. These include the heat loss due to heat transfer with the surroundings, loss due to possible air leakages, and loss due to some of the ash leaving the system at elevated temperatures.

Heat transfer with the surroundings is the primary source of energy loss from the system. This is due to the increased temperature of the outside of the combustion unit. Radiation heat transfer is dominant but some is also due to convection. The amount of energy lost in heat transfer can vary widely in combustors depending on type, shape, and mode of operation.

Air leakages occur primarily at the point where the fuel enters the system. Wood cannot be fed into a unit without a certain amount of ambient air entering with it. Compared to the mass of air being fed in, this leaking air is generally insignificant and also varies depending on the feed system. For this reason, the leak air is not considered in the mass balance and is simply lumped in with other losses in the energy balance.

For accounting purposes, the intrinsic ash is treated separately from the dirt. Some of it will be separated out and removed with the dirt while some of it will pass through with the flue gases and collect elsewhere. The same thing happens with the dirt, but more of

it falls out because it is generally more dense. For simplicity and lack of any accurate way to predict the amounts of each going the two directions, the dirt is assumed to all be collected and the ash is assumed to all pass through to other components where the heat carried in the ash can still be used. The uncertainty in this method is absorbed in the general losses figure.

These losses are entered as a fraction of available heat to the flue-gases. Available heat is the heat from combustion (heating value) plus the heat provided by the inlet air in dropping its temperature to ambient. This loss term is expressed as follows:

$$Q_{loss} = (Q_{rel} + Q_{air}) * LOSS$$

where

Q_{loss} = heat loss due to heat transfer, leakage, and ash.

LOSS = fraction of available heat lost.

3.6.3 Exit Temperature Calculation

Calculation of the flue-gas exiting temperature is simply a matter of combining all of the parts of the energy balance together and iterating for the temperature. The basic heat balance is as follows:

$$\text{energy released} = \text{energy absorbed} + \text{energy lost}$$

where

$$\text{energy released} = Q_{rel} - Q_{wc} + Q_{air}$$

$$\text{energy absorbed} = Q_{wf1} + Q_{wf2} + Q_{wf3} + Q_{wa} + Q_{gas}$$

$$\text{energy lost} = Q_{\text{dirt}} + Q_{\text{co}} + Q_{\text{unbc}} + Q_{\text{loss}}$$

Therefore the total equation may be written as

$$Q_{\text{rel}} - Q_{\text{wc}} + Q_{\text{air}} = Q_{\text{wf1}} + Q_{\text{wf2}} + Q_{\text{wf3}} + Q_{\text{wa}} + Q_{\text{gas}} + Q_{\text{dirt}} + Q_{\text{co}} + Q_{\text{unbc}} + Q_{\text{loss}}$$

As was mentioned in the individual sections explaining each component, some of these are a function of the unknown exit temperature and require iteration. These variables are Q_{wf3} , Q_{wa} , Q_{gas} , and Q_{dirt} . All of the other variables are lumped together and calculated at one point so they do not have to be recalculated in each iteration.

The method of solution used in determining the exit temperature is a simple root finding technique known as the Newton-Raphson method. The equation must first be moved entirely to one side of the equal sign such that:

$$\begin{aligned} f(x) &= 0 \\ \text{or} \\ f(T_{\text{exit}}) &= 0 \end{aligned}$$

as in this case. This numerical root-finding technique then quickly converges on the temperature that will satisfy the equation. The process is actually quite complex because every iteration requires many calculations of water and gas properties but the routine converges in relatively few iterations so the overall time used by the computer is small.

Once the exit temperature is found, the numerical values for all

components of the energy balance are calculated and then tabulated under specific categories in the printout.

3.7 Second Law Analysis

A second law analysis of a system determines the "potential" that the system has for doing work. This potential is known as availability or exergy. In general, the availability of a substance is the maximum theoretical work that can be done by bringing the substance into equilibrium with the environment. The second law analysis of wood combustion uses an approximation for the availability of the wood entering the system and is therefore not an exact calculation. For simple, non-reacting, continuous flow systems, availability is calculated as:

$$(H - H_0) - T_0(S - S_0) = A$$

where

H, S represent enthalpy and entropy of substance at its conditions.

H_0, S_0 represent enthalpy and entropy of same substance at equilibrium with the environment.

T_0 = Temperature of environment.

A = Availability of substance.

The term "equilibrium with environment" is not a well defined term and can vary in meaning between sources. Probably the most common interpretation is to say that the substance must be in temperature, pressure, and chemical equilibrium with the environment (which is usually ambient air conditions). These conditions are commonly called the dead state.

Temperature equilibrium is self-explanatory. Pressure equilibrium can get complicated but for this purpose, it is fairly straight forward. It does not effect the solids or liquids involved here, but the gases are somewhat involved. The dead state pressure for each gas is not simply the ambient pressure, but the partial pressure of the specific gas in the immediate atmosphere. To determine the availability of a particular gas mixture, the composition of the mixture as well as that of the surrounding atmosphere must be known along with the temperature and pressure.

Chemical equilibrium can get very complex and will not be explained in detail here. For a substance to be in chemical equilibrium with the environment, it must be inert relative to the environment. In other words it cannot react with the environment. Obviously, wood is not inert relative to the environment. The problem that arises in analyzing wood is that its exact chemical structure is unknown and varies substantially which makes a calculation of it's availability impossible. Because of this problem, the availability of wood for this purpose is assumed to be the higher heating value.

The second law efficiency of a process is defined as the total availability of the components out of the system divided by the total availability of the components into the system.

$$\eta_{2L} = \sum_i A_{i,ex} / \sum_i A_{i,in}$$

where

η_{2L} = second law efficiency.
 $A_{i,ex}$ = availability rate of exiting components.
 $A_{i,in}$ = availability rate of inlet components.

The irreversibility of a continuous process such as this is defined as the total availability of the components into the system minus the total availability of the components out of the system.

$$I = \sum_i A_{i,in} - \sum_i A_{i,ex}$$

The second law analysis of wood combustion is broken down by components and summarized in the following sections.

1. Wood

As mentioned earlier, the wood fuel availability is assumed to be the higher heating value. Because the fuel enters the combustor at ambient temperature, no availability due to the temperature exists.

2. Water in the Fuel

The water entering the burner through the fuel enters as liquid. To simplify calculations, the water is assumed to be a saturated liquid which is also chosen as the dead state of liquid water for this case. Therefore, the availability of this water entering the combustor is zero. The error incorporated in the assumption of saturated liquid is small because the water is actually a slightly compressed liquid with enthalpy and entropy values close to that of saturated liquid.

3. Air

The air enters at elevated temperature and pressure. The composition is the same as atmospheric air because it is chemically unchanged from entrance. Calculation of the availability of the air is a simple matter utilizing the gas functions. The integrated specific heat equations from table 3.4 are used to determine the enthalpy of the gases. Similar functions are used to determine entropy values. The entropy equations are taken from the relationship:

$$S_2 - S_1 = \int_{T_0}^{T_2} (C_p/T) dT - \int_{T_0}^{T_1} (C_p/T) dT - R \ln(P_2/P_1)$$

where

- S_2 = entropy at state 2.
- S_1 = entropy at state 1.
- T_2 = temperature at state 2.
- T_1 = temperature at state 1.
- T_0 = reference temperature (dead state used).
- P_2 = pressure at state 2.
- P_1 = pressure at state 1.
- R = universal gas constant.

For second law analysis, the entropy is needed with respect to the dead state, so in the above equation, T_1 would be the same as T_0 . Also, the pressure relationship described earlier comes into play here. The current partial pressure of the gas component in question is compared to that component's dead state partial pressure using mole fractions and Dalton's Law of Partial Pressures (Smith, Van Ness, 1975)

$$P = y_i * P_i$$

where

P = total pressure.

y_i = mole fraction of substance i in mixture.

P_i = partial pressure of substance i in the mixture.

Therefore the final entropy calculation of a component for availability purposes follows the equation:

$$S - S_0 = \int_{T_0}^T (C_p/T) dT - R * \ln (y_i * P / y_{i0} * P_0)$$

where

S = entropy at current conditions.

S_0 = entropy at the dead state.

T = current temperature.

P = current pressure.

P_0 = dead state pressure (atmospheric).

y_{i0} = mole fraction of gas in question in the atmosphere.

For a gas mixture, these entropy values relative to the dead state are summed together for each individual component in the mixture. A function called S_{gasT} was written to do exactly that (see Appendix D). Therefore, by simply utilizing the gas conditions (temperature, pressure, and composition), the dead state conditions, and the enthalpy and entropy functions, the availability analysis of a gas mixture is a simple matter.

4. Exiting Gases

The availability analysis of the exhaust gases is done in exactly the same way as for the air. All conditions are known once the calculations have been done and all that is required is to plug these conditions and the dead state conditions into the functions and

run it on the computer. The combustor program is set up to do all of the analysis without any extra work to the user.

Once all of the components have been analyzed, the second law efficiency is calculated by:

$$(A_{\text{wood}} + A_{\text{water}} + A_{\text{air}}) / A_{\text{gases}}$$

where

A_{wood} = availability rate of wood into the burner.
 A_{water} = availability rate of water in the wood.
 A_{air} = availability rate of the air into the burner.
 A_{gases} = availability rate of the exhaust gases.

The irreversibility rate is calculated by:

$$A_{\text{wood}} + A_{\text{water}} + A_{\text{air}} - A_{\text{gases}}$$

3.8 The Combustor Program

The combustor model subroutine follows the same steps outlined in this chapter and will therefore not be presented in greater detail. For further reference, a documented computer listing of the subroutine is given in appendix A.

4. WOOD DRYING

A number of similarities exist in the ways that combustion and drying are treated. For this reason, some of the aspects of the dryer analysis will only be explained briefly and reference will be made to the corresponding area in the combustor analysis.

4.1 Principles of Drying Wood

In drying wood with hot gases, the basic principles involved are always the same no matter what type of dryer is used. Sufficient energy must be provided such that the desired amount of water in the wood can be vaporized.

In this particular application, the dryer size requirement is secondary. The most important parameters to be specified are inlet and exit fuel moisture, inlet fuel feed rate and gas flow rate, and exiting gas temperature. Inlet gas pressure is also specified but is relatively unimportant compared to the other parameters mentioned. Other input parameters to the computer program are mass rate of dry wood, higher heating value, ambient temperature, fraction of available heat lost, pressure loss, inlet gas composition, and dead state conditions.

The major purpose of the model is to determine the temperature of the incoming gases required to reduce the specified inlet wood moisture content to the specified exiting moisture content given the

exiting gas temperature. In other words "how much heat must be extracted from the rest of the system to perform the required amount of drying."

The model consists of an energy balance similar to that used in the combustor model but simpler because no chemical changes are considered to take place.

4.2 Mass Balance

The mass balance is very simple and is done in the same basic way as was done in the combustor program. The incoming fuel is broken down into dry fuel and dirt together, and water in the fuel, using the moisture content and composition information. Exactly the same thing is done for the dryer exit using the exiting information. This determines the amount of water that must be vaporized for the desired conditions. This value is then added to the incoming gas flow rate to determine the exiting gas rate.

4.3 Energy Balance

The energy requirements for drying wood are broken down into the following areas:

- a. Heat required to raise the temperature of the wood and the dirt.
- b. Heat required raise the temperature of the water in the wood.
- c. Heat required to vaporize the water.
- d. Heat required to raise the temperature of the water vapor to the exiting gas temperature.
- e. Heat loss of the system due to leakage and heat transfer.

- f. Heat loss from the gases for all of the previous (a, b, c, d, and e) purposes.

These will be discussed in more detail in the next sections.

Several simplifying assumptions were made in the analysis.

1. The water is assumed to all vaporize at 212 deg. F but no condensation takes place at temperatures somewhat below 212 deg. F due to the dew point. This provides known numbers for the heat required to vaporize the water and allows the exit temperature to drop below 212 deg. F without releasing the heat of vaporization back out of the water vapor.
2. The wood and dirt are considered to leave the dryer at 212 deg. F or the exiting gas temperature, whichever is less. This assumes that due to the evaporation of water at 212 deg. F, the wood and dirt temperature will go no higher, but if the exiting gas temperature is lower than 212 deg. F, they will exit at that temperature. An energy balance is not done on the wood particle itself due to the complexity of the problem.
3. Leakage is not considered in the mass balance, but the heat loss due to possible leakage is lumped into a loss term which includes heat transfer losses.

A. Sensible Heat of the Wood and Dirt

The wood and dirt enter the dryer at ambient temperature and raise in temperature as they progress through the dryer. The quantity of heat required to raise the temperature of these constituents from one temperature to another is determined by the

specific heats of the substances. The mean specific heat of wood over a given temperature range is determined by (Oswald, Junge 1980):

$$C_{\text{wood}} = 0.266 + 0.000322 * (T_{\text{out}} - T_{\text{in}} - 64), \quad \text{Btu/lb-deg F} \quad (4.1)$$

That of dirt is again considered to be a constant 0.20 Btu/lb deg. F. Therefore the energy required to raise the temperature of the wood and dirt to it's final temperature is:

$$Q_{\text{fuel}} = ((M_{\text{dcf}} * C_{\text{wood}}) + (M_{\text{dirt}} * C_{\text{pdirt}})) * (T_{\text{amb}} - T_{\text{ex}})$$

where

T_{ex} = exit temperature of the fuel.
 M_{dcf} = flow rate (lb/hr) of dry, clean fuel.

B. Sensible Heat of the Water

As mentioned earlier, the vaporization of water is considered to take place at 212 deg. F and the water that is not vaporized leaves the system at either 212 deg. F or the exiting gas temperature, whichever is lower. Therefore, the water in the wood requires:

$$Q_{\text{liq}} = C_{\text{wat}} * ((212 - T_{\text{amb}}) * M_{\text{vap}} + (T_{\text{exit}} - T_{\text{amb}}) * (M_{\text{wat}} - M_{\text{vap}}))$$

where

Q_{liq} = energy to heat the liquid water.
 M_{vap} = vaporization rate of water.
 T_{exit} = exiting temperature of non-vaporized water.
 M_{wat} = flow rate of water from wood.

in Btu/lb in the liquid form.

C. Heat of Vaporization and Desorption

This is the same process that was described for the combustor analysis. The water in the wood is found as free water and bound water and the relationship between moisture content and heat required for vaporization and desorption is shown in figure 3.1. The curved section of the figure is again modeled as a straight line and the average heat requirement for vaporization and desorption over the range of moisture contents in the dryer is a simple calculation. The equation governing this heat requirement is

$$Q_{\text{vap}} = M_{\text{vap}} * Q_v$$

where

Q_v = average heat of vaporization and desorption over the desired range of moisture content.

D. Heat Required for Water Vapor

The water, once vaporized, must be further heated to the exhaust gas temperature. Again this calculation was done for the combustor. The specific heat equation is integrated over the temperature range desired to get an enthalpy change (H Btu/lbmole). The equation is as follows:

$$Q_{\text{sh}} = M_{\text{vap}} / MW_w * \int_{212}^{T_{\text{ex}}} C_{p_w}(T) dT$$

where

Q_{sh} = heat requirement to superheat the water vapor to exit temperature.

MW_w = molecular weight of water (18 lb/lbmole).

T_{ex} = exiting gas temperature.

In this case, the exit temperature is known so this part of the equation need not be iterated on.

E. Heat Loss of the System

Heat losses are entered into the program as a fraction of "available heat" where available heat is defined as the difference in enthalpy between the entering gases and the dead state conditions.

$$Q_{av} = M_{gas} / MW_{gas} * \int_{T_{ds}}^{T_{in}} C_{p_{gas}}(T) dT$$

where

M_{gas} = flow rate of gases into the dryer.
 MW_{gas} = molecular weight of inlet gases.
 T_{ds} = dead state temperature (ambient).
 T_{in} = inlet gas temperature.
 $C_{p_{gas}}(T)$ = specific heat equation(s) for gases (Btu/lbmole) as a function of temperature.

The quantity of heat lost due to leakage and heat transfer is simply a function of this value.

$$Q_{loss} = LOSS * Q_{av}$$

where

Q_{loss} = heat loss.
 $LOSS$ = fraction of available heat lost.

The inlet gas temperature is unknown so this loss quantity must be iterated for.

F. Heat Transfer From the Entering Gases

The heat loss of the gases is the sum of all of the previous quantities. It is also determined by the equation

$$Q_{\text{gas}} = M_{\text{gas}} / MW_{\text{gas}} * \int_{T_{\text{ex}}}^{T_{\text{in}}} C_{p_{\text{gas}}}(T) dT$$

where

Q_{gas} = heat loss of the incoming gases.
 T_{in} = inlet gas temperature.
 T_{ex} = exit gas temperature.

Again, the inlet gas temperature is unknown so this quantity is iterated for.

4.4 Solution Method

The method of solution (determining the inlet gas temperature) is exactly the same as it was for the combustor program. The equation to be solved is:

$$Q_{\text{gas}} = Q_{\text{loss}} + Q_{\text{sh}} + Q_{\text{vap}} + Q_{\text{liq}} + Q_{\text{fuel}}$$

Q_{gas} and Q_{loss} are both a function of the unknown inlet temperature and the rest of the quantities are known. Finally the equation is put into the form

$$Q_{\text{sh}} + Q_{\text{vap}} + Q_{\text{liq}} + Q_{\text{fuel}} + Q_{\text{loss}} - Q_{\text{gas}} = 0$$

and the equation is solved for the inlet temperature by the Newton-Raphson root finding method.

4.5 Second Law Analysis

As with the energy balance, the second law analysis of the dryer is quite similar to that of the combustor and again it is only an

approximate analysis. The analysis includes availability calculations as well as second law efficiency and irreversibility calculations through the device.

The constituents involved in this analysis are:

- a) The dry wood into and out of the dryer,
- b) The dirt into and out of the dryer,
- c) The water in the wood in and out of the dryer,
- d) The exhaust gases into and out of the dryer.

Each of these constituents are discussed below.

