This study evaluates the feasibility of retrofitting a rotary dryer to a hog fuel boiler, using the boiler exhaust gases as the drying medium.

Two simulation models were developed. As substantiated by experimental measurement of existing boiler/dryer systems, each model accurately predicts system performance given site-specific parameters such as boiler steam demand, fuel moisture content, boiler exhaust temperature and combustion excess air. Both models predict system performance in terms of boiler efficiency, fuel consumption and dryer exit fuel moisture content.

Three rotary dryers/hog fuel boilers currently in operation in the forest products industry were analyzed. The data obtained were used to validate the accuracy of the simulation models and to establish the performance of boiler/dryer systems under field conditions. A wide range of operating conditions were encountered. Of particular
interest, the boiler exhaust temperatures observed ranged from 340-500°F, indicating that significant drying could be realized at moderate stack temperatures, as substantiated by experimental moisture content data.

The simulation models were used to evaluate a general boiler/dryer system's sensitivity to variation in operating conditions. The sensitivity analyses indicated that under moderate conditions (400°F boiler exhaust, etc.) the installation of a rotary dryer results in a 7% increase in boiler efficiency and a 7% decrease in fuel consumption. Both the field data and sensitivity analyses indicated that a greater increase in boiler efficiency could be realized at higher stack temperatures, approximately a 12% increase in boiler efficiency for a stack temperature of 600°F.

The economic analysis was based on capital cost estimates for retrofitting a rotary dryer to an existing boiler, and considered federal and State of Oregon investment and energy tax credits. Payback periods for both cash flow and income bases were determined based on 7% fuel savings, and were contrasted to equivalent BTU savings of natural gas and No. 6 heating oil.

The cash flow basis payback periods based on hog fuel savings due to dryer installation ranged from 4.7 years for a used dryer to 7.8 years for a new dryer. The payback periods for equivalent BTU savings of gas and oil ranged from 2.5 to 3.6 years for gas and from 2.7 to 3.8 years for oil.
In summary, this study concludes that retrofitting a rotary dryer to an existing boiler is an economically feasible option to the forest products industry.
THE SIMULATED AND MEASURED PERFORMANCE OF ROTARY DRYERS
USED TO DRY WOOD WASTE FUELS USING
BOILER EXHAUST GASES

by
Raymond W. Kirk

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APPROVED:

Redacted for Privacy
Charles E. Wicks
Professor of Chemical Engineering in charge of major

Redacted for Privacy
James B. Wilson
Professor of Forest Products in charge of research

Redacted for Privacy
Charles G. Wills
Head of Department of Chemical Engineering

Redacted for Privacy
Dean of Graduate School

Date thesis is presented May 2, 1983

Typed by Mary Ann (Sadie) Airth for Raymond W. Kirk
ACKNOWLEDGEMENTS

So comes the end of an era. This thesis is the culmination of my graduate work at Oregon State University. I have made many friends during my stay, and I shall cherish the memories of our times together.

Each of these many friends has contributed in some fashion to this thesis, either directly or by contributing in their own way to the person that I am. I regret that I cannot individually acknowledge each one of them, yet I thank them all for the good times. I wouldn't have made it this far without them.

I wish to express sincere thanks and appreciation to Dr. James B. Wilson, who directed my research and was always willing to lend a hand when needed. I especially thank him for being understanding and supportive during those trying times that enter into everyone's lives. Jim was a constant source of encouragement.

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I greatly appreciated the courtesy of those firms that allowed access to their facilities for the sake of experimentation. In particular, I wish to thank Bud Keene and Vern Wheeler for their cooperation with the field studies.

Lastly, I find that mere words cannot express the deep love and gratitude that I have for my mother Emily Beatrice Kirk and my father Harry Lee Kirk (1898-1976), to whom this thesis is dedicated.
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THE SIMULATED AND MEASURED PERFORMANCE OF ROTARY DRYERS USED TO DRY WOOD WASTE FUELS USING BOILER EXHAUST GASES

I. INTRODUCTION

Wood waste-fired boilers are ubiquitous to the forest products industry; in the United States alone there are approximately 1,700 currently in operation. Together they consume approximately 30 million dry tons of wood and bark residue annually.