A. Dry Wood

The wood enters the dryer at ambient conditions and leaves at some elevated temperature. Two separate parts exist for the availability. First, the availability due to the heating value of the wood is again assumed to be the higher heating value. This is the case both into and out of the dryer. Second, heat effects must be considered. Since the wood temperature entering the unit is ambient and the dead state is also ambient, no availability exists due to temperature for the wood at the inlet. At the exit however, the wood temperature is elevated relative to the surroundings. The availability of the wood due to temperature is:

$$AV_{wdex} = C_{wdex} * (T_{exit} - T_{ds}) - T_{ds} * C_{wdex} * \ln(T_{exit}/T_{ds})$$

where

C_{wdex} = specific heat of wood at the exit temperature.
 T_{exit} = exit temperature.
 Subscript ds designates dead state.

The equation for the specific heat of dry wood is equation 4.1. The total availability of the wood entering the unit is simply the higher heating value and the availability out is the higher heating value plus that due to the elevated temperature.

B. Dirt

Because dirt is inert within the environment, the only availability that it can possess is due to temperature. As with the wood, the dirt comes in at atmospheric conditions and therefore has zero availability. It leaves at the same elevated temperature as the wood and its availability is calculated in exactly the same way.

$$AV_{drte} = C_{dirt} * (T_{exit} - T_{ds}) - T_{ds} * C_{dirt} * \ln(T_{exit}/T_{ds})$$

where

AV_{drte} = availability of the dirt exiting the dryer.
 C_{dirt} = specific heat of dirt.

C. Water in the Wood

The analysis of the availability of the water in the wood is done in the same manner as was done for the combustor. Again, the dead state for water is considered to be saturated liquid at ambient temperature. For ease of calculation, the liquid water in the fuel is considered to be saturated throughout the drying process. Under these conditions, the water in the fuel entering the dryer is at the dead state and therefore has zero availability. The liquid water exiting the dryer is at an elevated temperature (T_{exit}) and therefore

has an availability. The calculation procedure follows the equation:

$$AV_w = (H - H_{ds})_w - T_{ds} * (S - S_{ds})_w \quad (4.2)$$

where

AV_w = availability of the water in the wood.

H = enthalpy.

S = entropy.

Subscript ds designates property value at the dead state.

Functions were written for the overall program to model the properties of water at various conditions. The areas modeled are saturated water and superheated steam and they are modeled as functions of various parameters such as temperature and pressure. To obtain the enthalpies and entropies needed above, all that is required is to call the saturated liquid functions with respect to temperature and input the appropriate temperature. From that point, equation 4.2 is evaluated for the exit conditions of the water.

D. Drying Gases

For the case of the drying gases, the availability calculation is exactly the same as it was for the gases leaving the combustor. As was discussed, the flue-gas properties functions will calculate the enthalpy and entropy of a mixture of gases relative to the dead state temperature, pressure, and composition. The calculation is done using:

$$AV_{gas} = (H - H_{ds})_{gas} - T_{ds} * (S - S_{ds})_{gas}$$

where

AV_{gas} = availability of gas mixture at specified conditions.
Subscript gas designates properties for the gases.

In this case, the dead state enthalpy and entropy need not be calculated independently because the dead state conditions are used as a reference.

When put on a rate basis (multiplying by the flow rate of the gas), the inlet gas availability and the exiting gas availability may be very close due to the fact that the exiting gas rate is greater than the inlet rate due to the evaporation of water.

The second law efficiency of the dryer is calculated by the total availability rate out divided by the total availability rate into the unit.

$$\eta_{2L} = (AV_{\text{wdex}} + AV_{\text{gasex}} + AV_{\text{drtex}} + AV_{\text{wex}}) / (AV_{\text{wdin}} + AV_{\text{gasin}} + AV_{\text{drtin}} + AV_{\text{win}})$$

where all of the availabilities are on a rate basis.

The irreversibility rate of the process is the difference between the total availability rate into the system and that out of the system.

$$I = (AV_{\text{wdin}} + AV_{\text{gasin}}) - (AV_{\text{wdex}} + AV_{\text{gasex}} + AV_{\text{drtex}} + AV_{\text{wex}})$$

where

$$I = \text{Irreversibility rate (Btu/sec).}$$

4.6 The Dryer Program

Like the combustor subroutine in chapter 3, the dryer subroutine follows the steps outlined in this chapter. For more details of the subroutine itself, see the computer listing presented in appendix B.

5. RESULTS OF SIMULATIONS

Several different sets of computer simulations were run to determine the effects of varying different parameters, involving the combustor and dryer, on the system performance. Performance here refers to output power and efficiency. One group of simulations was made to determine the effects of the combustion air-fuel ratio on the overall system performance. The largest group of simulations consisted of holding the wood moisture content before preparation (drying etc.) at 50% and varying the amount of drying and other fuel preparation. Finally, a group of simulations were made to determine the effects of changing the wood moisture content before drying (to model different wood conditions for use in the power plant).

It must be kept in mind that the results presented represent the performance of one-half of a twin system since the entire plant is simulated by only modeling one half of it. Thus, the power outputs shown in the figures are half of the total, while the efficiencies are the same as for the entire plant. Also, the efficiencies mentioned are based on the higher heating value of the fuel. Finally, both "gross" and "net" results are presented; a "gross" parameter represents that parameter before auxiliary power is taken into account and a "net" parameter takes the auxiliary power into account.

5.1 System Analysis

Some of the parameter variations require that variations be made in the power plant configurations. These are treated as separate "systems". These systems are described in the following sections.

A. System 1

System 1 consists essentially of the power plant configuration laid out in the base case diagram (figure 1.1). The fuel preparation for each half of the twin system consists of a dryer with cyclones, two pulverizers, and various other minor pieces of equipment. The combustor for system 1 is a suspension burner, and as mentioned earlier, requires very dry (15 percent moisture on a wet basis or less) fuel and also small particles (1/8" minus) for efficient burning. For this reason, the dryer for system 1 is required to dry the fuel from 50% to 12% moisture on a wet basis. Pulverization takes place before and after the dryer. The pulverizer ahead of the dryer aids in the drying process by breaking up all of the larger particles. The pulverizer following the dryer breaks the dried fuel up into small enough particles to be used in the suspension burner.

In this system, the temperature of gas exiting the dryer is held at 190 deg. F and the dryer program calculates the inlet gas temperature required for the specified amount of drying. The gas entering the dryer comes from the boiler. No loss in temperature is considered in between so that the dryer specifies the exit

temperature from the boiler which will in turn influence the steam flow rate and the performance of the entire steam system.

B. System 2

System 2 is similar to system 1 but has some differences. The fuel is not dried to below 15% moisture so the grate burner must be substituted for the suspension burner. Because of this, the fuel does not have to be broken down into as small of particles as in system 1 so the pulverizer following the dryer was taken out (no power consumption). The pulverizer ahead of the dryer was left in because it aids the drying process. As in system 1, the temperature exiting the dryer is set at 190 deg. F and the effect on the steam system is the same.

System 2 is considered in two steps, with these being designated as 2a and 2b. System 2a represents the physical configuration of system 2 with fuel being dried from 50% moisture to 25% moisture. System 2b is the same but the fuel is only dried to 35% moisture. The difference between system 2a and system 2b is simply in the amount of drying done.

C. System 3

System 3 represents the plant with no drier or other fuel preparation equipment. The fuel is burned as it arrives at the plant (considered to be 50% moisture). All pressure drops and power consumption in the fuel preparation area are set to zero. Because no fuel preparation is done, a grate burner must be used.

In this system, the gas temperature leaving the plant is the same as that exiting the boiler. In most of the simulations for system 3, this temperature was set at 350 deg. F although a set of simulations was run to determine the effect that this temperature has on the performance of the plant.

5.2 Simulations

A. Effect of Air-Fuel Ratio

Variation of the air-fuel ratio has a significant effect on the overall performance of the system. In changing the air-fuel ratio, the flow rate of air is held constant so that only the rate of fuel input is effected. The rate of fuel varies inversely with the air-fuel ratio so by increasing the air-fuel ratio, the rate of wood used decreases as does the flue-gas flow rate within the power plant. The plant performance was simulated for air-fuel ratios of 10, 14, 18, and 22. The effect of air-fuel ratio on the performance of the power plant can be seen in several of the figures in this chapter.

In general, an increasing air-fuel ratio results in decreasing power due to the decreasing fuel input. The difference between gross and net power output also decreases with increasing air-fuel ratio because less auxiliary power is required to pump the substantially decreased amount of required recirculation gas through the recirculation loop.

Also, the efficiency increases significantly with air-fuel ratio. The principal reason for the increase in efficiency with air-

fuel ratio is that the fraction of total plant power output that comes from the gas turbine cycle increases with increasing air-fuel ratio. The gas turbine cycle is more efficient in this power plant than is the steam cycle. By holding the air flow rate constant and decreasing the fuel used (increasing air-fuel ratio), the gas turbine cycle power output remains essentially the same but the power output from the steam system decreases. By increasing the fraction of total power output coming from the more efficient gas turbine cycle, the efficiency of the entire plant increases.

B. Effect of System Variations

In general, the system variations represent mostly changes in the amount of drying and other fuel preparation done. System 1 represents the most fuel preparation, system 2 represents less fuel preparation and system 3 represents no fuel preparation. Each system was simulated using air-fuel ratios of 10, 14, 18, and 22.

Figure 5.1 is a plot of power output vs. as-burned wood moisture content at the various air-fuel ratios. The gross power output for systems 1 and 2 are essentially the same at the same air-fuel ratios. System 3 however, shows a drop in gross efficiency from the other systems. Two principal factors come into play in this analysis. When a dry fuel is burned (i.e. system 1), the combustor exit temperature is very high which requires a large amount of cooler mixing gas (from the boiler) to bring the temperature down to that which is allowed in the heat exchanger (approximately 1675 deg. F). This produces a larger flow rate of hot gas through the boiler which

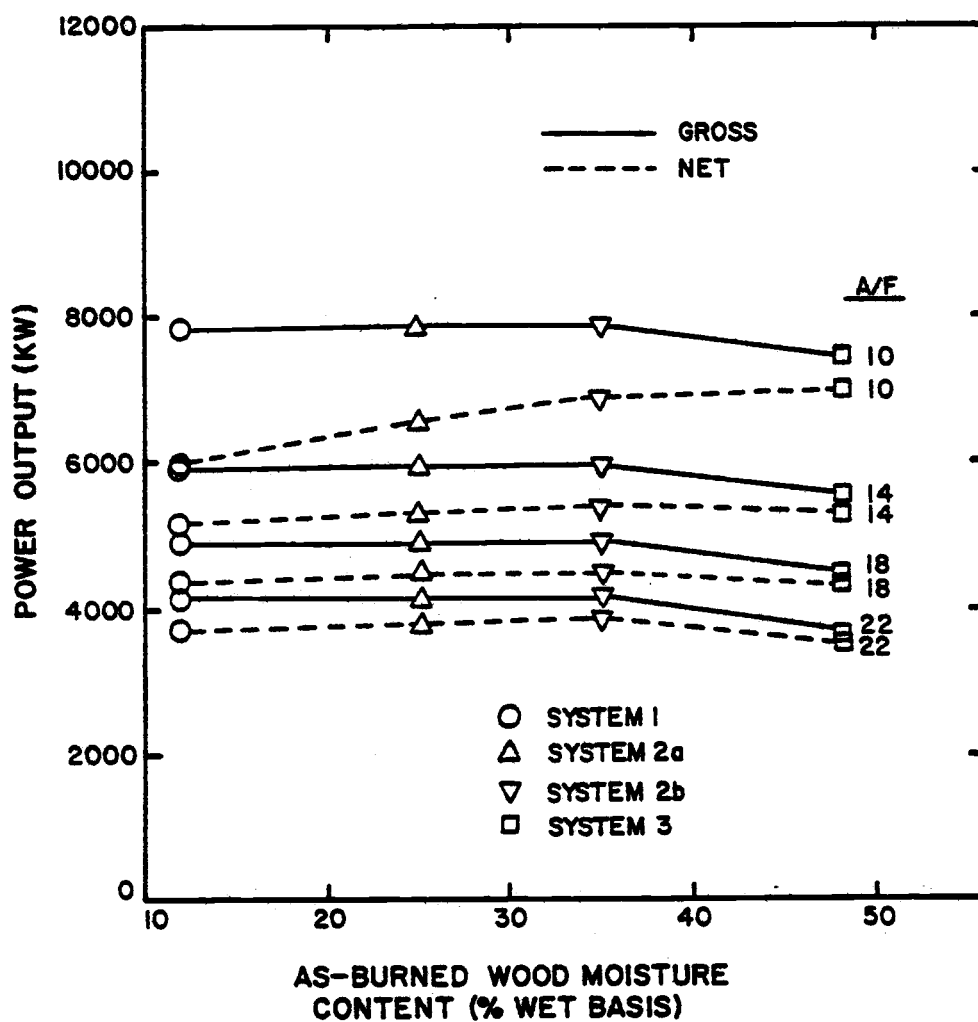


Figure 5.1 Gross and net power output as a function of "as-burned" wood moisture content at various air-fuel ratios

in turn increases the steam flow rate and increases the power out of the steam system. On the other hand, a larger amount of heat from the boiler is required to dry the fuel which brings the potential steam flow rate back down and tends to decrease the power from the steam system. What seems to be happening between systems 1 and 2 is that a balance between these factors is achieved. Less drying is done in system 2 than in system 1, however wetter fuel is burned requiring less recirculation and thus a lower gas flow rate. The two factors work against each other but tend to even out so that when drying is done, gross efficiency is approximately constant in this system with a constant air-fuel ratio.

When considering system 3, it must be emphasized that the boiler exit temperature is not effected by anything. It is an input and does not change unless the temperature is not within reason. For most of the simulations, 350 deg. F was used for this temperature. In this system, the first factor mentioned in the previous paragraph comes into play, but the second does not. When 50% moist wood is burned, the exit temperature from the combustor is lower, requiring less recirculation gas. This tends to decrease the steam flow and thus the power from the steam system. The gas exiting the boiler is at a specified temperature and therefore temperature variation of this gas does not come into play. The detrimental effect of the loss of recirculation gas is not offset in this system as it was in the other systems. The effect can be offset manually by reducing the specified temperature from the boiler. Figure 5.2 shows the effect

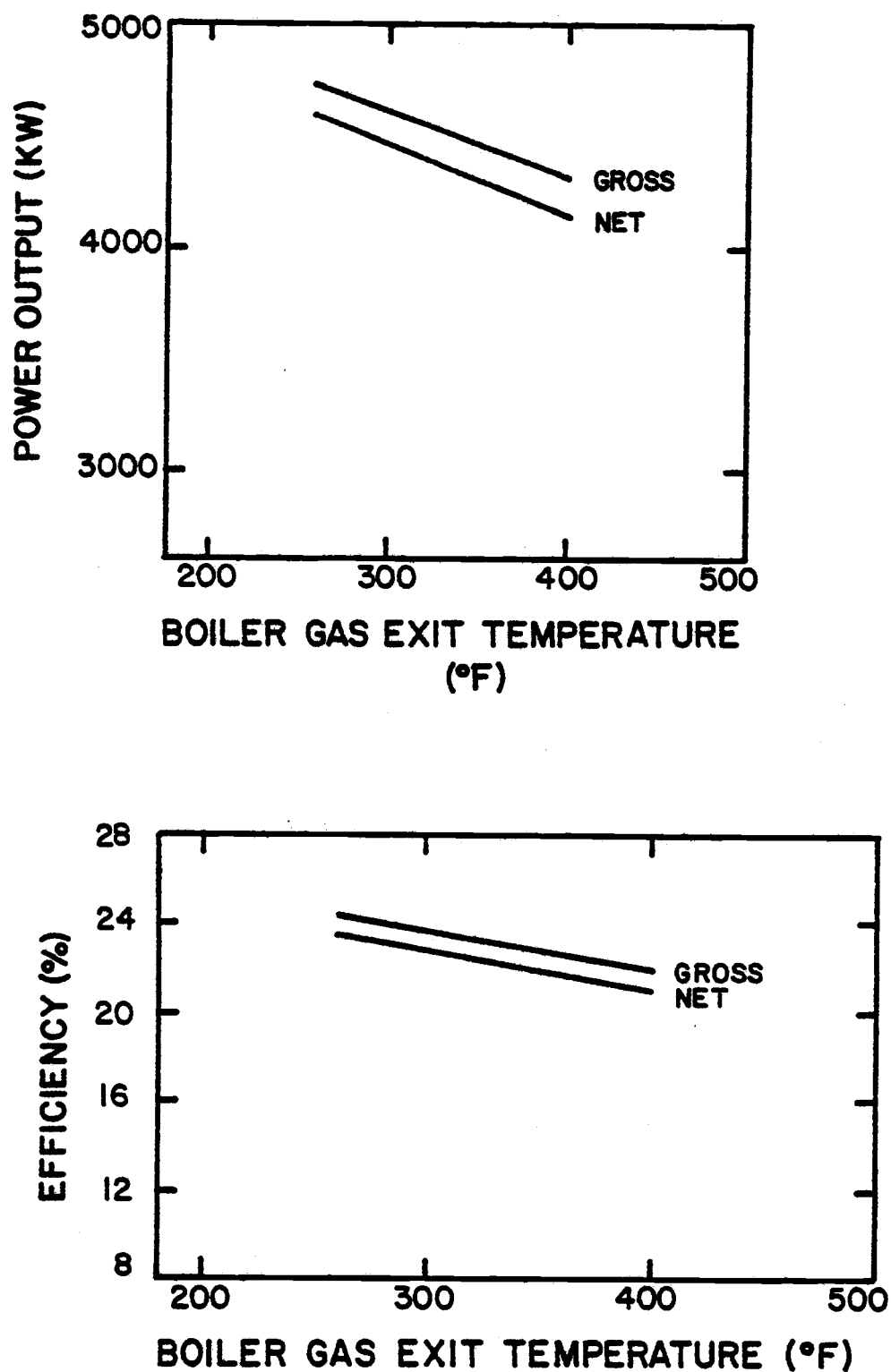


Figure 5.2 Gross and net power output and efficiency as a function of boiler gas exit temperature for system 3

of reducing this temperature on the performance of system 3. A problem arises in reducing this temperature however. As the temperature is reduced, the size of the boiler increases generally, and cost will increase. Also, the temperature can only be reduced a certain amount before the pinch point temperature in the boiler is too small.

Also from figure 5.1, it is seen that the net power output tends to increase from system 1 to systems 2a and 2b and then drops back down again (except when the air-fuel ratio was 10) for system 3. The primary reason behind the general increase in net power output with as-burned fuel moisture content has to do with the fan power. When the fuel is dried to 12% (system 1), a larger flow rate of recirculation gas is required which in itself increases the fan power in the recirculation loop. Also, a larger gas temperature is required from the boiler for drying. This increases the volume flow rate and thus the fan power required for moving the gases to the dryer and in the recirculation loop. System 2 also requires approximately 60 KW less in pulverizer power. All of the extra auxiliary power required when more drying is done decreases the net power output.

The primary reason that the net power output for system 3 decreases from system 2 is simply that the gross power output is lower (for the reasons previously discussed). The auxiliary power consumption is less for system 3 as can be seen by examining the difference between the gross and net power. The decrease in

auxiliary power consumption however, is not enough to offset the loss in power output of the steam system.

Figure 5.3 is a plot of plant efficiency vs. as-burned wood moisture content at various air-fuel ratios. With regard to air-fuel ratio, the efficiency plots are the opposite of the power plots. As mentioned previously, efficiency increases with air-fuel ratio while power output decreases as air-fuel ratio increases. The general trends of efficiency with respect to fuel moisture content however, are very similar to the power output. Note that gross efficiency for each air-fuel ratio for systems 1 and 2 is essentially the same. Also, the gross efficiency drops for system 3. These trends are the same as for the gross power output as they should be. For the same air-fuel ratio, the fuel energy into the system is the same, therefore the efficiency (gross or net) will follow the same pattern as the power output for each air-fuel ratio. Following the same line of reasoning, the plant efficiency decreases with increasing boiler gas exit temperature in system 3 in the same way that the power output decreases (see figure 5.2).

The general performance trends of the power plant with as-burned fuel moisture content are shown in figure 5.4. These plots are for system 2 (with both pulverizers) and for an air-fuel ratio of 17. Notice that gross power output and efficiency are constant while net power output and efficiency increase slightly with increasing moisture content. The reason for this has been explained previously.

Figures 5.5 through 5.8 are cross plots of figures 5.1 and 5.3

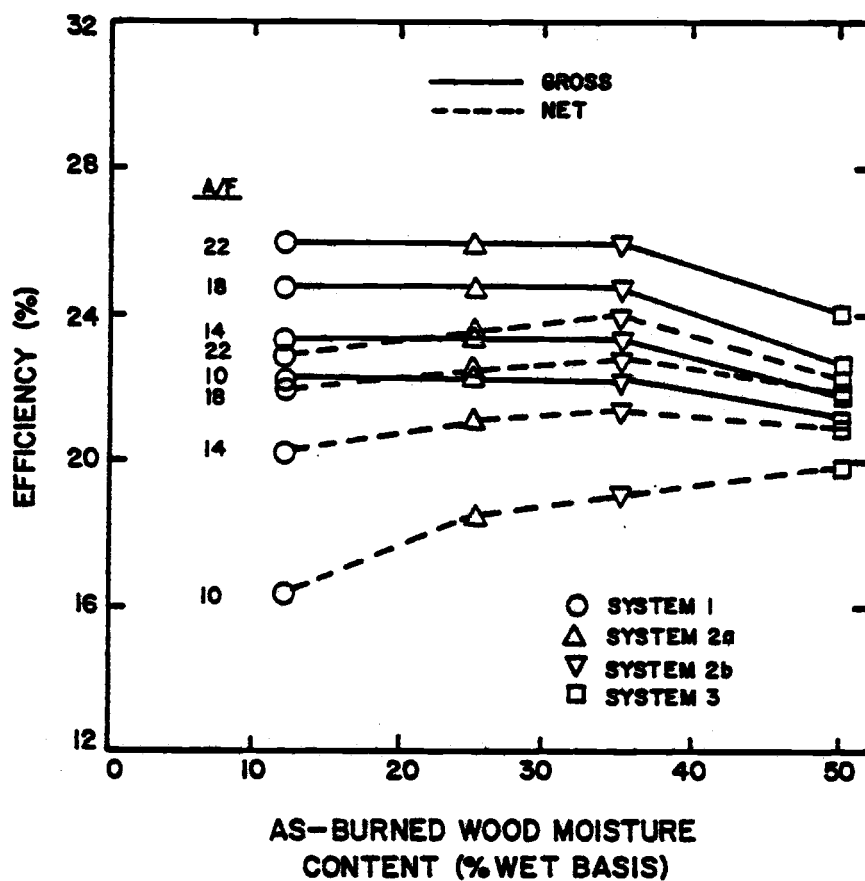


Figure 5.3 Gross and net efficiency as a function of "as-burned" wood moisture content at various air-fuel ratios

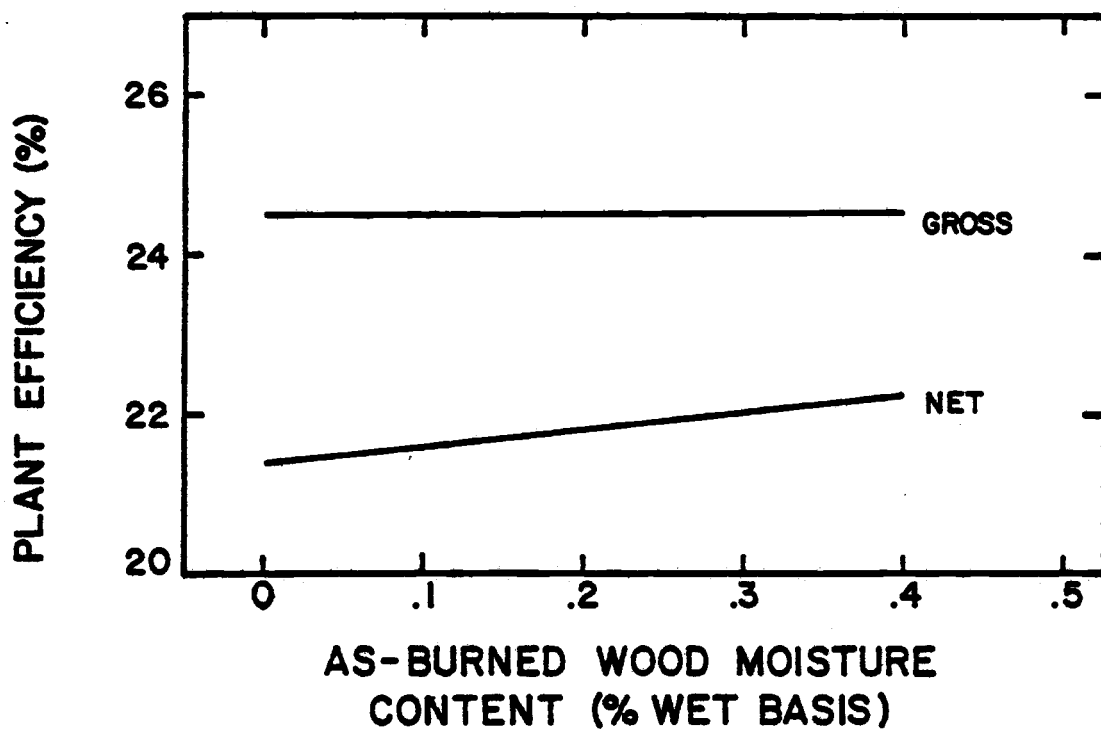
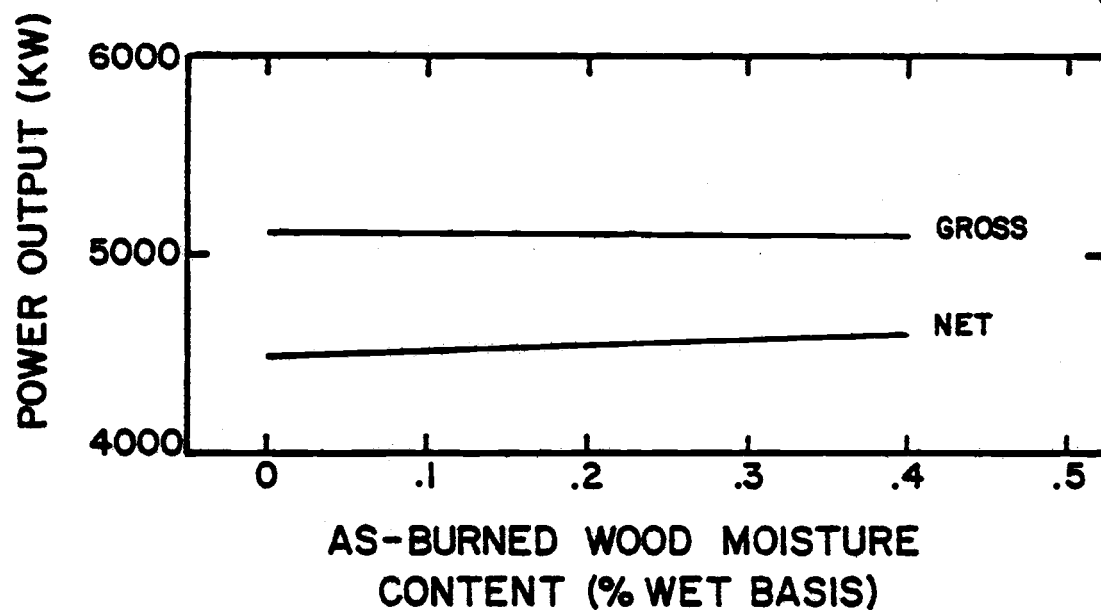


Figure 5.4 Gross and net power output and efficiency as a function of "as-burned" wood moisture content for system 2 with two pulverizers and an air-fuel ratio of 17

and show the same trends from a slightly different perspective. Figure 5.5 shows gross power output vs. air-fuel ratio for each of the systems. As previously discussed, systems 1 and 2 produce the same gross power output at each air-fuel ratio. Also, the gross power production of system 3 lies below that of systems 1 and 2 because of the lower power output of the steam cycle for system 3.

Figure 5.6 shows net power output vs. air-fuel ratio for each system. Note that at an air-fuel ratio of 10, system 3 produces the greatest net power of the systems but that as air-fuel ratio is increased, the net power from system 3 decreases more rapidly than for the other systems and actually is the lowest of the systems for an air-fuel ratio of 22. At relatively low air-fuel ratios, the fuel input rate is high causing large gas flow rates and high temperatures from the combustor. More recirculation gas is required to cool the combustion gas in this case which tends to increase efficiency. When drying is done however (systems 1 and 2), the gas temperature from the boiler is greater than when drying is not done and, because of the high gas flow rate initially, the fan power consumption is very large. The great fan power requirements for systems 1 and 2 actually offsets the greater gross power outputs of these systems and causes the net power output to be lower. As air-fuel ratio increases, the gas flow rate decreases and fan power decreases, causing the net power output of systems 1 and 2 to rise above that of system 3 as is the gross power.