Fuel Moisture Content Strongly Influences Boiler Performance

The overall efficiency of these boilers is markedly affected by the moisture content of the residual fuel, as a certain amount of the heating value of the fuel is required to vaporize that water entering the boiler with the fuel. Occasionally the residual fuel is saturated with water to the extent that the limits of combustion (approximately 68% moisture, wet basis (Johnson, 1975)) are approached, necessitating the use of fossil fuel to overfire the boiler in order to sustain combustion and achieve the desired steaming rate. In some instances the steaming rate of the boiler is so reduced by wet fuel that auxiliary fossil fuel-fired boilers are used, if available, to displace steam "lost" in evaporating water (from the fuel) within the furnace. Even with the current (May 1983) trends of lower gas and oil prices, the use of such fuels results in considerable additional expense. It is thus in the interest of the
The forest products industry to develop means of reducing and controlling the moisture content of wood residual fuels.

**Many Benefits to be Realized from the Reduction of Fuel Moisture Content**

The improvements in boiler performance which result from a reduction in the wood waste fuel moisture content are the following (MacCallum, et al., 1982):

* increased steaming capacity
* increased boiler efficiency
* reduced consumption of auxiliary (fossil) fuels
* improved stability of boiler operation
* increased rate of response to boiler load changes
* decreased power consumption by forced-draft and induced-draft fans
* higher combustion zone temperatures
* increased combustion efficiency (more complete combustion)
* reduced particulate emissions

**Many Types of Dryers Available**

There is a variety of equipment used in the industry to reduce solids moisture content. Among these are several types of dryers that use various methods of continuous gas/solid contacting to affect drying. In addition to the several classifications of tunnel-truck and tray drying, these dryers fall into two categories: Those that
use boiler exhaust gas as the drying medium, in direct contact with the residual, or hog fuel (Thompson, 1975; Vala, 1982; Mohr, 1982), and those that use steam indirectly as the drying medium (Svensson, 1981). Those dryers using flue gas as the drying medium may be further classified as rotary dryers, cascade dryers, fluidized bed dryers and flash dryers. It is suggested that the reader consult an excellent study by MacCallum, et al. (1982) for detailed descriptions of some of the various dryers available.

This Report Considers Rotary Dryers Only

The topic of this study is the rotary dryer which uses boiler exhaust gases as the drying medium. Several dryers of this type are currently in operation throughout the United States and Canada (Vala, 1982; Mohr, 1982; Young, 1983; MacCallum, et al., 1982), and are considered to be among the least expensive of the dryer options available. Three of these dryers were analyzed throughout the course of this study. The primary objectives of this study are considered as follows.

(1) Development of a general simulation model of the boiler/dryer system

Computer simulation models of the boiler/dryer system have been developed previously (Oswald, 1980; Young, 1983); at least one of these models (Oswald, 1980) is available to the general public, yet
is largely a theoretical effort to evaluate the heat and mass balances of a rotary dryer/wood waste-fired boiler system.

The performance of a boiler/dryer system is primarily a function of the operation conditions and parameters peculiar to that system. In order to critically evaluate the performance of said system, any simulation model developed must be general enough to be site specific, using temperatures normally seen for the boiler exhaust gas, the average steam demand, the typical range of fuel moisture content entering the boiler, etc., to predict fuel savings and boiler efficiency, etc. If it was possible to accurately predict the annual fuel savings for a given plant, the economic feasibility of installing a rotary dryer could be determined. Thus one of the primary objectives of this study was the development of a general computer-simulated model of the boiler/dryer system.