Figure 5.7 shows the difference in gross efficiency between

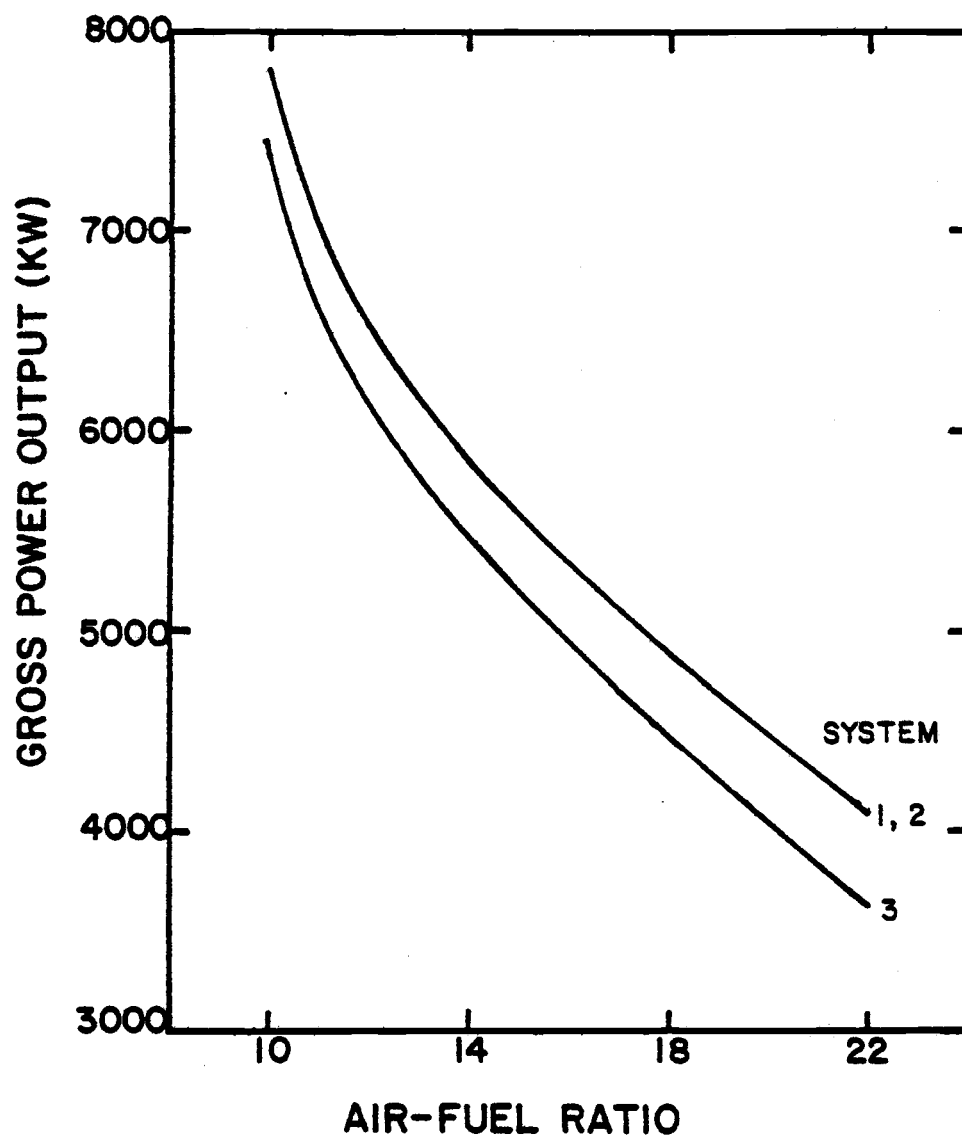


Figure 5.5 Gross power output as a function of air-fuel ratio

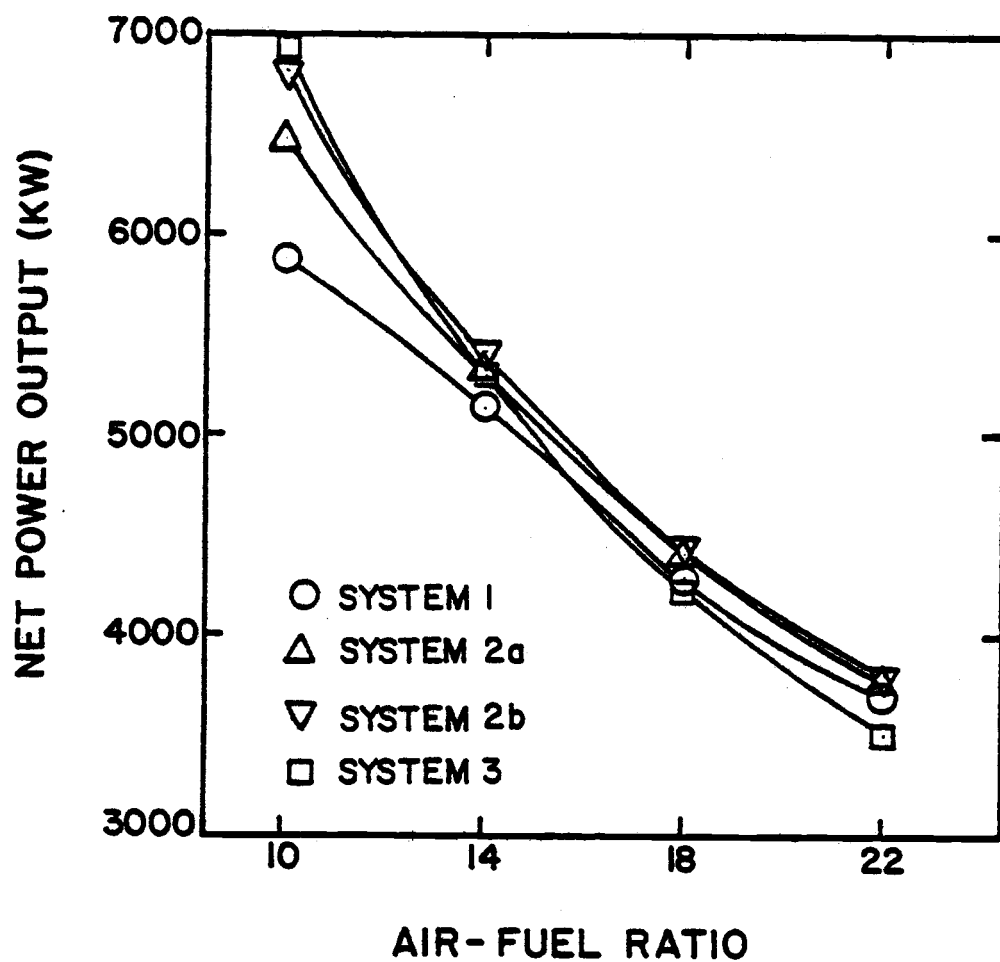


Figure 5.6 Net power output as a function of air-fuel ratio

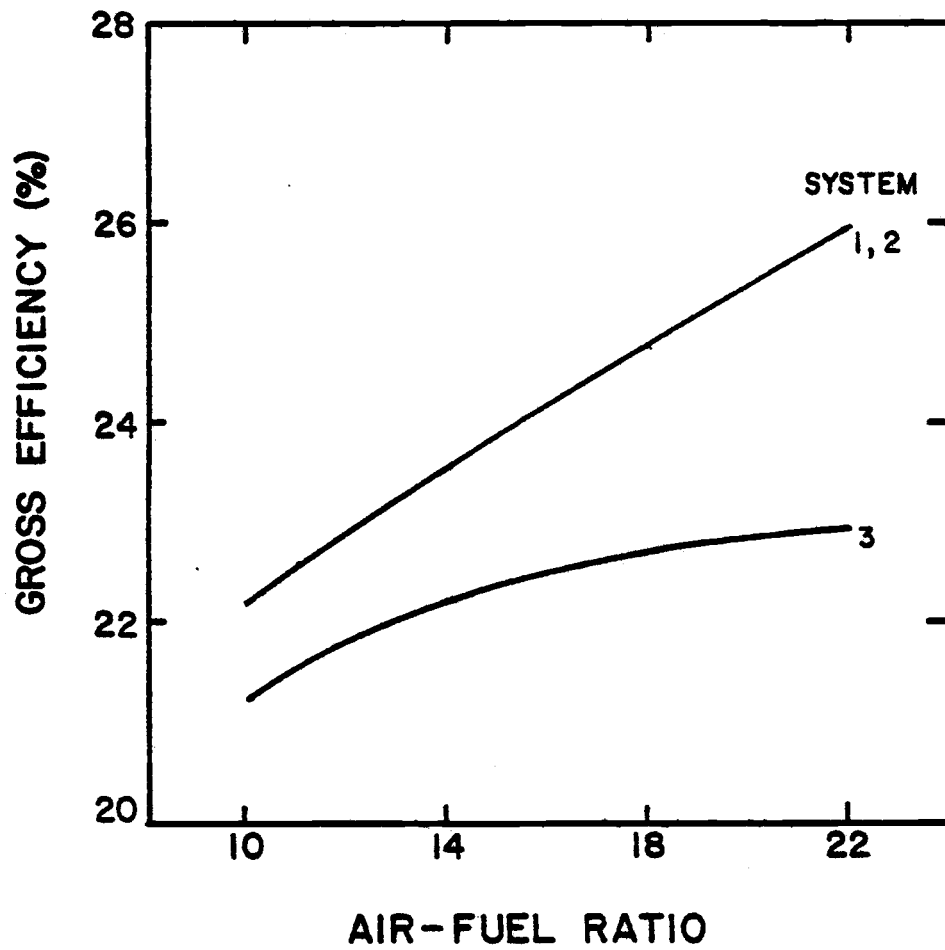


Figure 5.7 Gross plant efficiency as a function of air-fuel ratio

systems 1 and 2 and system 3 as air-fuel ratio changes. Note that this difference increases as air-fuel ratio increases. At greater air-fuel ratios, more gas exits the system per unit of fuel which means that more energy will be lost in the exhaust gas per unit of fuel energy into the system. For system 3, the exiting gas temperature is held at 350 deg. F while for systems 1 and 2, the exiting gas temperature is 190 deg. F. Because of this lower exhaust gas temperature for systems 1 and 2, the energy lost in the exhaust (per unit of fuel energy in) by increasing the air-fuel ratio is less than that in system 3.

As air-fuel ratio increases, the rate of recycle gas decreases in all systems, however to a slightly smaller degree in system 3 than in systems 1 and 2. This decreases the power output of the steam system in systems 1 and 2 slightly, but not significantly more than in system 3. However, because the gross power output of system 3 is less than that of systems 1 and 2, and the fuel energy in is the same for the same air-fuel ratio, approximately the same drop in power due to increasing the air-fuel ratio in system 3 and systems 1 and 2, will reduce the gross efficiency of system 3 a greater amount.

The next set of curves (figure 5.8) shows net plant efficiency as a function of air-fuel ratio for the different systems. Note that the net efficiency of system 3 is greater than that for systems 1 and 2 at an air-fuel ratio of 10 but drops below that for systems 1 and 2 when air-fuel ratio is increased to 22. At an air-fuel ratio of approximately 17 or 18, systems 1 and 3 are essentially equivalent in

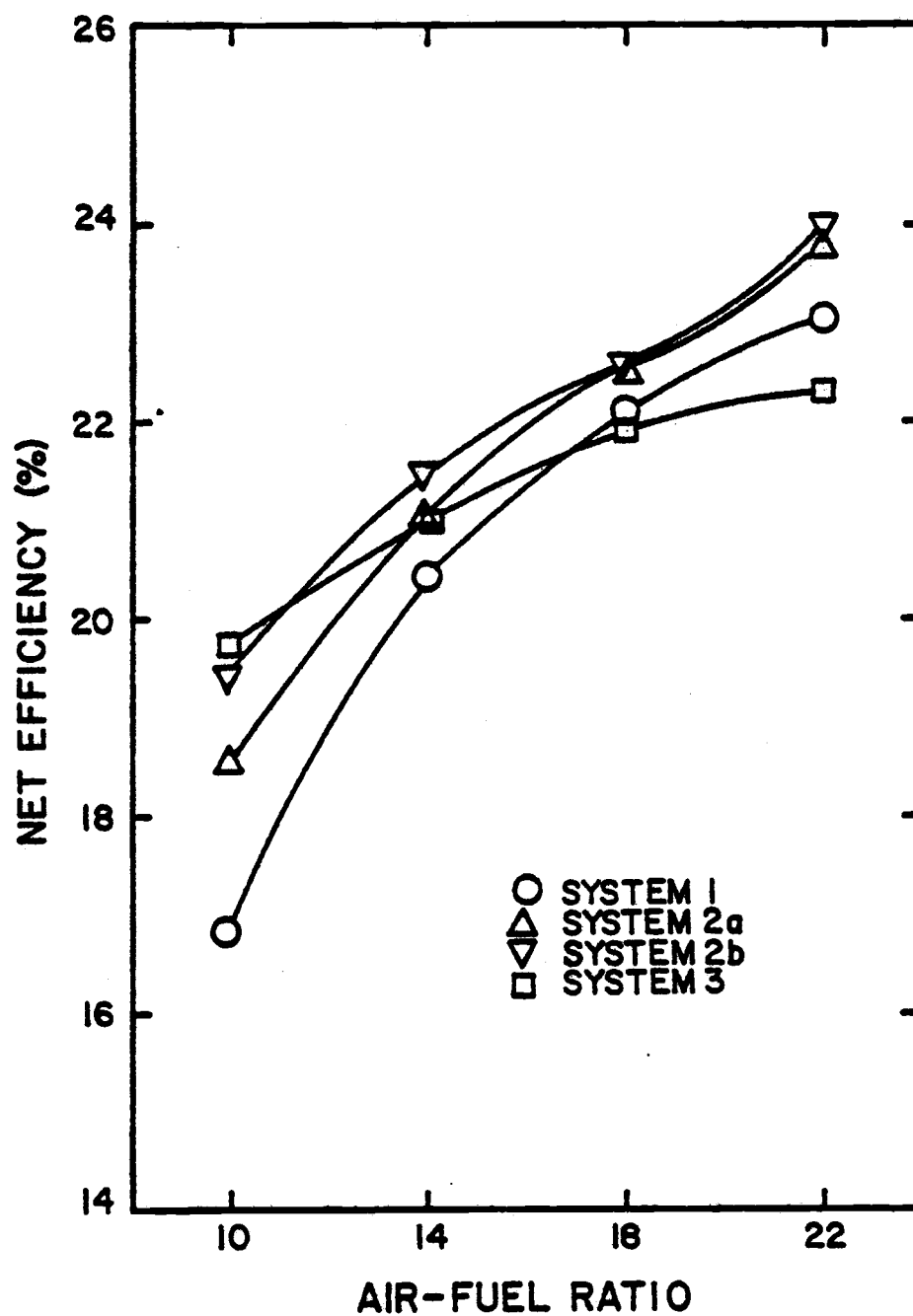


Figure 5.8 Net plant efficiency as a function of air-fuel ratio

efficiency. These trends are exactly the same as for the net power output again because at the same air-fuel ratio, fuel energy input is the same so net efficiency and net power will be directly related. Note also that system 2 net efficiency is greater than system 1 and with less drying (system 2b vs. 2a), the net efficiency increases as did net power output. This is again due to the greater auxiliary power required for greater amounts of drying.

The final set of simulations was done to determine the effect of varying the moisture content of the fuel before any preparation is done. The dried fuel moisture content was held at 12 percent and the wet fuel moisture was varied from 20 to 60 percent (system 1 with various amounts of drying). Figure 5.9 shows the results of these tests. As would be expected, the power and efficiency of the system decreased substantially with increasing fuel moisture. This is simply due to the loss of larger amounts of water vapor up the stack for higher moisture content fuels. This fuel moisture however is relatively uncontrollable so these curves simply give an indication as to what will happen to the plant performance if different moisture content woods are used.

5.3 Summary of System Comparisons

From the previous discussion and analysis of the systems, several points are particularly notable. First, system 2 shows better performance than does system 1. Also the performance of system 2 increases as less drying is done. System 3 however, again

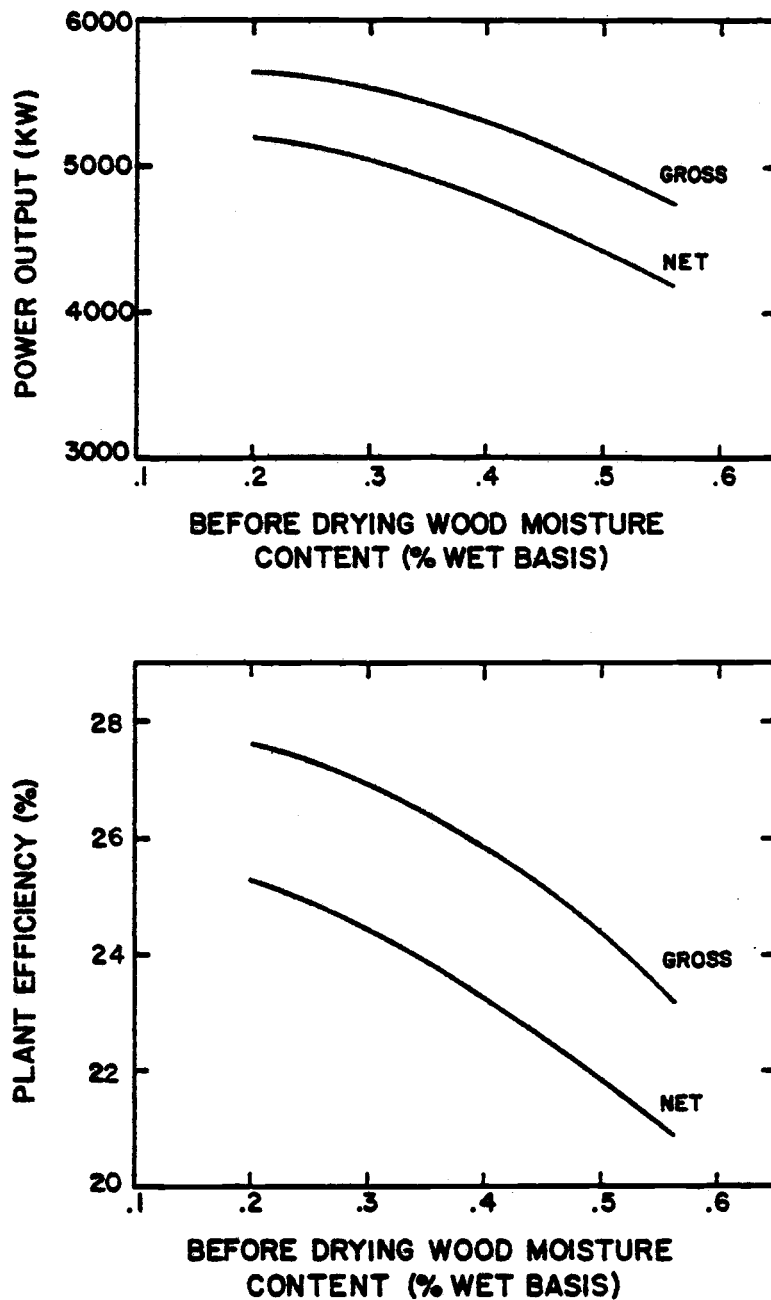


Figure 5.9 Gross and net power output and efficiency as a function of before drying fuel moisture content for system 2

shows worse performance than system 2. What this essentially means is that the performance of the system increases with decreasing drying up to the point when the dryer is taken out and then there is a "step" drop in performance. This is due to the fixed boiler gas exit temperature for system 3 as explained previously. The step drop in performance of system 3 can at least partially be eliminated by decreasing the boiler exit gas temperature. If this temperature is decreased to as low a value as possible before pinch point problems develop in the boiler, the performance of this modified system 3 is as good or better than system 2. This is not completely realistic however because as the temperature is lowered, the size of the boiler increases and thus cost constraints may prevent this option. It may be proposed then to use system 2 but with only a minimal amount of drying. In this case, the same problem arises because the dryer will set the boiler exit gas temperature at a very low value and again pinch point, size, and cost problems occur. Probably the most realistic alternative is to use system 2 with not a lot of drying but enough so that boiler problems do not arise. System 2b might be a good option.

The air-fuel ratio proposed for the power plant is in the neighborhood of 17. At this air-fuel ratio, systems 1 and 3 are essentially equivalent with regard to performance although an economic analysis would probably dictate the use of one or the other. System 2 however, is again the best from a performance standpoint.

5.4 Conclusions

The objective of this study was to analyze the effects of parameter changes regarding the combustor and dryer on the performance (power output and efficiency) of the power plant. The first thing required was to model all of the components in the system and link them together with an executive program. Computer models were written to simulate the performance of a combustor and a dryer utilizing wood as the fuel for the plant. The models are general and use mass and energy balances over a control volume to simulate the appropriate process.

Simulations were run to determine the effect of varying the air-fuel ratio and the amount of drying and other fuel preparation done on system performance. The simulations were separated to represent three "systems". System 1 included the dryer to dry the fuel down to 12% wet basis moisture content, two pulverizers, and a suspension burner. System 2 included the dryer, 1 pulverizer, and a grate burner. System 2 was analyzed as two different systems: system 2a dried the fuel to 25% wet basis moisture content, and system 2b dried the fuel to 35% moisture content. Exiting gas temperature from systems 1 and 2 was set to 190 deg. F. Finally, system 3 has no dryer or any other fuel preparation equipment, and a grate burner. Exiting gas temperature for system 3 was held at 350 deg. F. Simulations were also run to determine the performance effect of varying the exiting gas temperature for system 3 and the effect of varying the "before drying" fuel moisture content on system 1. All

other parameters involved in the process were held constant for each set of simulations.

The systems simulated were chosen to represent realistic equipment arrangements. The proposed suspension burner requires very strict fuel preparation that would only allow its use when the fuel was dried to below 15% wet basis moisture content and was pulverized into very small particles. This represents the test case with maximum drying and fuel preparation (system 1). The proposed alternative to this was to use a grate type burner which has few restrictions on the fuel. The simulations where the fuel was prepared less or not at all, represent the use of a grate type burner (systems 2 and 3). Parameters within the combustor, such as heat losses, unburned carbon etc., were not changed between the simulations representing the different combustors.

From the analysis, several things become evident.

1. In general, increasing air-fuel ratio means decreasing power output while plant efficiency increases. This is the case for every set of simulations.

2. A relatively dry "source" of fuel offers substantial performance benefits over wetter fuel. The source of fuel however, is generally going to be unchangeable so that this factor will not usually come into play in optimizing the system performance.

3. System 2 showed performance advantages over both system 1 and system 3, and decreased drying in system 2 further improved performance. From a practical standpoint, system 2b represented a

good system because performance is good relative to the other systems yet boiler problems would probably not arise.

4. Performance of system 3 can be improved substantially (although generally not up to that of system 2b) by decreasing the boiler gas exit temperature below the 350 deg. F temperature used for most simulations. However, problems may develop in the boiler if the temperature is lowered too much.

5. At the proposed air-fuel ratio of 17, systems 1 and 3 show similar performance. The performance of system 3 can be improved slightly again by decreasing the boiler exit gas temperature. System 2 however, shows better performance than either system 1 or system 3.

Several factors related to this analysis have not been considered in depth here. First is the size of the components. Some of the conditions tested may actually require a component to be much larger than would actually be acceptable (or practical). Closely related to the size of components is the cost. Very large components would cost too much to be economically worthwhile. Also, the subject of movability of the system has not been considered. The power plant is supposed to meet movable for fuel supply conditions which places some restrictions on the components and ducting, but these restrictions have not been considered here. This analysis simply demonstrated performance effects without the specific size, cost, and movability constraints. These, of course, will have to be taken into account in the final analysis and will govern the final design of the system.