(2) Evaluation of existing industrial rotary dryers

Of secondary importance to this study was the testing of three rotary dryers currently in operation in the forest products industry. The data obtained from these case studies were then used to evaluate the performance of said dryers, in terms of thermodynamic, or heating efficiency, and in terms of fuel moisture content reduction. In addition, and of considerable importance to this study, the data obtained were also used to evaluate the accuracy and reliability of the boiler/dryer simulation model mentioned above.
A broad range of boiler/dryer size was encountered throughout the course of this study, in a variety of forest products manufacturing facilities. The boilers examined ranged in capacity from a 180,000 pph spreader-stoker to a 9,000 pph fuel cell. The accompanying dryers ranged in size from 11½ x 50 feet (diameter x length) to 5 x 20 feet, respectively.

(3) Economic analysis of dryer installation

The third part of this study was the evaluation of the economic feasibility of installing a rotary dryer, or retrofitting an existing boiler with said dryer. The economic analysis considered the capital cost of installing a rotary dryer, and examines the payback periods based on wood waste fuel savings, for two options: the purchase of a new dryer, with all required engineering and contracting done by consulting or dryer manufacturing firms, and the purchase of used drying equipment, with all the necessary engineering and contracting done by plant personnel. In addition, the economics of dryer installation based on hog fuel savings was contrasted with the economics based on BTU-equivalent savings of natural gas and No. 6 heating oil.

This Report Presented as a Guide to use When Considering Dryer Installation

This report is presented as a guide to those readers considering the installation of a rotary dryer. Should the owner of a wood waste-fired boiler consider the option of installing a dryer, the
data obtained from the evaluation of the existing boiler/dryer systems (presented in the Case Studies Section of this report) should provide a sufficiently broad range of boiler sizes to allow comparison.

The simulation programs provided in this report may be modified (for use on the available computer systems) to predict the boiler/dryer performance peculiar to (almost) any situation encountered. In addition, the predicted boiler/dryer performance trends (generated using both simulation models developed; see Performance Trends Section of this report) presented here should provide the reader with quick estimates of the fuel savings and boiler efficiency increases expected from the installation of a rotary dryer, providing that the reader has some indication of the operating characteristics of the boiler in question.

The economic analysis presented in this report gives sample installation costs of a rotary dryer; these costs are based on representative capital cost estimates obtained from forest products and related industries, and are in terms of May 1983 dollars.
II. SIMULATION PROGRAM DEVELOPMENT

Models Developed to Predict Performance Characteristics of Boiler/Dryer Systems

One of the primary objectives of this study was to develop a simulation model that would accurately predict the performance characteristics of a boiler/dryer system, given a set of specified operating parameters, mainly those pertaining to the boiler. The simulation model could be used to predict fuel savings resulting from the installation of a rotary dryer, thus providing a basis for subsequent economic studies to evaluate the feasibility of installing said equipment. The evaluation of the various industrial dryers encountered within the contexts of this study fills a supporting role, and was done primarily to estimate the reliability of the models developed (see Case Studies Section).

Two such simulation models were developed throughout the course of this study, differing only in the treatment of the energy balances around the dryer. These differences are accounted for in some detail in the ensuing pages of this section.

A block diagram representative of the boiler/dryer system and the accompanying streams is shown in Figure 1. Brief descriptions of the process streams are listed with the variable names and descriptions in Table 1 (a more complete listing may be found in Table A.1); note that the variables' names are identical to the Fortran variables used in both simulation programs, and represent the
Figure 1. Process flow diagram of general boiler/dryer system
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<td>2</td>
<td>wet fuel that bypasses the dryer and is fed to the boiler</td>
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<tr>
<td>3</td>
<td>dry fuel that exits the dryer and is fed to the boiler</td>
</tr>
<tr>
<td>4</td>
<td>combustion air</td>
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<tr>
<td>5</td>
<td>boiler exhaust</td>
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<td>6</td>
<td>air leakage into the dryer</td>
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<td>7</td>
<td>dryer exhaust</td>
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<td>Qsteam</td>
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<td>Qheat</td>
<td>radiative, conductive and convective losses from the boiler</td>
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<tr>
<td>EA</td>
<td>Combustion excess air (decimal percent)</td>
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<td>FFRD1</td>
<td>Fuel flow rate, bone-dry, stream 1</td>
</tr>
<tr>
<td>FFRD2</td>
<td>Fuel flow rate, bone-dry, stream 2</td>
</tr>
<tr>
<td>FFRD3</td>
<td>Fuel flow rate, bone-dry, stream 3</td>
</tr>
<tr>
<td>FHR</td>
<td>Ambient humidity ratio (lbs water/lb dry air)</td>
</tr>
<tr>
<td>FR</td>
<td>Feed ratio, defined as the ratio of the dryer feed flow rate to the dryer bypass flow rate</td>
</tr>
<tr>
<td>FMCD1</td>
<td>Fuel moisture content (dry basis), stream 1 (dryer inlet) (decimal percentage)</td>
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<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>FMCD2</td>
<td>Fuel moisture content (dry basis), stream 2 (dryer bypass) (decimal percent)</td>
</tr>
<tr>
<td>FMCD3</td>
<td>Fuel moisture content (dry basis), stream 3 (dryer exit) (decimal percent)</td>
</tr>
<tr>
<td>HHV</td>
<td>Fuel higher heating value (BTU/lb dry wood)</td>
</tr>
<tr>
<td>HTLF</td>
<td>Boiler heat loss factor, expressed as a percentage of the fuel higher heating value</td>
</tr>
<tr>
<td>HTLOSSB</td>
<td>Boiler heat loss (BTU/hour)</td>
</tr>
<tr>
<td>PCTCL</td>
<td>Percent carbon loss, expressed as a percentage of the fuel ultimate analysis carbon</td>
</tr>
<tr>
<td>PCT1</td>
<td>Percent of the total available energy in the boiler exhaust that is used for drying</td>
</tr>
<tr>
<td>PCT2</td>
<td>Percent of the total available energy in the boiler exhaust that is used to heat the (wood waste) fuel, and the water contained in the fuel at the dryer exit, from the entrance to the exit temperature of the dryer</td>
</tr>
<tr>
<td>TAM</td>
<td>Ambient temperature (°F)</td>
</tr>
<tr>
<td>TBE</td>
<td>Boiler exhaust temperature (°F)</td>
</tr>
<tr>
<td>TDE</td>
<td>Dryer exhaust temperature (°F)</td>
</tr>
<tr>
<td>TDI</td>
<td>Dryer inlet temperature (usually assumed to be the boiler exhaust temperature) (°F)</td>
</tr>
<tr>
<td>TF1</td>
<td>Dryer inlet fuel temperature (°F)</td>
</tr>
<tr>
<td>TF2</td>
<td>Bypass stream fuel temperature (°F)</td>
</tr>
<tr>
<td>TF3</td>
<td>Dryer exit fuel temperature (°F)</td>
</tr>
<tr>
<td>QSTEAM</td>
<td>Boiler steam demand (BTU/hour)</td>
</tr>
<tr>
<td>ULTC</td>
<td>Ultimate analysis carbon (lbs carbon/lb dry wood)</td>
</tr>
<tr>
<td>ULTH</td>
<td>Ultimate analysis hydrogen (lbs hydrogen/lb dry wood)</td>
</tr>
<tr>
<td>ULTO</td>
<td>Ultimate analysis oxygen (lbs oxygen/lb dry wood)</td>
</tr>
</tbody>
</table>
same quantities. Copies of each simulation program are found in Appendix E.

**Program SIM1 Fixes Dryer Exhaust Temperature**

Although both simulation programs make use of the same material and energy balances around the boiler, they do differ somewhat in the methods used to characterize the dryer. The treatment of the dryer section used in Program SIM1 consisted of the development of typical material and energy balances of the input and output streams of the dryer, ultimately resulting in an overall energy equation for the dryer. This equation, which is written in comparable form to a first law (of thermodynamics) description of a steady-state, steady-flow process, initially contains four unknowns, none of which is specified in terms of the remaining three. As a result, the system of equations describing the boiler/dryer system (an overall energy equation for each the boiler and the dryer) has more degrees of freedom (unknowns) than equations (two equations, four unknowns). Consequently, two of the unknowns must be specified, or fixed, in order to satisfy the criteria for the solution of the system of equations. Thus Program SIM1 fixes the dryer exhaust temperature (TDE) and the dryer exit fuel temperature (TF3). The flow rate of oven-dry wood through the dryer (FFRD3) and the dryer exit fuel moisture content (FMCD3) remain as unknowns.
Program SIM1 Works Well for Dryers with Feedback Control Systems