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APPENDICIES

APPENDIX A

COMBUSTOR MODEL SUBROUTINE

```

SUBROUTINE BURNER(HHV,radlos,xash,xdir,XC,XH2,XN2,XO2,XH2O,
12      unbcbn,XCCO,AFrat,yCO2in,yH2Oin,yO2in,yN2in,yArin,yCOin,
12      yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO,Tds,Pds,Pair,dPburn,Tair,
12      MRair,Tamb,yeCO2,yeH2O,yeO2,yeN2,yeAr,yeCO,LHV1,LHV2,
12      MRwdin,Mrbdwd,Metot,Tadflm,Pfgex,Qrel2,PRINT)

```

```

C-----
C  SUBROUTINE BURNER
C    THIS SUBROUTINE TAKES THE INPUT VARIABLES PROVIDED BY OTHER
C    COMPONENTS, OR DIRECT INPUTS AND CALCULATES EXIT TEMPERATURES,
C    GAS COMPOSITIONS, CONDITIONS OF THE EXIT STREAMS, LOSSES DUE
C    TO RADIATION, UNBURNED CARBON, FORMATION OF CO, DIRT IN THE
C    FUEL ETC.. IT ALSO CALCULATES AND PRINTS OUT A BREAKDOWN OF
C    THE FUEL COMPOSITION, FLUE-GAS, DOES AN ENERGY BREAKDOWN AND
C    A SECOND LAW ANALYSIS OF THE COMBUSTOR.
C    THIS IS A GENERAL PROGRAM NOT SET UP FOR A SPECIFIC UNIT.
C    LOSSES DUE TO RADIATION, UNBURNED CARBON, AND CO ARE CALCU-
C    LATED FROM INPUTS OF FRACTIONS OR PERCENTAGES INDICATING
C    AMOUNTS FOR THE LOSSES.
C
C    THE ENERGY BALANCE FOR THIS PROGRAM USES VARIABLE Cp
C    EQUATIONS IN ANOTHER FUNCTION FOR THE FLUE-GAS.
C
C    WRITTEN BY TIM BAUER
C    DEPARTMENT OF MECHANICAL ENGINEERING
C    OREGON STATE UNIVERSITY
C    AUGUST 11, 1983
C-----

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* NOMENCLATURE:

* Most of the variables are abbreviations or shortened
 * statements describing the variable. Many of them consist of
 * two or three parts each of which means something. For example,
 * AVrtea: the AV means availability, the rte means rate, and the a
 * stands for the substance in question - air. Put together, it
 * means the availability rate of the air into the combustor.
 * Below, the parts will be split up into abbreviations and
 * substance abbreviations.

* Substance Abbreviations:

* a or air - air
 * ar - argon
 * ash - ash
 * C or cbn - carbon

*	CO	- carbon monoxide
*	CO2	- carbon dioxide
*	dir or dirt	- dirt or other noncombustibles (excl. ash)
*	f	- fuel
*	fg or fgas or g	- flue-gas
*	H2	- hydrogen
*	H2O or watr	- water
*	N2	- nitrogen
*	O2	- oxygen
*	prod	- products of combustion
*	wd or wood	- wood

Abbreviations:

*	AF	- air-fuel
*	AV	- availability
*	bd	- bone-dry
*	brn or burn	- burn (condition happens during burning)
*	d	- dry
*	dcf	- dry, clean fuel
*	Dp	- pressure drop through unit
*	e or ex	- exiting condition
*	in	- inlet condition
*	irr	- irreversibility
*	m or MW	- molecular weight (lb/mole)
*	M	- mass
*	MR	- mass rate
*	ni	- number of moles into unit/lb of fuel in
*	P	- pressure (generally inches H2O)
*	Q	- heat released, absorbed, or lost
*	rat	- ratio (when used with a substance abbreviation it is lb subst/lb wet, dirty fuel)
*	rte	- rate (generally lb/sec, but depends on input)
*	T	- temperature (deg. F)
*	unb	- unburned
*	x(C,O2,N2,H2,ASH)	- mass ratio of subst. in list to dry clean fuel.
*	wdin	- wood into unit
*	y??in	- mole fraction of subst. ?? into unit
*	yd??	- mole fraction of subst. ?? in dry gas
*	ye??	- mole fraction of subst. ?? exiting unit
*	yr??	- dead state mole fractions

Others

*	HHV	- higher heating value
*	metot	- total mass rate of gas exiting combustor
*	Miatd	- total mass of dry air in/lb fuel burned

```

*      radios      - fraction of available energy lost to radiation
*      seceff      - second law efficiency
*      Tadflm      - adiabatic flame temperature
*      XA          - fraction excess air
*      xcco        - fraction of carbon burned to CO
*      xdcf        - 1b dry, clean fuel/1b wet, dirty fuel
*      xdirt       - 1b dirt/1b dry, clean fuel
*      XH2O        - 1b H2O/1b wet, clean fuel
*      xwcf        - 1b wet, clean fuel/1b wet, dirty fuel
*

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      implicit real (m-n)
      real irrbrn,LHV1,LHV2
      logical print*2
      data mCO2,mH2O,mO2,mN2,mAr /44.01,18.016,32.,28.016,39.944/
      data mCO /28.01/
      xdirt2=xdirt*(1.-xH2O)
      xwcf=1./(1.+xdirt2)
      Cpdirty=.20
      H2Orat=xH2O*xwcf
      dirrat=xdirt2*xwcf
      dcfrat=(1.-xH2O)*xwcf
      Crat=dcfrat*xC
      H2rat=dcfrat*xH2
      O2rat=dcfrat*xO2
      N2rat=dcfrat*xN2
      ashrat=dcfrat*xash
      MWair=yO2in*mO2+yN2in*mN2+yArin*mAr+yCO2in*mCO2+yH2Oin*mH2O
      MRdair=(1.-(yH2Oin*mH2O)/MWair)*MRair
      MRbdwd=MRdair/AFrat
C-----CALCULATE MASS RATE OF BIOMASS INTO COMBUSTOR-----
      MRwdin=MRbdwd/dcfrat
      MRH2Ow=H2Orat*MRwdin
      MRdirt=MRwdin*dirrat
      MRash=MRwdin*ashrat
      MRdcf=MRwdin*dcfrat
      W=(yH2Oin*mH2O)/(yN2in*mN2+yO2in*mO2+yArin*mAr+yCO2in*mCO2)
C-----PERFORM STOICHIOMETRY-----
      CALL STOICH(XC,XO2,XH2,XN2,XASH,XH2O,yCO2in,yH2Oin,yO2in,yN2in,
1/2      yArin,yCOin,w,MRair,MRwdin,unbcbn,xcco,mwfg,mwfgd,
1/2      netot,netotd,XA,xwcf,mwair,xdcf,yeCO2,yeH2O,yeO2,yeN2,
1/2      yeAr,yeCO,ydCO2,ydO2,ydN2,ydAr,ydCO,nCO,MCunb,NIH2,
1/2      wfgex,niatd,niatw,niH2Of,niH2Oa,miatd)
C-----TOTAL WEIGHT OF FLUE-GAS EXITING COMBUSTOR (FOR MASS BALANCE)-
      metot=netot*mwfg*MRwdin
      MRunbC=MCunb*MRwdin
      Mextot=Metot+MRash+MRdirt+MRunbC
C-----PRESSURE LOSS THROUGH THE COMBUSTOR (GENERALLY 16" BUT VARIABLE
      Pfgex=Pair-dpburn
      Pfgex2=Pfgex*.0361+Pds

```

```

Pair2=pair*.0361+Pds
C-----CALCULATION OF DRY AIR MOLE FRACTIONS-----
nrCO2=Niatw*yCO2in
nrO2=Niatw*yO2in
nrN2=Niatw*yN2in
nrAr=Niatw*yArin
nrCO=Niatw*yCOin
nrfgt=nrCO2+nrO2+nrN2+nrAr+nrCO
ydaCO2=nrCO2/nrfgt
ydaO2=nrO2/nrfgt
ydaN2=nrN2/nrfgt
ydaAr=nrAr/nrfgt
ydaCO=nrCO/nrfgt
Mwdair=ydaCO2*mCO2+ydaO2*mO2+ydaN2*mN2+ydaAr*mAr+ydaCO*mCO
C-----HEAT RELEASED IN COMBUSTION (PER LB OF WET FUEL)-----
Qrel=xdcf*HHV
Qrel2=Qrel*MRwdin
C-----HEAT PROVIDED FROM HOT, DRY INLET AIR-----
Qair=(Niatd*(hgast(Tair,Tds,ydaCO2,0.,ydaO2,ydaN2,ydaAr,ydaCO)-
1/2 hgast(Tamb,Tds,ydaCO2,0.,ydaO2,ydaN2,ydaAr,ydaCO)))*mwaIr
Qair2=Qair*MRwdin
C-----HEAT LOSS DUE TO RADIATION-----
Qloss=radlos*(Qrel+Qair)
Qloss2=Qloss*MRwdin
C-----HEAT REQUIRED TO EVAPORATE WATER FORMED IN COMBUSTION (FROM THE
C-----DEFINITION OF HIGHER HEATING VALUE)-----
qlh=nih2*mH2O*1060.
LHV1=HHV-qlh/dcfraT
C-----HEAT TO HEAT UP AND BOIL OFF THE WATER IN THE FUEL-----
if (xh2o .lt. .25) then
HfgH2O=((1335.-1456.*xh2o)+1335.)/2.
else
HfgH2O=(971.*(xh2o-.25)+288.25)/xh2o
endif
qboil=nih2of*18.*(1.*(212.-tamb)+HfgH2O)
LHV2=LHV1-(nih2of*18.*HfgH2O)/dcfraT
C-----
C      QW1 IS THE HEAT REQUIRED TO RAISE THE WATER ORIGINALLY IN THE
C      WOOD FROM 212. TO EXIT TEMPERATURE. IT IS BROKEN UP INTO 2
C      PARTS DUE TO THE NATURE OF THE EQUATION (CONTAINS THE UNKNOWN
C      TEXIT WHICH MUST BE ON THE OTHER SIDE OF THE EQUAL SIGN.
C      QW1A IS ONLY THE PART AT 212.. THE SAME THING HOLDS FOR QW2
C      BUT IT IS FOR THE WATER FORMED IN COMBUSTION RAISING FROM
C      TAMB NOT 212. ALSO IT HOLDS FOR QH2OA WHICH STANDS FOR THE
C      HEAT REQUIRED TO HEAT THE WATER IN THE AIR FROM AMBIENT TEMP
C      TO EXIT TEMP. ALSO QPROD IS THE HEAT ABSORBED BY THE
C      COMBUSTION GASES IS GOING FROM AMBIENT TO EXIT TEMPERATURE AND
C      IS ALSO BROKEN UP FOR THE SAME REASON.
C-----
qwlA=nih2of*hgast(212.,Tds,0.,1.,0.,0.,0.,0.)*mH2O

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qw2a=nih2*hgast(Tamb,Tds,0.,1.,0.,0.,0.,0.)*mH2O
qh2oaa=nih2oa*hgast(tair,Tds,0.,1.,0.,0.,0.,0.)*mH2O
qproda=netotd*hgast(tamb,Tds,ydCO2,0.,ydO2,ydN2,ydAr,ydCO)*mwfgd
C-----NIWATR IS THE TOTAL NO. OF MOLES OF H2O EXITING THE BURNER-----
niwatr=nih2of+nih2+nih2oa
C-----HEAT LOSS DUE TO SPECIFIED AMOUNT OF UNBURNED CARBON-----
QunbC=MCunb*14100.
QunbC2=QunbC*MRwdin
C-----HEAT LOSS DUE TO CARBON BURNING TO CO INSTEAD OF CO2-----
QCO=NCO*mCO*9755.
QCOB=QCO*MRwdin
C-----HEAT LOSS DUE TO HEATING UP THE DIRT ETC. THEN LOSING IT-----
Qdirta=dirrat*Cpdirt*tamb
C-----Q1 REPRESENTS ONE SIDE OF THE EQUATION-----
Q1=Qrel+Qair-Qloss-Qlh-Qboil+Qwla+Qw2a+QH2Oaa+Qproda-QunbC-QCO+
  1/2 Qdirta
C-----ITERATE FOR TEXIT THROUGH THE ENTHALPY FUNCTIONS
C      USING NEWTONS METHOD-----
      toler=.0005
      t=2000.
      deltat=100.
      itsmax=100
      do 1 iter=1,itsmax
        r=Q2(t,Tds,Q1,netot,dirrat,Cpdirt,yeCO2,yeH2O,yeO2,yeN2,yeAr,
          1/2 yeCO,mwfg)
        dQdt=(Q2(t+deltat,Tds,Q1,netot,dirrat,Cpdirt,yeCO2,yeH2O,yeO2,
          1/2 yeN2,yeAr,yeCO,mwfg)-r)/deltat
        deltat=r/dQdt
        t=t-deltat
        if (abs(deltat) .lt. toler*t) go to 2
      1 continue
      2 continue
      if (iter .gt. itsmax) write(8,10) iter
10 format(' warning: ',i3,' ITERATIONS WITH NO CONVERGENCE.')
      tadflm=t
      IF (PRINT) THEN
C-----
C      THESE WITH A b ARE THE SECOND PARTS OF THE VARIABLES LISTED
C      EARLIER.
C-----
      Qwlb=nih2of*hgast(tadflm,Tds,0.,1.,0.,0.,0.,0.)*mH2O
      Qh2oab=nih2oa*hgast(tadflm,Tds,0.,1.,0.,0.,0.,0.)*mH2O
      Qw2b=nih2*hgast(tadflm,Tds,0.,1.,0.,0.,0.,0.)*mH2O
      Qprodb=netotd*hgast(tadflm,Tds,ydCO2,0.,ydO2,ydN2,ydAr,ydCO)*
        1/2 mwfgd
      Qdirtb=dirrat*Cpdirt*tadflm
C-----HEAT REQUIRED BY THE WATER IN THE WOOD FROM TAMB TO TEXIT-----
      Qh2owd=Qboil-Qwla+Qwlb
C-----HEAT REQUIRED BY THE WATER IN THE AIR FROM TAMB TO TEXIT-----
      Qh2oa=Qh2oab-Qh2oaa

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C-----TOTAL HEAT REQUIRED BY THE WATER FORMED IN COMBUSTION-----
  Qh2o1=Q1h-Qw2a+Qw2b
C-----TOTAL HEAT REQUIRED BY ALL OF THE WATER INVOLVED-----
  Qh2o=Qh2owd+Qh2oa+Qh2o1
  QH2O2=QH2O*MRwdin
  Qdirt=Qdirtb-Qdirta
  Qdirt2=Qdirt*MRwdin
C-----TOTAL HEAT ABSORBED BY THE DRY PRODUCTS OF COMBUSTION-----
  Qprod=Qprodb-Qproda+QH2O
  Qprod2=Qprod*MRwdin
c-----TOTAL HEAT LOST DUE TO EXITING PRODUCTS-----
  Qtot1=QunbC+QCO+Qdirt+Qprod+Qloss
  Qtot2=Qtot1*MRwdin
c-----SECOND LAW ANALYSIS-----
  AVwood=HHV
  AVwatr=hfwat(tamb)-(Tds+459.67)*sfwt(Tamb)-(hfwat(Tds)-(Tds+459.67)*
  1/2 sfwt(Tds))
  AVrtew=AVwatr*MRH2Ow
  AVrtef=HHV*MRbdwd*1.0551
  AVair=HgasT(Tair,Tds,yCO2in,yH2Oin,yO2in,yN2in,yArin,yCOin)-(Tds+
  1/2 459.67)*SgastP(Tair,Pair2,Tds,Pds,yCO2in,yH2Oin,yO2in,yN2in,
  1/2 yArin,yCOin,yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
  AVfgas=HgasT(Tadflm,Tds,yeCO2,yeH2O,yeO2,yeN2,yeAr,yeCO)-(Tds+
  1/2 459.67)*SgastP(Tadflm,Pfgex2,Tds,Pds,yeCO2,yeH2O,yeO2,yeN2,
  1/2 yeAr,yeCO,yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
  AVrtea=MRair*AVair*1.0551
  AVrteg=AVfgas*Metot*1.0551
  Irrbrn=AVrtef+AVrtea+AVrtew-AVrteg
  seceff=AVrteg/(AVrtef+AVrtea+AVrtew)*100.
C-----TABULATION OF RESULTS-----
  WRITE(8,20) 'COMBUSTOR.....REV. NO. 3'
  20 FORMAT(8X,A/'O')
  Snodebug
  WRITE(8,30) 'FUEL SPECIFICATIONS'
  30 FORMAT(8X,A/' ')
  WRITE(8,40) 'Constituent          Mass Fraction          Mass',
  1/2 '          Fraction'
  40 FORMAT(11X,A,A)
  WRITE(8,40) '
  1/2 ' Burned'
  write(8,50) 'Carbon          ',XC,Crat
  write(8,60) 'Oxygen          ',XO2,O2rat
  write(8,60) 'Hydrogen        ',XH2,H2rat
  write(8,60) 'Nitrogen        ',XN2,N2rat
  write(8,60) 'Ash             ',Xash,ashrat
  write(8,70) 'Water           ', '-----',H2Orat
  write(8,70) 'Dirt etc.       ', '-----',dirrat
  50 format('O',10X,a,f5.4,19x,f5.4)
  60 format(11x,a,f5.4,19x,f5.4)
  70 format(11x,a,a,19x,f5.4)

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write(8,80)'NOTE: Input wood moisture content is ',XH20,' lb ',
1/2      'H2O/lb WET, CLEAN fuel'
80 format('0',10X,a,f4.3,a,a)
write(8,82)'      Dirt etc. is input as ',xdirt,' lb dirt etc./',
1/2      'lb. dry, clean fuel'
82 format(11X,a,f5.4,a,a)
write(8,90)'Higher Heating Value          ',HHV,' Btu/lb (dry, ',
1/2      'clean) fuel'
write(8,90)'Lower Heating value (def)      ',LHV1,' Btu/lb (dry,',
1/2      'clean) fuel'
write(8,90)'Lower Heating value (2nd def) ',LHV2,' Btu/lb (dry,',
1/2      'clean) fuel'
90 format('0',10X,a,f7.1,a,a/'0')
write(8,30)'INPUT CONDITIONS TO COMBUSTOR'
write(8,100)'Air-Fuel ratio (dry to dry)      ',AFrat,' '
write(8,100)'Fraction radiation loss          ',radlos,' '
write(8,100)'Fraction unburned carbon          ',unbcbn,' '
write(8,100)'Fraction of carbon burned to CO    ',xcco,' '
write(8,100)'Mass rate of inlet air            ',MRair,' lb/sec'
write(8,100)'Inlet air humidity ratio          ',w,' '
WRITE(8,100)'Inlet air temperature            ',Tair,' deg. F'
WRITE(8,100)'Ambient air temperature          ',Tamb,' deg. F'
WRITE(8,100)'Inlet air pressure                ',PAIR,' in H2~'
write(8,100)'Reference temperature            ',Tds,' deg. F'
write(8,110)'Reference pressure                ',Pds,' in H2O'
100 format(11X,a,f10.4,a)
110 format(11X,a,f10.4,a/'0')
write(8,30)'INLET AND EXIT STREAMS'
WRITE(8,200)'Mass rate of ',XH20*100.,'% moist fuel required ',
1/2      ' = ',MRwdin,' lb/sec'
write(8,210)'Mass rate of inlet air from turbine      = ',
1/2      MRair,' lb/sec'
200 format(11X,a,f4.1,a,a,f8.4,a)
210 format(11X,a,f8.4,a)
write(8,'(10X,a,a)')'
1/2      ' -----'
write(8,220)'Total Inlet
1/2      MRwdin+MRair
220 format(11X,a,f8.4/' ')
write(8,230)'Mass rate of flue-gas exiting (before mixing) = ',
1/2      Metot,' lb/sec'
write(8,230)'Mass rate of ash exiting with flue-gas      = ',
1/2      MRash,' lb/sec'
write(8,230)'Mass rate of dirt etc.                  = ',
1/2      mrdirt,' lb/sec'
write(8,230)'Mass rate of unburned Carbon exiting with gas = ',
1/2      MRunbC,' lb/sec'
write(8,'(10X,a,a)')'
1/2      ' -----'
write(8,235)'Total Exit