Several of the rotary dryers currently in operation have feedback control of the dryer exhaust temperature, as was the case of Dryer A. In such a system the dryer exhaust temperature is maintained, for a variety of reasons, at a specified value, or set point, through the use of a feedback control loop which regulates the fuel flow to the dryer by diverting part of the fuel directly to the boiler.

Program SIM1, which fixes the dryer exhaust temperature, is well adapted to the modeling of such a system. For example, SIM1 allows the user to evaluate dryer performance over a range of dryer exhaust temperature settings, selecting the optimum temperature within the operating constraints of the system, i.e., minimizing the dryer exhaust temperature, yet maintaining it at a value high enough (greater than the expected dew point temperature) to prevent condensation on metal surfaces.

Also, SIM1 could be modified from a steady-state basis to a "real-time" basis, accounting for fluctuations in fuel and boiler exhaust conditions, regulating the fuel flow rate through the dryer by diverting some fuel directly to the boiler. (Both programs have the ability to specify the relative flow rates of dryer feed fuel and bypass, or blend fuel, through use of a "feed ratio" (FR), which is defined as the ratio of the flow rate of the fuel fed to the dryer to the flow rate of the bypass, or blend stream.)
Program SIM1 is less effective in predicting the behavior of those systems that experience large fluctuations in boiler exhaust or fuel conditions, and those that do not have the capacity to regulate the dryer feed flow rate (or the dryer exhaust temperature) by diverting part of the fuel to the boiler directly. As an alternative to SIM1, Program SIM2 was developed, using a different approach to the modeling of the processes occurring within the dryer.

Program SIM2 Uses Thermodynamic Heating Efficiency to Predict Dryer Performance

Program SIM2 was developed partly in response to the limitations of SIM1, and partly as the result of the analysis of actual dryer performance data. Material and energy balances of each of the industrial dryers studied indicated that the available energy, relative to the ambient temperature, contained within the boiler exhaust stream could be "partitioned" into four separate flows, or segments, as illustrated by Figure 2. These flows, or segments, are categorized as follows:

(A) The heat carried out of the dryer in the dryer exhaust stream and thus purged to the ambient air; this stream exits at the dryer exit temperature; the energy contained within the dryer exhaust is relative to the ambient temperature.

(B) That energy actually used to evaporate water from the wood waste fuel stream
Figure 2. Partitioning of energy flows for rotary drying of hog fuel (Dryer A); (A) energy purged to the ambient air in dryer exhaust, (B) energy used to evaporate water from hog fuel (PCT1), (C) sensible heat requirement of hog fuel and water remaining with fuel at dryer exit (PCT2), (D) sensible heat required to raise air leakage from ambient temperature to dryer exhaust temperature.
(C) The sensible heat required to heat the fuel, and the water remaining in the fuel at the dryer exit, from its initial temperature to the dryer fuel exit temperature, and

(D) The sensible heat required to raise the temperature of any air leaking into the dryer from its initial (ambient) temperature to the dryer exhaust temperature.

The energy used for evaporation, when expressed as a percentage of the total available energy entering the dryer, may be considered to be the thermodynamic, or heating efficiency of the dryer. The dryer performance data collected in this study indicated dryer heating efficiencies in a range of roughly 35 to 55 percent, with an average value of approximately 50 percent (the average of Plants A and C, the measurements of which were considered to be of greater reliability than those of Plant B). The average value of 50 percent is in relatively good agreement with the heating efficiencies of rotary dryers reported in the literature, ranging from roughly 25 to 60 percent for materials dried under medium-low temperatures (Sloan, 1967).

Analogous to the development of the overall energy equation for the dryer in SIM1, the equations developed in SIM2 describing the dryer initially contain at least four unknowns. As with SIM1, two of the unknowns must be specified or otherwise accounted for, to allow solution of the system of equations describing the entire boiler/dryer system. Consequently SIM2 specifies the heating
efficiency, or the amount of energy used in evaporation, and the sensible heat requirement of the fuel and the water contained in the fuel at the dryer exit, each as percentages of the total available energy in the boiler exhaust stream, respectively as PCT1 and PCT2 (see Figure 2). The dryer exhaust temperature is then calculated as a function of the energy remaining after removing the PCT1 and PCT2 "slices" from the total "pie", as well as the respective boiler exhaust and air leakage flow rates and initial (prior to entry into the dryer) conditions.

Program SIM2 Works Well as a General All-around Model

The utility of Program SIM2 is that it allows the use of thermodynamic, or heating efficiencies to predict the general behavior of a rotary dryer. Exit conditions need not be explicitly specified as in SIM1. Also, as with SIM1, SIM2 could be modified to a "real-time" basis, allowing the user to evaluate the effects of boiler exhaust and fuel conditions on overall system performance. SIM2 also allows the user to evaluate the optimum feed ratio of dryer feed to bypass feed flow rates, determining the ideal value that would maintain the dryer exhaust temperature well above the dew point, yet make the most of the available energy, in effect maximizing the heating efficiency of the dryer.
Programs SIM1 and SIM2 Use Actual Boiler Conditions

Both Programs SIM1 and SIM2 require a variety of input variables to adequately model the behavior and performance of a boiler/dryer system. These input variables may be divided into two categories: (1) those variables that can be measured or obtained from appropriate literature, and, (2) those variables that must be specified or estimated by the user.

In the first category, those variables that have the greatest effect on the behavior of the boiler/dryer system, and that can be easily measured by plant personnel are the following:

- Boiler steam demand (or load), in energy terms (QSTEAM)
- Combustion excess air (EA)
- Boiler exhaust temperature, after last heating surface (TBE)
- Stockpile fuel moisture content (FMCD1)

Those variables of secondary, yet significant, importance to the accurate modeling of the boiler/dryer system that can be readily measured or obtained from literature data, are as follows:

- Fuel higher heating value (HHV)
- Fuel ultimate analysis (carbon, hydrogen, and oxygen) (ULTC, ULTH, ULTO)
- Stockpile fuel temperature (usually assumed to be the ambient temperature) (TF1)
- Ambient temperature (TAM)
- Ambient humidity ratio (FHR)
Those variables of the second category, those that must be specified or estimated by the user, are listed below. All variables listed below are used by both simulation programs, unless otherwise indicated. Common estimated (or suggested) values of several of the quantities are given in parenthesis.

* Boiler convective, radiative and conductive heat losses, expressed as a percentage of the higher heating value of the fuel (5%) (HTLFB)

* Carbon losses (carryover), expressed as percent ultimate analysis carbon (8.6%, which corresponds to roughly 5% of the total mass of the fuel) (PCTCL)

* Dryer inlet temperature (usually assumed to be equal to the boiler exhaust temperature) (TDI)

* Dryer air leakage, expressed as percent of the dry gas flow of the boiler exhaust (ALF)

* Dryer exhaust temperature (TDE) - input variable; SIM1

* Dryer exit fuel temperature (TF3) - input variable; SIM1

* Dryer thermodynamic or heating efficiency (PCT1) - input variable; SIM2

* Sensible heat requirement of the fuel stream, expressed as a percentage of the total available energy input to the dryer (PCT2) - input variable; SIM2

* Feed ratio, expressed as the ratio of the flow rate of the dryer feed to the flow rate of the bypass, or blend stream (FR)
Programs SIM1 and SIM2 Predict Boiler Efficiencies and Fuel flows

Programs SIM1 and SIM2 provide estimates of the flows and conditions of interest in the boiler/dryer system, given the appropriate input variables listed above. Those output variables of particular importance to the user, especially when evaluating the feasibility of using a rotary dryer in conjunction with a wood waste-fired boiler, either currently in use or on the drawing board, are the following:

* Boiler efficiency
* Fuel consumption
* Fuel savings resulting from the addition of a dryer
* Dryer exit fuel moisture content

Where applicable, SIM1 and SIM2 predict both the stream flows and conditions for both "without dryer" and "with dryer" cases. In addition, both programs predict the percent changes of the appropriate stream flows and conditions, relative to the case of the boiler alone. (For example, both programs predict the percentage increase in boiler efficiency resulting from the addition of a dryer. In order to eliminate any uncertainty in the definition of percentage changes, consider that an increase in boiler efficiency from 50 to 55 percent represents a five percentage-point increase, yet also represents a ten percent increase in efficiency; the latter is the method used in this study to report percentage change.

Those quantities of secondary importance to the user in evaluating the feasibility of dryer use are listed below. These quantities
are of importance in the design of the boiler/dryer system, particularly in the sizing of transport equipment (fuel conveyors, fans, etc.).

* All gas stream flow rates, both volumetric and mass
* All fuel stream flow rates
* Gas and fuel stream conditions, such as temperature, humidity and moisture content

Programs SIM1 and SIM2 Assume Steady-State Conditions

Programs SIM1 and SIM2 were developed under the following assumptions:

* The entire process is steady-state, steady-flow
* The fuel is composed entirely of wood waste (bark and wood)
* Essentially complete combustion of the fuel to carbon dioxide and water (carryover carbon present as charcoal)

In response to possible questions regarding the validity of the first assumption, it is a fully-acknowledged fact that any industrial boiler experiences fluctuations in both steam demand and fuel conditions. However, when considered over time, these fluctuations tend to average out, and the system may be assumed to be steady-state.

In summary, both simulation programs use typical material and energy balances to develop two equations, those being the overall energy balances of the boiler and the dryer. The equations developed are nonlinear in nature, and require an iterative-type solution technique; brief flow charts of each program are presented in
Appendix E. Both programs are written in Fortran IV, and may be modified for use with Fortran V and Fortran 77 operating systems. (For a more rigorous development of SIM1 and SIM2, see Appendix E - Program Development.)
III. CASE STUDIES

Case Studies Used to Evaluate the Reliability of SIM1 and SIM2

The evaluation of the industrial dryers encountered in this study serves two purposes. The primary purpose of the case studies was to determine the reliability and accuracy of the two simulation models/programs developed. In addition, the case studies allow a side-by-side comparison of actual dryer performance over a broad range of boiler operating conditions. The significant operating parameters and associated process flows and properties of the three boiler/dryer systems analyzed in this study are presented in Table 2, which illustrates the wide range of conditions encountered in the field.

Accurate evaluation of the boiler/dryer systems required that a variety of measurements be made. These measurements include the following:

* Gas stream flow rates (from standard pitot traverse)
* Gas stream composition (CO, CO2, O2 - from dry gas analysis)
* Gas stream humidity (from wet bulb/dry bulb measurement)
* Fuel stream flow rates (bucket and scale)
* Fuel stream moisture contents (standard technique of weigh-dry-weigh)
* Temperatures of all streams of interest (thermocouple)
### TABLE 2. Summary of Boiler/Dryer Comparisons