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      1/2      mextot
      write(8,230)'Mass rate of bone-dry, clean wood      = ',
      1/2      MRbdwd, ' lb/sec'
230 format(11x,a,f8.4,a)
235 format(11x,a,f8.4/' ')
      write(8,240)'FLUE-GAS ANALYSIS'
240 format('0',7x,a/'0')
      Write(8,'(10x,a,a/1x)')' Constituent      Mole ',
      1/2      'Fraction'
      write(8,250)'Carbon dioxide      ',yeCO2
      write(8,250)'Nitrogen      ',yeN2
      write(8,250)'Oxygen      ',yeO2
      write(8,250)'Water vapor      ',yeH2O
      write(8,250)'Carbon monoxide      ',yeCO
      write(8,250)'Argon      ',yeAr
250 format(11x,a,f5.4)
      write(8,260)'Molecular weight of flue-gas      = ',
      1/2      mwfg,' lbs/mol'
260 format('0',10x,a,f8.4,a)
      write(8,270)'Humidity ratio (1b H2O/1b dry gas) of flue-gas = ',
      1/2      wfgex, ' '
      write(8,270)'Excess air level      = ',
      1/2      XA*100., ' percent'
      write(8,265)'Exit pressure      = ',
      1/2      pfgex,' inches H2O'
265 format(11x,a,f8.4,a)
270 format(11x,a,f8.4,a)
      write(8,240)'ENERGY BALANCE'
      write(8,280)'Source or Sink      Btu/lb fuel',
      1/2      ' Btu/sec'
280 format(15x,a,a/' ')
      write(8,290)'Heat released by combustion      ',Qrel,Qrel2
      write(8,290)'Heat provided by inlet air      ',Qair,Qair2
290 format(15x,a,f7.1,9x,f10.4)
      write(8,'(10x,a,a)')'      ',
      1/2      '-----'
      write(8,290)'Total      ',Qrel+Qair,
      1/2      Qrel2+qair2
      write(8,300)'Heat loss from radiation      ',Qloss,Qloss2
300 format(' ' /15x,a,f7.1,9x,f10.4)
      write(8,290)'Heat loss from unburned Carbon      ',QunbC,QunbC2
      write(8,290)'Heat loss from formation of CO      ',QCO,QCOb
      write(8,290)'Heat loss in dirt etc.      ',Qdirt,Qdirt2
      write(8,290)'Heat absorbed by exhaust gases      ',Qprod,Qprod2
      write(8,'(10x,a,a)')'      ',
      1/2      '-----'
      write(8,290)'Total      ',Qtot1,Qtot2
      write(8,310)'Adiabatic flame temperature = ',Tadflm,' de
310 format('0',10x,a,f7.1,a/'0')
      write(8,'(8x,a/1x)')'SECOND LAW ANALYSIS'

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```

      write(8,320) '      Stream      Availability      Availability rate'
      write(8,320) '                        Btu/lb                        KW'
      write(8,330) '      Biomass      ',AVwood,'      ',AVrtef
      write(8,330) '      Water      ',AVwatr,'      ',AVrtew
      write(8,330) '      Air      ',AVair,'      ',AVrtea
      write(8,330) '      Flue-gas      ',AVfgas,'      ',AVrtcg
320 format(11x,a)
330 format(11x,a,f7.1,a,f8.1)
      write(8,340) 'Irreversibility rate = ',irrbrn,' KW'
      write(8,350) 'Second Law Efficiency = ',seceff,' Percent'
340 format('0',10x,a,f7.1,a)
350 format(11x,a,f8.2,a)
Sdebug
      write(8,'(1x)')
      ENDIF
C(BUG) RETURN
      END

      SUBROUTINE STOICH(XC,XO2,XH2,XN2,XASH,XH2O,yCO2in,yH2Oin,yO2in,
1/2      yN2in,yArin,yCOin,w,MRair,MRwdin,unbcbn,xCCO,mwfg,
1/2      mwfgd,netot,netotd,XA,xwcf,mwair,xdcf,yeCO2,yeH2O,yeO2,
1/2      yeN2,yeAr,yeCO,ydCO2,ydO2,ydN2,ydAr,ydCO,nCO,MCunb,
1/2      NIH2,wfgex,niatd,niatw,niH2Of,niH2Oa,miatd)
C-----
C      SUBROUTINE STOICH
C      RETURNS THE NO. OF MOLES, MOLAR RATIOS, AND MASSES OF EACH
C      COMPONENT GAS EXITING THE COMBUSTOR.
C-----
      IMPLICIT REAL (A-Z)
      data mO2,mCO2,mN2,mH2O,mAr /32.,44.01,28.016,18.016,39.944/
      data mCO,mC,mH2 /28.01,12.011,2.016/
C-----
C      NOMENCLATURE:
C      NO2STA-NO. OF MOLES OF STOICH O2 FROM AIR/LB WET FUEL IN
C      NIO2ST-STOICH. AMOUNT OF O2 NEEDED/LB WET FUEL IN
C      NIN2T -TOTAL N2 NEEDED/LB WET FUEL IN
C      NIN2ST-STOICH. AMOUNT OF N2 NEEDED/LB WET FUEL IN
C      NIATD -TOTAL AMOUNT OF DRY AIR IN/LB WET FUEL IN
C      MWAIR -MOLECULAR WEIGHT OF WET AIR
C      NIAST -STOICH. AMOUNT OF DRY AIR/LB WET FUEL IN
C      NIATW -TOTAL AMOUNT OF WET AIR IN/LB WET FUEL IN
C      NIH2OT-TOTAL H2O IN/LB WET FUEL IN
C      NE... -NO. OF MOLES OF SUBST.'...' EXITING/LB WET FUEL IN
C      YE... -MOLAR RATIO OF SUBST.'...' EXITING COMBUSTOR
C      W      -HUMIDITY RATIO OF AIR BY MASS
C      XA      -EXCESS AIR RATIO FOR COMBUSTION
C      ME... -LB OF SUBST.'...' EXITING GIVEN INPUT WOOD RATE
C      MRwdin -BIOMASS FEED RATE (LB/HR)
C      MWFG -MOLECULAR WEIGHT OF FLUE GAS
C-----

```

```

C
C-----INLET CALCULATIONS-----
  xdcf=(1.-xH2O)*xwcf
  NIC=xdcf*XC/mC
  NIH2=xdcf*XH2/mH2
  NIO2f=xdcf*XO2/mO2
  NIO2st=NIC+NIH2/2.
  NO2Sta=NIO2st-NIO2f
  NCunb=unbcbn*NIC
  MCunb=NCunb*mC
  NCO=xCCO*NIC
  NCO2=NIC-NCunb-NCO
  MWdair=yO2in*mO2+yN2in*mN2+yArin*mAr+yCO2in*mCO2
  wair=(yH2Oin*mH2O)/MWdair
  XA=((MRair*yO2in/MWair)/(nO2sta*MRwdin))-1.
  niO2a=(1.+XA)*nO2sta
  niO2t=niO2a+niO2f
  niN2f=xdcf*XN2/mN2
  niN2a=(yN2in/yO2in)*niO2a
  niN2t=niN2f+niN2a
  niAra=(yArin/yO2in)*niO2a
  niCO2a=(yCO2in/yO2in)*niO2a
  niCOa=(yCOin/yO2in)*niO2a
  niatd=niN2a+niO2a+niAra+niCO2a
  miatd=niatd*MWdair
  niH2Of=(XH2O/mH2O)*xwcf
  niH2Oa=(yH2Oin/yO2in)*niO2a
  niH2Ot=niH2Of+niH2Oa
  niatw=niN2a+niO2a+niAra+niCO2a+niH2Oa
C-----EXIT CALCULATIONS-----
  neCO2=neCO2+niCO2a
  neH2O=niH2+niH2Ot
  neO2=niO2t-nCO/2.-neCO2-niH2/2.
  neN2=niN2t
  neAr=niAra
  neCO=neCO+niCOa
  netot=neCO2+neH2O+neO2+neN2+neAr+neCO
  netotd=netot-neH2o
  ydCO2=neCO2/netotd
  ydO2=neO2/netotd
  ydN2=neN2/netotd
  ydAr=neAr/netotd
  ydCO=neCO/netotd
  yeCO2=neCO2/netot
  yeH2O=neH2O/netot
  yeO2=neO2/netot
  yeN2=neN2/netot
  yeAr=neAr/netot
  yeCO=neCO/netot
  mwfg=yeCO2*mCO2+yeH2O*mH2O+yeO2*mO2+yeN2*mN2+yeAr*mAr+yeCO*mCO

```

```

      mwfgd=ydCO2*mCO2+ydO2*mO2+ydN2*mN2+ydAr*mAr+ydCO*mCO
      wfgex=(yeH2O*mH2O)/(yeCO2*mCO2+yeCO*mCO+yeN2*mN2+yeO2*mO2+yeAr*
1/2      mAr)
C(BUG)RETURN
      END

```

```

      function Q2(t,Tds,Q1,netot,dirrat,Cpdirt,yeCO2,yeH2O,yeO2,yeN2,
1/2      yeAr,yeCO,mwfg)
C-----
C      This function is used in iterating for the exit temperature,
C      using the enthalpy functions above.
C-----
      real netot,mwfg
      Q2=netot*mwfg*hgast(t,Tds,yeCO2,yeH2O,yeO2,yeN2,yeAr,yeCO)+
1/2      dirrat*Cpdirt*t-Q1
C(bug)return
      end

```

APPENDIX B

DRYER MODEL SUBROUTINE

```

SUBROUTINE DRYER(MRwdfe,MRbdwd,HHV,MRfgin,Pfgin,Tfgex,XH2Oex,
1/2 XH2Oin,Tamb,loss,dPdry,yiCO2,yiH2O,yiO2,yiN2,
1/2 yiAr,yiCO,yCO2,yH2O,yO2,yN2,yAr,yCO,Tds,Pds,
1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO,Pfgex,Tfgin,
MRwdin,MRfgex,powdry,print)

```

```

C-----
C THIS SUBROUTINE TAKES ALL OF THE INPUTS TO THE DRYER FROM OTHER
C COMPONENTS AND INPUT CONSTANTS AND DOES AN ENERGY BALANCE ON THE
C DRYER TO DETERMINE THE TEMPERATURE NEEDED INTO THE DRYER TO
C OBTAIN THE AMOUNT OF DRYING SPECIFIED BY THE INPUTS. IT ALSO
C CALCULATES THE EXITING PRESSURE FROM A SIMPLE DELTA T ENTERED
C AS A CONSTANT. THE PROGRAM ALSO DOES A SECOND LAW ANALYSIS ON
C THE UNIT.
C
C WRITTEN BY TIM BAUER
C DEPARTMENT OF MECHANICAL ENGINEERING
C OREGON STATE UNIVERSITY
C AUGUST 12, 1983

```

* NOMENCLATURE:

* Most of the variables are abbreviations or shortened
 * statements describing the variable. Many of them consist of
 * two or three parts each of which means something. For example,
 * AVrtea: the AV means availability, the rte means rate, and the a
 * stands for the substance in question - air. Put together, it
 * means the availability rate of the air into the combustor.
 * Below, the parts will be split up into abbreviations and
 * substance abbreviations.

* Substance Abbreviations:

* ar - argon
 * CO - carbon monoxide
 * CO2 - carbon dioxide
 * f - fuel
 * fg or fgas or g - flue-gas
 * H2O or watr - water
 * N2 - nitrogen
 * O2 - oxygen
 * wd or wood - wood

* Abbreviations:

* AV - availability
 * bd - bone-dry

```

*      d          - dry
*      dcf        - dry, clean fuel
*      Dp         - pressure drop through unit
*      e or ex    - exiting condition
*      in         - inlet condition
*      irrev      - irreversibility
*      m or MW    - molecular weight (lb/mole)
*      M          - mass
*      MR         - mass rate
*      P          - pressure (generally inches H2O)
*      Q          - heat released, absorbed, or lost
*      T          - temperature (deg. F)
*      yi??       - mole fraction of subst. ?? entering unit
*      yr??       - dead state mole fractions

```

Others

```

*      HHV        - higher heating value
*      xdcf       - lb dry, clean fuel/lb wet, dirty fuel
*      xdirt      - lb dirt/lb dry, clean fuel

*      MRwdin    = MASS RATE (LB/HR) OF WET WOOD INTO THE DRYER.
*      MRFGIN    = MASS RATE (LB/HR) OF HOT FLUE-GAS INTO DRYER.
*      WFGIN     = HUMIDITY RATIO (LB H2O/LB GAS) OF GAS INTO DRYER.
*      PFGIN     = PRESSURE OF GAS INTO DRYER.
*      TFGEX     = SPECIFIED TEMPERATURE OF THE GAS EXITING THE DRYER.
*      XH2OEX    = MOISTURE CONTENT (LB H2O/LB WOOD) OF EXITING FUEL.
*      XH2OIN    = MOISTURE CONTENT (LB H2O/LB WOOD) OF INLET FUEL.
*      Tamb      = AMBIENT AIR TEMPERATURE (DEG F)
*      WFGEX     = HUMIDITY RATIO OF GAS OUT OF DRYER.
*      H2OEV     = MASS RATE OF WATER VAPORIZED FROM WOOD.
*      QH2O      = HEAT REQUIRED TO HEAT WATER IN WOOD FROM INLET TO EXIT
*                  CONDITIONS.
*      QWOOD     = HEAT TO RAISE TEMPERATURE OF WOOD TO EXIT CONDITIONS.
*      TGASEX    = TEMPERATURE OF THE GAS (EXCLUDING EVAPORATED WATER)
*                  EXITING DRYER (INTERMEDIATE CALCULATION).
*      dPdry     = PRESSURE DROP (IN. H2O) ACROSS DRYER

```

```

*****
implicit real (1-n)
real irrev
logical*2 print
data mCO2,mH2O,mO2,mN2,mAr /44.01,18.016,32.,28.016,39.944/
data mCO /28.01/
if (XH2Oin .le. XH2Oex) then
    XH2Oex=XH2Oin
    MRwdin=MRwdfe
    MRfgex=MRfgin
    Pfgex=Pfgin
    Tfgin=Tfgex

```

```

        yCO2=yiCO2
        yH2O=yiH2O
        yO2=yiO2
        yN2=yiN2
        yAr=yiAr
        yCO=yiCO
        powdry=0.
        Qgas=0.
        Qwood=0.
        QH2O=0.
        Qloss=0.
        AVwdin=0.
        AVfgin=0.
        AVH2Oin=0.
        AVrtei=0.
        AVwdex=0.
        AVfgex=0.
        AVH2Oex=0.
        AVrtee=0.
        irrev=0.
        eff=1.
        go to 16
    endif
    mwfg=yiCO2*mcO2+yiH2O*mH2O+yiO2*mO2+yiN2*mN2+yiAr*mAr+yiCO*mcO
    MRH2Oin=MRbdwd*(xH2Oin/(1.-xH2Oin))
    MRH2Oex=MRbdwd*(xH2Oex/(1.-xH2Oex))
    H2Oevp=MRH2Oin-MRH2Oex
    MRwdin=MRwdfe+H2Oevp
    MRfgex=MRfgin+H2Oevp
    MRdirt=MRwdfe-MRbdwd-MRh2oe
    Cpdir=.20
    A=MRfgin/mwfg
    nrCO2=a*yiCO2
    nrH2O=a*yiH2O
    nrO2=a*yiO2
    nrN2=a*yiN2
    nrAr=a*yiAr
    nrCO=a*yiCO
    nrH2Oe=H2Oevp/mH2O
    nrfgt=nrCO2+nrH2O+nrH2Oe+nrO2+nrN2+nrAr+nrCO
    yCO2=nrCO2/nrfgt
    yH2O=(nrH2O+nrH2Oe)/nrfgt
    yO2=nrO2/nrfgt
    yN2=nrN2/nrfgt
    yAr=nrAr/nrfgt
    yCO=nrCO/nrfgt
C.....USE 971 BTU/LB AS HEAT OF VAPORIZATION OF WATER (JUNGE)
10 IF (TFGEX .LT. 212.) THEN
    TEXTIT=TFGEX
else

```

```

      Texit=212.
    ENDIF
    IF (XH2OEX .GT. .25) THEN
      QV =971.
    ELSE
      QV=1335.-1456.*XH2OEX
    ENDIF
  C.....Heat of vaporization and desorption.....
  QDESPN=(971.*(XH2OIN-.25)+((QV+971.)/2.)*(.25-XH2OEX))/(XH2Oin-
  1/2 XH2Oex)
  C.....Heat Requirement of Water.....
  QH2O=H2OEV* ((212.-Tamb)+QDESPN)+(XH2OIN*(MRwdin-MRdirt)*(TEXTIT-
  1/2 Tamb))+H2OEV*(Hgst(TfgEX,Tds,0.,1.,0.,0.,0.,0.))-
  1/2 Hgst(212.,Tds,0.,1.,0.,0.,0.,0.))
  SIDE2=MRFGIN*(1.-LOSS)*HGAST(TFGEX,Tds,yiCO2,yiH2O,yiO2,yiN2,
  1/2 yiAr,yiCO)+MRbdwd*.266322*((textit-Tamb)-.0206)+QH2O+MRdirt*Cpdirt
  TOLER=.0005
  t=500.
  deltat=30.
  itsmax=100
  do 11 iter=1,itsmax
    r=Q4(t,Tds,MRFGIN,loss,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO,
    1/2 mwfg,side2)
    dQdt=(Q4(t+deltat,Tds,MRFGIN,loss,yiCO2,yiH2O,yiO2,yiN2,
    1/2 yiAr,yiCO,mwfg,side2)-r)/deltat
    deltat=r/dQdt
    t=t-deltat
    if (abs(deltat) .lt. toler*t) go to 20
  11 continue
  20 continue
    if (iter .gt. itsmax) write (8,101) iter
  101 format(' warning: ',i3,' ITERATIONS WITH NO CONVERGENCE.')
    TFGIN=t
    Pfgex=Pfgin-dPdry
    powdry=25.
  16 continue
    if (print) then
      if (XH2Oex .eq. XH2Oin) then
        write(8,'(10x,a)') ' NO DRYER USED.....'
        go to 17
      endif
      Qwood=MRbdwd*(.266322*(Textit-Tamb)-.0206)
      Qgas=(HgasT(Tfgin,Tds,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO)-
      1/2 HgasT(Tfgex,Tds,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO))*MRFGIN
      Qloss=qgas*loss
  C.....Conversion to Absolute Pressures.....
  Pfgin2=(Pfgin*.0361)+Pds
  Pfgex2  -x*.0361)+Pds
  C.....Second Law Analysis.....
  c      Availability of the Wood (Heating Value and Temperature Eff.)

```



```

AVwdi1=MRbdwd*HHV
cpwdin=.266+.000322*(Tamb+Tds-64.)
AVwdi2=(cpwdin*(Tamb-Tds)-(Tds+459.67)*cpwdin*log((Tamb+459.67)/
1/2 (Tds+459.67)))*MRbdwd
AVwdei=AVwdi1
cpwdex=.266+.000322*(Texit+Tds-64.)
AVwdei2=(cpwdex*(Texit-Tds)-(Tds+459.67)*cpwdex*log((Texit+
1/2 459.67)/(Tds+459.67)))*MRbdwd
AVwdin=AVwdei1+AVwdei2
AVwdex=AVwdei1+AVwdei2
c ---Availability of the Dirt-----
AVdrti=(Cpdirt*(tamb-Tds)-(Tds+459.67)*Cpdirt*log((Tamb+459.67)/
1/2 (Tds+459.67)))*MRdirt
AVdrte=(Cpdirt*(Texit-Tds)-(Tds+459.67)*Cpdirt*log((Texit+
1/2 459.67)/(Tds+459.67)))*MRdirt
c ---Availability of the Flue Gases-----
AVfgex=(HgasT(Tfgex,Tds,yCO2,yH2O,yO2,yN2,yAr,yCO)-(Tds+459.67)*
1/2 SgasTP(Tfgex,Pfgex2,Tds,Pds,yCO2,yH2O,yO2,yN2,yAr,yCO,
1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO))*MRfgex*1.0551
AVfgin=(HgasT(Tfgin,Tds,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO)-(Tds+
1/2 459.67)*SgasTP(Tfgin,Pfgin2,Tds,Pds,yiCO2,yiH2O,yiO2,
1/2 yiN2,yiAr,yiCO,yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO))*MRfgin*
1/2 1.0551
c ---Availability of the Water in the Wood-----
AVH20i=MRH20i*((Hfwt(tamb)-(Tds+459.67)*sfwt(Tamb))-(hfwT(Tds)-
1/2 (Tds+459.67)*sfwt(Tds)))*1.0551
AVH20e=MRH20e*((Hfwt(Tfgex)-(Tds+459.67)*Sfwt(Tfgex))-(hfwT(Tds)-
1/2 (Tds+459.67)*sfwt(Tds)))*1.0551
c ---Availability Rates in and out-----
AVrtei=AVwdin+AVfgin+AVH20i+AVdrti
AVrtee=AVwdex+AVfgex+AVH20e+AVdrte
c ---Irreversibility Calculation-----
irrev=AVrtei-AVrtee
c ---Second Law Efficiency Calculation-----
eff=AVrtee/AVrtei
c-----Tabulation of results-----
17 write(8,22)'DRYER.....REV. NO. 3'
22 FORMAT(8X,A/'0')
WRITE(8,23)'INPUT PARAMETERS'
23 FORMAT('0'/8X,a/' ')
WRITE(8,25)'Exiting gas temperature',
1/2 TFGEX,' deg. F'
WRITE(8,25)'Moisture content of inlet wood' = ',
1/2 XH20IN,' lb/lb wet, cln wood'
WRITE(8,25)'Moisture content of exiting wood' = ',
1/2 XH20EX,' lb/lb wet, cln wood'
WRITE(8,25)'Mass rate of dried wood exiting dryer' = ',
1/2 MRwde,' lb/sec'
WRITE(8,25)'Mass rate of entering gases' = ',
1/2 MRFGIN,' lb/sec'

```

```

WRITE(8,25)'Pressure of entering flue-gas      = ',
  1/2 PFGIN,' inches H2O'
write(8,25)'Fraction of available energy lost   = ',
  1/2 loss,' '
25 format(11x,a,f8.4,a)
WRITE(8,30)'OUTPUT PARAMETERS'
30 FORMAT('0'/8x,A/' ')
WRITE(8,35)'Mass rate of wet wood entering dryer = ',
  1/2 MRwdin,' lb/sec'
WRITE(8,35)'Mass rate of gas leaving dryer      = ',
  1/2 MRFGEX,' lb/sec'
WRITE(8,35)'Pressure of gas leaving dryer       = ',
  1/2 PFGEX,' inches H2O'
WRITE(8,35)'Temperature of gas entering dryer  = ',
  1/2 TFGIN,' deg. F'
WRITE(8,35)'Power consumption                   = ',
  1/2 POWDRY,' KW'
35 format(11x,a,f8.2,a)
WRITE(8,40)'HEAT BALANCE                        BTU/SEC'
40 FORMAT('0'/8x,A/' ')
WRITE(8,45)'Heat loss by gases                  = ',QGAS
WRITE(8,50)'Heat absorbed by wood               = ',QWOOD
WRITE(8,50)'Heat absorbed by water              = ',QH2O
WRITE(8,50)'Heat loss from leakage etc.         = ',QLOSS
45 format(11x,a,f8.2/' ')
50 format(11x,a,f8.2)
write(8,55)'                                     -----'
55 format(11x,a)
write(8,50)'                                     ',Qwood+
  1/2 QH2O+Qloss
write(8,60)'SECOND LAW ANALYSIS'
60 format('0',7x,a/' ')
write(8,65)' Stream                               Availability Rate'
write(8,65)'                                     KW
write(8,70)' Fuel in                             ',AVwdin
write(8,70)' Gas in                              ',AVfgin
write(8,70)' Water in fuel in                    ',AVH2O1
write(8,70)' Dirt in                             ',AVdrt1
write(8,65)'                                     -----'
write(8,70)' Total                               ',AVrtei
write(8,75)' Fuel out                             ',AVwdx
write(8,70)' Gas out                             ',AVfgex
write(8,70)' Water in fuel out                   ',AVH2Oe
write(8,70)' Dirt out                             ',AVdrte
write(8,65)'                                     -----'
write(8,70)' Total                               ',AVrtee
65 format(11x,a)
70 format(11x,a,f8.1)
75 format('0',10x,a,f8.1)
write(8,80)' Irreversibility rate                ',irrev,' KW'

```

```

      80 format('0',10x,a,f8.1,a)
        write(8,85)' Second law efficiency      ',eff*100.,' Percent'
      85 format(11x,a,f8.1,a)
        write(8,'(a)')' '
      endif
C(BUG)RETURN
      END

      FUNCTION Q4(t,Tds,MRfgin,loss,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO,
12      mwfg,side2)
C-----
C      THIS FUNCTION IS USED IN THE ITERATION FOR THE INLET TEMP.
C      TO THE DRYER.
C-----
      REAL MRfgin,loss,mwfg
      Q4=MRfgin*(1.-loss)*HgasT(t,Tds,yiCO2,yiH2O,yiO2,yiN2,yiAr,yiCO)-
12      side2
C(BUG)RETURN
      END

```

APPENDIX C

SAMPLE OVERALL SIMULATION

A/F=18 no fuel prep

5 iterations, specified tolerance: .0100, actual tolerance: 3.1279

----- Constants -----

AFrat	18.0000 lb air/lb fuel	Pds	14.6960 psia
chx1	.2540	Pe61	.7000 in. h2o
chx2	.5070	Pe64	.7000 in. h2o
cmpbld	4.0000 %	Prcinj	.0000 % injection
dPap1	5.0000 in. h2o	Prcmp	9.1000 press. ratio
dPap2	5.0000 in. h2o	Ps31	650.0000 psia
dPap3	.0000 in. h2o	Ps40	1.5000 psia
dPbag	.0000 in. h2o	radlos	.0200 frac. HHV
dPblrg	8.0000 in. h2o	rufhx1	.0020
dPblrw	10.0000 psia	rufhx2	.0020
dPcmb	11.0000 in. h2o	SnDhx1	2.0000
dPcmp	4.0000 in. h2o	SnDhx2	1.7000
dPcyc1	.0000 in. h2o	SpDhx1	2.0000
dPcyc3	5.0000 in. h2o	SpDhx2	1.5000
dPdry	.0000 in. h2o	Ta01	59.0000 F
dPgtb	2.0000 in. h2o	Ta031	1450.0000 F
dPhx1g	.2100 in. h2o	Tc112	1675.0000 F
dPhx1m	7.0000 psi	Tc21	350.0000 F
dPhx1w	2.8637 psi	Tds	59.0000 F
dPhx2a	3.1992 psi	Te61	350.0000 F
dPhx2g	2.7590 in. h2o	Ts38	900.0000 F
dPhx2m	7.0000 psi	Tsuper	207.0000 F
drylos	.0500 fract ht loss	typhx1	1.0000 1 = in-line
EFFcmp	83.2000 %	typhx2	2.0000 2 = staggered
EFFfn1	63.0000 %	Ublr	10.0000 btu/hr-ft2-F
EFFfn3	63.0000 %	Uecon	12.0000 btu/hr-ft2-F
EFFfn4	63.0000 %	unbcbn	.0200 lb/lb
EFFfn5	63.0000 %	Usuper	8.0000 btu/hr-ft2-F
EFFgb1	96.0000 %	Wa01	.0070 lb h2o/lb dry a
EFFgb2	96.0000 %	Wb51	.5000 lb h2o/lb fuel
EFFgn1	95.5000 %	Wb52	.5000 lb h2o/lb fuel
EFFgn2	95.5000 %	WRcnv	12.0000 kW ????
EFFgtb	91.2000 %	WRctr	45.0000 kW
EFFpmp	68.0000 %	WRhml	.0000 kW ????
EFFstb	80.0000 %	WRscw	10.0000 kW ????
fshx1	.9000 factor safety	Xash	.0050 lb ash/lb dry f
fshx2	.9000 factor safety	XC	.5230 lb C/lb dry fue
HHV	8800.0000 btu/lb	XCCO	.0100 lb C burned CO/
MRC16m	15.0000 lb/s	Xdirt	.0350 lb dirt/lb dry
MRC23m	.1000 lb/s	XH2	.0630 lb H2/lb dry fu
MRstp	38.7500 lb/s	xhx1	.6320

npnhx1	60.0000	pipes normal	xhx2	.5640	
npnhx2	72.0000	pipes normal	XN2	.0010	1b N2/1b dry fu
npphx1	1.0000	pipes parallel	XO2	.4050	1b O2/1b dry fu
npphx2	8.0000	pipes parallel	ydsCO	.0003	
nuhx1	1.0000	no. of U's	ydsW	.0111	
nuhx2	3.0000	no. of U's	ydsO2	.2072	
Pa01	14.6960	psia	ydsN2	.7722	
Pa04	26.0000	in. h2o	ydsAr	.0092	
Pc22	5.5000	in. h2o	ydsCO	.0000	
dPhx1g was changed from			2.00000 to		.21002
dPhx1w was changed from			4.50000 to		2.86373
dPhx2a was changed from			3.50000 to		3.19920
dPhx2g was changed from			4.00000 to		2.75901

----- Variables -----

Ma03	28.8445	lb/mol	Ps38	637.1360	psia
Ma04	28.8445	lb/mol	Ta032	1450.0000	F
MRA032	36.6792	lb/s	Ta04	715.6650	F
MRA04	38.2075	lb/s	Tc111	1741.8000	F
MRb52	4.2895	lb/s	Tc13	1626.1500	F
MRbdwd	2.1079	lb/s	Tc14	1000.2200	F
MRC111	42.3843	lb/s	Tc26	350.0000	F
MRC112	44.6878	lb/s	Ts31	700.8910	F
MRC12	44.6878	lb/s	Ts36	115.2230	F
MRC16	.0000	lb/s	Xs40	.9369	lb/lb quality
MRC231	2.3035	lb/s	ya03CD	.0003	mol CO2/mol tot
MRC25	42.3843	lb/s	ya03W	.0111	mol H2O/mol tot
MRC26	42.3843	lb/s	ya03O2	.2072	mol O2/mol tot
MRs31	6.3389	lb/s	ya03N2	.7722	mol N2/mol tot
MRs39	6.3389	lb/s	ya03Ar	.0092	mol Ar/mol tot
Pa031	129.2190	psia	ya03CO	.0000	mol CO/mol tot
Pa032	129.2190	psia	ya04CO	.0003	mol CO2/mol tot
Pc111	15.0000	in. h2o	ya04W	.0111	mol H2O/mol tot
Pc112	15.0000	in. h2o	ya04O2	.2072	mol O2/mol tot
Pc113	10.0000	in. h2o	ya04N2	.7722	mol N2/mol tot
Pc13	9.7900	in. h2o	ya04Ar	.0092	mol Ar/mol tot
Pc14	7.0310	in. h2o	ya04CO	.0000	mol CO/mol tot
Pc211	-.9690	in. h2o	yc11CD	.0595	mol CO2/mol tot
Pc212	-.9690	in. h2o	yc11W	.1316	mol H2O/mol tot
Pc232	20.0000	in. h2o	yc11O2	.1190	mol O2/mol tot
Pc26	5.5000	in. h2o	yc11N2	.6812	mol N2/mol tot
Pc27	5.7000	in. h2o	yc11Ar	.0081	mol Ar/mol tot
Pc29	.7000	in. h2o	yc11CO	.0006	mol CO/mol tot
Ps36	640.0000	psia			

----- Results -----

Ma02	28.8445 lb/mol	WRgn2	2451.8400 kW	
MRa02	36.6792 lb/s	WRgtb	7558.7000 kW	
MRa06	1.5283 lb/s	WRpmp	19.9864 kW	
MRb51	4.2895 lb/s	WRstb	2674.3500 kW	
MRe61	42.3843 lb/s	ya02CD	.0003 mol	CO2/tot mol
Pa02	132.4180 psia	ya02W	.0111 mol	H2O/tot mol
Pe62	.7000 in. h2o	ya02O2	.2072 mol	O2/tot mol
Pe63	.7000 in. h2o	ya02N2	.7722 mol	N2/tot mol
Ta02	595.5190 F	ya02Ar	.0092 mol	Ar/tot mol
WRcmp	5310.0800 kW	ya02CO	.0000 mol	CO/tot mol
WRdry	.0000 kW	ye61CD	.0595 mol	CO2/tot mol
WRfn1	.0000 kW	ye61W	.1316 mol	H2O/tot mol
WRfn3	67.4298 kW	ye61O2	.1190 mol	O2/tot mol
WRfn4	7.5961 kW	ye61N2	.6812 mol	N2/tot mol
WRfn5	1.9612 kW	ye61Ar	.0081 mol	Ar/tot mol
WRgn1	2061.5400 kW	ye61CO	.0006 mol	CO/tot mol

A/F=18 no fuel prep

----- COMPRESSOR -----

Conditions at:	Inlet	Exit
Pressure	14.70	132.42
Temperature	59.00	595.52 F
Mass flow rate	36.68	36.68 lb/s
Exergy	.00	4644.46 kW

Inlet pressure loss	4.00 in. h2o
Bleeding air	4.00 %
Efficiency	83.20 %
Power to drive	5310.08 kW
Irreversibility	665.61 kW

----- GAS TURBINE -----

Conditions at:	Inlet	Exit
Pressure	128.92	26.00
Temperature	1450.00	715.67 F
Mass flow rate	36.68	36.68 lb/s
Exergy	10248.00	2421.28 kW

Mass flow rate	36.68 lb/s
Cooling flow	1.53 lb/s
Power output	7558.70 kW
Irreversibility	461.60 kW

----- COMBUSTOR -----

Air-Fuel ratio (dry to dry) 18.0000
 Fraction radiation loss .0200
 Fraction unburned carbon .0200
 Fraction of carbon burned to CO .0100
 Excess air level = 179.8950 percent
 Adiabatic flame temperature = 1741.8 deg F
 Irreversibility rate = 9101.6 KW
 Second Law Efficiency = 58.61 Percent

----- MIXER after combustor -----
 Irreversibility = 124.82 kW

----- Cyclone #3 -----
 Pressure loss = 5.000

----- Splitter: after combustor -----

A/F=18 no fuel prep

----- STEAM-GAS HEAT EXCHANGER -----

Flow conditions:	flue gas	steam
Temperature at inlet, F :	1675.000	700.891
Pressure at inlet, psia :	15.057	640.000
Massflow, lbm/sec :	44.688	6.339
Temperature at exit, F :	1626.150	900.000
Pressure at exit, psia :	15.050	637.136
Exergy at inlet, KW :	12831.400	3514.310
Exergy at exit, KW :	12295.900	3929.290

Specifications of Heat Exchanger:

Tube arrangement:	in-line
Spacing of tubes normal to flow, Sn/d:	2.000
Spacing of tubes parallel to flow, Sn/d:	2.000
Number of tubes normal to flow:	60
Number of tubes parallel to flow direction:	1
Number of U's:	1
Outside diameter of pipes:	.750 inches
Height of the heat exchanger:	6.010 ft
Width of the heat exchanger:	7.625 ft

Heat Transfer Data:

"C" - to calculate Nusselt Number:	.254	
"X" - to calculate Nusselt Number:	.632	
Safety factor on the shell side:	.900	
Safety factor due to cross flow:	.999	
Safety factor due to few pipes:	.797	
H out - heat transfer coeff.:	22.887	btu/h/sqft/F
H in - heat transfer coeff.:	254.822	btu/h/sqft/F
U - Overall heat transfer coeff.:	20.429	btu/h/sqft/F
UA - value:	2832.830	btu/h/F
Maximum wall temperature:	963.870	F
Total heat transfer:	708.775	kW
Irreversibility:	120.451	KW

Pressure drops:

Actual pressure drop inside pipes	:	2.864	psi
Pressure drop on gas side	:	.210	in W.C.

A/F=18 no fuel prep

----- AIR-GAS HEAT EXCHANGER -----

Flow conditions:	flue gas	air
Temperature at inlet, F :	1626.150	595.519
Pressure at inlet, psia :	15.050	132.418
Massflow, lbm/sec :	44.688	36.679
Temperature at exit, F :	1000.220	1450.000
Pressure at exit, psia :	14.950	129.219
Exergy at inlet, KW :	12295.900	4644.470
Exergy at exit, KW :	6087.300	10251.200

Specifications of Heat Exchanger:

Tube arrangement:	staggered
Spacing of tubes normal to flow, Sn/d:	1.700
Spacing of tubes parallel to flow, Sn/d:	1.500
Number of tubes normal to flow:	72
Number of tubes parallel to flow direction:	8
Number of U's:	3
Outside diameter of pipes:	1.000 inches
Height of the heat exchanger:	9.501 ft
Width of the heat exchanger:	10.342 ft

Heat Transfer Data:

"C" - to calculate Nusselt Number:	.507	
"X" - to calculate Nusselt Number:	.564	
Safety factor on the shell side:	.900	
Safety factor due to cross flow:	1.000	
Safety factor due to few pipes:	1.000	
H out - heat transfer coeff.:	18.799	btu/h/sqft/F
H in - heat transfer coeff.:	49.754	btu/h/sqft/F
U - Overall heat transfer coeff.:	12.819	btu/h/sqft/F
UA - value:	108748.000	btu/h/F
Maximum wall temperature:	1498.310	F
Total heat transfer:	8791.350	kW
Irreversibility:	601.869	KW

Pressure drops:

Actual pressure drop inside pipes	:	3.199	psi
Pressure drop on gas side	:	2.759	in W.C.

A/F=18 no fuel prep

----- MIXER to dryer -----
 Irreversibility = .00 kW

----- Air pollution dev 1 -----
 Pressure loss = 5.000

NO DRYER USED.....

----- DRYER -----
 Moisture content of inlet wood = .5000 lb/lb wet, cln wood
 Moisture content of exiting wood = .5000 lb/lb wet, cln wood
 Temperature of gas entering dryer = 350.00 deg. F

Irreversibility rate .0 KW

----- Cyclones #1, #2 -----
 pressure loss = .000

----- Bag house -----
 Pressure loss = .000

----- WASTE HEAT BOILER -----

Flow conditions:	flue gas	steam
Temperature at inlet, F :	1000.220	115.223
Pressure at inlet, psia :	14.950	650.000
Massflow, lbm/sec :	44.688	6.339
Temperature at exit, F :	350.000	700.891
Pressure at exit, psia :	14.661	640.000

Heat Transfer Data:

dT at pinch point:	67.201	F
Saturation temperature:	494.721	F
Superheater surface area:	881.480	sqft
Boiler surface area:	8486.550	sqft
Economizer surface area:	5635.100	sqft
Total heat transfer:	8418.480	KW
Irreversibility:	1017.880	KW

Pressure drops:

Pressure drop on steam side (approx) :	10.000	psi
Pressure drop on gas side :	8.000	in W.C.

----- STEAM TURBINE -----

Conditions at:	Inlet	Exit
Pressure	637.14	1.50
Temperature	900.00	115.22 F
Mass flow rate	6.34	6.34 lb/s
Exergy	3798.50	520.95 kW
Efficiency	80.000 %	
Exit quality	93.692 %	
Power output	2674.350 kW	
Irrevers.	603.201 kW	

A/F=18 no fuel prep

----- CONDENSER -----

Pressure	1.50 psia
Quality of steam	93.69 %
Mass flow rate	6.34 lbm/s
Cooling load	6452.47 KW
Coolant flow rate	611.49 lbm/s
Irreversibility	631.03 KW

----- PUMP -----

Mass flow rate	6.339 lbm/s
Inlet pressure	1.500 psia
Exit pressure	650.000 psia
Efficiency	68.000 %
Power required	19.986 kW
Irreversibility	6.396 kW

----- Air pollution dev 3 -----

Pressure loss =	.000
-----------------	------

----- Splitter: after fan #3 -----

----- Air pollution dev 2 -----

Pressure loss =	5.000
-----------------	-------

```

----- Fan: FAN #1
Conditions at:      Inlet      Exit
Pressure           .70        .70
Temperature        350.00     350.00 F
Mass flow rate     42.38     42.38 lb/s
Exergy             .00        .00 kW
Power required     .00 kW
Irreversibility    .00 kW

```

```

----- Fan: FAN #3
Conditions at:      Inlet      Exit
Pressure           -.97       5.50
Temperature        350.00     350.00 F
Mass flow rate     44.69     44.69 lb/s
Exergy             .00        .00 kW
Power required     67.43 kW
Irreversibility    24.95 kW

```

```

----- Fan: FAN #4
Conditions at:      Inlet      Exit
Pressure           5.50       20.00
Temperature        350.00     350.00 F
Mass flow rate     2.30       2.30 lb/s
Exergy             .00        .00 kW
Power required     7.60 kW
Irreversibility    2.81 kW

```

```

----- Fan: FAN #5
Conditions at:      Inlet      Exit
Pressure           5.50       5.70
Temperature        350.00     350.00 F
Mass flow rate     42.38     42.38 lb/s
Exergy             .00        .00 kW
Power required     1.96 kW
Irreversibility    .73 kW

```

A/F=18 no fuel prep

```

----- Generator/Gear box: Gas-Turbine
Irreversibility    187.09 kW

```

```

----- Generator/Gear box: Steam-Turbine
Irreversibility    222.51 kW

```

----- Plant Summary -----

Auxilliary Power (kW)

Pump	19.99
Cooling twr	45.00
Fan #1	.00
Fan #3	67.43
Fan #4	7.60
Fan #5	1.96
Conveyor	12.00
Hammermill	.00
Screw	10.00
Dryer	.00
TOTAL.....	163.97

Generator Power (kW)

Gasturb/Compressor	2061.54
Steam turbine	2451.84

First Law Summary (kW)

Work Rate (gross)	4513.38
Work Rate (net)	4349.41
Fuel Energy	19893.20

Plant Efficiency (%)

Gross	22.69
Net	21.86

APPENDIX D

GAS PROPERTIES FUNCTION

```

c ----- Enthalpy of gas, HGAST(T,Tref,yCO2,yH2O,...,yCO) -----
c
c This function calculates the enthalpy of a gas as a function
c of temperature and mole fractions. The equations for Cp are
c from "Fundamentals of Classical Thermodynamics", G.J. Van Wylen
c and R.E. Sonntag, pp. 683 - 684. Cp for argon is assumed to be
c constant: 5.005 btu/lbmole R. Maximum error for air was
c around 0.5 %.
c
c function HGAST (T,Tref,yCO2,yH2O,yO2,yN2,yAr,yCO)
c
c   real Mm,mO2,mN2,mCO2,mH2O,mAr,mCO
c   data R /1.9858/
c   data a1,a2,a3,a4 /9.3355,-122.56,256.38,-196.08/
c   data b1,b2,b3,b4 /8.9465,4.8044E-03,-42.679,56.615/
c   data c1,c2,c3,c4 /-.89286,7.2967,-.98074,5.7835E-03/
c   data d1,d2,d3,d4 /34.190,-43.868,19.778,-0.88407/
c   data e1,e2,e3,e4 /16.526,-0.16841,-47.985,42.246/
c   data mO2,mCO2,mN2,mH2O,mAr /32.,44.01,28.016,18.016,39.944/
c   data mCO /28.01/
c
c   Q = (T+459.67)/180.
c   Qref= (Tref+459.67)/180.
c
c   hN2=(a1*(Q-Qref)-a2*2.*(1./sqrt(Q)-1./sqrt(Qref))-a3*(1./Q-
1./Qref)-a4*.5*(1./Q**2-1./Qref**2))*180.
1/2 hO2=(b1*(Q-Qref)+b2*.4*(Q**2.5-Qref**2.5)-b3*2.*(1./sqrt(Q)-
1./sqrt(Qref))-b4*(1./Q-1./Qref))*180.
1/2 hCO2=(c1*(Q-Qref)+c2/1.5*(Q**1.5-Qref**1.5)+c3*.5*(Q**2-Qref**2)
+c4/3.*(Q**3-Qref**3))*180.
1/2 hH2O=(d1*(Q-Qref)+d2/1.25*(Q**1.25-Qref**1.25)+d3/1.5*(Q**1.5-
Qref**1.5)+d4*.5*(Q**2-Qref**2))*180.
1/2 hCO=(e1*(Q-Qref)+e2/1.75*(Q**1.75-Qref**1.75)+e3*2.*(sqrt(Q)-
sqrt(Qref))+e4*4.*(Q**.25-Qref**.25))*180
1/2 hAr=5.005*(Q-Qref)*180.
c
c   Mm=yN2*mN2+yO2*mO2+yCO2*mCO2+yH2O*mH2O+yAr*mAr+yCO*mCO
c
c   HGAST=(yN2*hN2+yO2*hO2+yCO2*hCO2+yH2O*hH2O+yAr*hAr+yCO*hCO)/Mm
c
c   end
c
c ----- Entropy, SGASTP(T,P,Tref,Pref,yCO2,...,yrefCO2,...) -----
c
c This function calculates the entropy of a gas as a function
c of temperature, pressure and mole fractions. The equations for
c Cp are from "Fundamentals of Classical Thermodynamics",
c G.J. Van Wylen and R.E. Sonntag, pp. 683 - 684. Maximum error
c for air was around 0.5 %.
c

```

```

C      function SGASTP (T,P,Tref,Pref,yCO2,yH2O,yO2,yN2,yAr,yCO,
1/2      yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
C
      real Mm,mO2,mN2,mCO2,mH2O,mAr,mCO
      data R /1.9858/
      data a1,a2,a3,a4 /9.3355,-122.56,256.38,-196.08/
      data b1,b2,b3,b4 /8.9465,4.8044E-03,-42.679,56.615/
      data c1,c2,c3,c4 /-.89286,7.2967,-.98074,5.7835E-03/
      data d1,d2,d3,d4 /34.190,-43.868,19.778,-0.88407/
      data e1,e2,e3,e4 /16.526,-0.16841,-47.985,42.246/
      data mO2,mCO2,mN2,mH2O,mAr /32.,44.01,28.016,18.016,39.944/
      data mCO /28.01/
C
      Q = (T+459.67)/180.
      Qref= (Tref+459.67)/180.
      sO2 =0.
      sN2 =0.
      sCO2=0.
      sH2O=0.
      sCO =0.
      sAr =0.
C
      if (yO2 .ne. 0.0) then
1/2          sO2=b1*log(Q/Qref)+b2/1.5*(Q**1.5-Qref**1.5)-b3/1.5*
1/2          (Q**(-1.5)-Qref**(-1.5))-b4*.5*(Q**(-2)-Qref**(-2))
1/2          -R*log(yO2*P/yrO2/Pref)
      endif
      if (yN2 .ne. 0.0) then
1/2          sN2=a1*log(Q/Qref)-a2/1.5*(Q**(-1.5)-Qref**(-1.5))-
1/2          a3*.5*(Q**(-2)-Qref**(-2))-a4/3.*(Q**(-3)-Qref**(-3))
1/2          -R*log(yN2*P/yrN2/Pref)
      endif
      if (yCO2 .ne. 0.0) then
1/2          sCO2=c1*log(Q/Qref)+c2*2.*(sqrt(Q)-sqrt(Qref))+
1/2          c3*(Q-Qref)+c4*.5*(Q**2-Qref**2)
1/2          -R*log(yCO2*P/yrCO2/Pref)
      endif
      if (yH2O .ne. 0.0) then
1/2          sH2O=d1*log(Q/Qref)+d2*4.*(Q**.25-Qref**.25)+
1/2          d3*2*(sqrt(Q)-sqrt(Qref))+d4*(Q-Qref)
1/2          -R*log(yH2O*P/yrH2O/Pref)
      endif
      if (yCO .ne. 0.0) then
1/2          sCO=e1*log(Q/Qref)+e2/.75*(Q**.75-Qref**.75)-e3/.5*(1.
1/2          /sqrt(Q)-1./sqrt(Qref))-e4/.75*(Q**(-.75)-Qref**(-.75))
1/2          -R*log(yCO*P/yrCO/Pref)
      endif
      if (yAr .ne. 0.0) then
          sAr=5.005*log(Q/Qref)-R*log(yAr*P/yrAr/Pref)

```

```

endif
C
C
Mm=yN2*mN2+yO2*mO2+yCO2*mCO2+yH2O*mH2O+yAr*mAr+yCO*mCO
C
SGASTP=(yN2*sN2+yO2*sO2+yCO2*sCO2+yH2O*sH2O+yAr*sAr+yCO*sCO)/Mm
C
end
C
C ----- Temperature of gas, TGASH (H,TREF,yCO2,...) -----
C
C      This program calculates the temperature of gas as a
C      function of the enthalpy, Tref and mole fractions. It uses
C      the function HGAST and iterates. 3-5 iterations are needed
C      for air. For low temperatures, it only takes 2-3.
C
function TGASH(H,TREF,yCO2,yH2O,yO2,yN2,yAr,yCO)
C
T1=TREF
H1=0.
T2=TREF+50.
H2=HGAST(T2,TREF,yCO2,yH2O,yO2,yN2,yAr,yCO)
C
C... Iteration:
C
DO 10 I=1,20
    T=T2-(H2-H)*(T2-T1)/(H2-H1)
    IF(ABS(T/T2-1.).LT.0.0005)GO TO 20
    T1=T2
    H1=H2
    T2=T
    H2=HGAST(T2,TREF,yCO2,yH2O,yO2,yN2,yAr,yCO)
10 CONTINUE
20 TGASH=T
C
END
C
C ----- Temperature of gas, f(S,Pref,Tref,Pref,yCO2,...,yCO) -----
C
C      This program calculates the temperature of gas as a
C      function of the entropy, P, Tref, Pref and mole fractions. It
C      uses the function SGASTP and iterates. 4-6 iterations are
C      needed for air. For low temperatures, it only takes 2-4.
C
FUNCTION TGASS(S,P,Tref,Pref,yCO2,yH2O,yO2,yN2,yAr,yCO,
1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
C
T1=TREF
S1=SGASTP(T1,P,Tref,Pref,yCO2,yH2O,yO2,yN2,yAr,yCO,
1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)

```

```

T2=TREF+50.
S2=SGASTP(T2,P,Tref,Pref,yCO2,yH2O,yO2,yN2,yAr,yCO,
  1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
C
C... Iteration:
C
DO 10 I=1,20
  T=T2-(S2-S)*(T2-T1)/(S2-S1)
  IF(ABS(T/T2-1.).LT.0.0005)GO TO 20
  T1=T2
  S1=S2
  T2=T
  S2=SGASTP(T2,P,Tref,Pref,yCO2,yH2O,yO2,yN2,yAr,yCO,
  1/2 yrCO2,yrH2O,yrO2,yrN2,yrAr,yrCO)
10 CONTINUE
20 TGASS=T
C
END
C
C ----- Mole fractions -----
C
C      This function calculates the mole fractions after
C      mixing two gas streams. The mole fractions of the mixing gases
C      and mass flows are input to the program. It then returns the
C      mass flow, mole fractions and molar mass of the new mixture.
C      ynO2,ynN2,... are number of moles pr. lb of "dry" gas.
C
  subroutine MOLFRC (MRi1,yi1CO2,yi1H2O,yi1O2,yi1N2,yi1Ar,yi1CO,
  1/2 M11,MRi2,yi2CO2,yi2H2O,yi2O2,yi2N2,yi2Ar,yi2CO,Mi2,
  1/2 MRO,yoCO2,yoH2O,yoO2,yoN2,yoAr,yoCO,Mo)
  real MRi1,MRi2,MRO,mO2,mN2,mCO2,mH2O,mAr,mCO,MOLi1,MOLi2,MOLo
  real M11,Mi2,Mo
  data mO2,mCO2,mN2,mH2O,mAr /32.,44.01,28.016,18.016,39.944/
  data mCO /28.01/
C
C... molar mass of inlet streams:
C
  M11=yi1O2*mO2+yi1 2*mN2+yi1CO2*mCO2+yi1Ar*mAr+yi1H2O*mH2O+
  1/2 yi1CO*mCO
  M12=yi2O2*mO2+yi2N2*mN2+yi2CO2*mCO2+yi2Ar*mAr+yi2H2O*mH2O+
  1/2 yi2CO*mCO
C
C... number of moles (pr.sec):
C
  MOLi1=MRi1 /M11
  MOLi2=MRi2/Mi2
  MOLo=MOLi1+MOLi2
C
  yoCO2=(yi1CO2*MOLi1+yi2CO2*MOLi2)/MOLo
  yoH2O=(yi1H2O*MOLi1+yi2H2O*MOLi2)/MOLo

```



```
yoO2=(y1O2*MOLi1+y12O2*MOLi2)/MOLo
yoN2=(y1N2*MOLi1+y12N2*MOLi2)/MOLo
yoAr=(y1Ar*MOLi1+y12Ar*MOLi2)/MOLo
yoCO=(y1CO*MOLi1+y12CO*MOLi2)/MOLo
c
MRo=MRi1+MRi2
Mo=yoO2*mO2+yoN2*mN2+yoCO2*mCO2+yoAr*mAr+yoH2O*mH2O+yoCO*mCO
c
end
```