<table>
<thead>
<tr>
<th>Category</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated boiler capacity (pph)</td>
<td>180,000</td>
<td>106,000 (^1)</td>
<td>20,000</td>
</tr>
<tr>
<td>Boiler steam demand during trials</td>
<td>170,000</td>
<td>60,000 (^1)</td>
<td>9,000</td>
</tr>
<tr>
<td>Dryer size (length, ft x diameter, ft)</td>
<td>50 x 11.5</td>
<td>50 x 10</td>
<td>20 x 5</td>
</tr>
<tr>
<td>Combustion excess air (%)</td>
<td>86</td>
<td>380</td>
<td>189</td>
</tr>
<tr>
<td>Boiler exhaust temperature (°F)</td>
<td>373</td>
<td>450-500</td>
<td>330-350</td>
</tr>
<tr>
<td>Stockpile fuel moisture content - MC(_d)/MC(_w) (%)</td>
<td>65.2/39.5</td>
<td>106.3/51.5</td>
<td>154.3/60.7</td>
</tr>
<tr>
<td>Dryer exit fuel moisture content - MC(_d)/MC(_w) (%)</td>
<td>39.4/28.3</td>
<td>30.9/23.6</td>
<td>104.2/51.0</td>
</tr>
<tr>
<td>Fuel flow rate through dryer (lb(_m) dry wood/hr)</td>
<td>26,280 (^2)</td>
<td>7,500</td>
<td>1,960</td>
</tr>
<tr>
<td>Fuel flow rate to boiler (lb(_m) dry wood/hr)</td>
<td>31,800 (^3)</td>
<td>8,820 (^3)</td>
<td>1,960</td>
</tr>
<tr>
<td>Dryer inlet dry gas flow rate (lb(_m) /hr)</td>
<td>380,350</td>
<td>301,320</td>
<td>38,420</td>
</tr>
<tr>
<td>Dryer air leakage (%)</td>
<td>11.75</td>
<td>64.34</td>
<td>67.06</td>
</tr>
<tr>
<td>Dryer inlet humidity ratio (lb(_m) H(_2)O/lb(_m) dry gas)</td>
<td>0.1053</td>
<td>0.0638</td>
<td>0.1145</td>
</tr>
<tr>
<td>Dryer exhaust humidity ratio (lb(_m) H(_2)O/lb(_m) dry gas)</td>
<td>0.1181</td>
<td>0.0580</td>
<td>0.0868</td>
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<tr>
<td>Dryer exit temperature (°F)</td>
<td>203</td>
<td>200-300</td>
<td>150</td>
</tr>
</tbody>
</table>
# TABLE 2 (Continued)

<table>
<thead>
<tr>
<th>Category</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer thermodynamic, or heating efficiency (%)</td>
<td>53.4</td>
<td>36.01</td>
<td>45.4</td>
</tr>
</tbody>
</table>

1 Two boilers, each with rated capacity of 53,000 pph and average steam demand of 30,000 pph

2 Measured using calibration method developed by staff of Plant A

3 Back-calculated from overall carbon balance
All of the above measurements were made both before and after the dryer, with the exception of gas stream flow rate, and were made as close to the dryer as possible. The data obtained from these measurements allowed the calculation of the following quantities through the use of typical material and energy balances:

* Combustion excess air
* Dryer air leakage
* Dryer thermodynamic, or heating efficiency
* Total fuel flow rate to the boiler, based on an overall carbon balance

Quantities such as the boiler capacity and average steam demand were obtained from plant personnel. These data were used in part as input to the simulation programs, and in part as comparison with simulation-predicted quantities such as fuel consumption and dryer exit fuel moisture content. For a complete development of the methods used to determine the various quantities mentioned above, see Appendix C - Experimental Method, and Appendix D - Data and Calculations.

Dryers Evaluated in a Variety of Forest Products Industries

The dryers that were evaluated throughout the course of this study were found in a variety of forest products industries. Each facility visited is described in brief detail below.

**Plant A.** The boiler/dryer tandem of Plant A generates process steam for use in a pulp and paper mill. Boiler A is a spreader-
Figure 3 Process flow diagram of Boiler/Dryer A
stoker type boiler, and is rated at 180,000 pph (of steam), at 580 °F and 480 psia. A schematic of Boiler/Dryer A is given in Figure 3. As seen in Figure 3, the system has the capacity to divert the stockpile fuel stream to either the boiler or the dryer, or a combination of the two, and uses a feedback control system which regulates the dryer feed rate using the dryer exhaust temperature as the control "set point". The fines entrained in the dryer exhaust are collected and are pneumatically conveyed to a fines surge bin and are fed to the boiler as needed, usually to compensate for sudden surges in steam demand.

Plant B. The boilers of Plant B deliver process steam to a sawmill and to a hardboard manufacturing plant. Each is a dutch-oven type boiler, and each is rated at a maximum steaming capacity of 53,000 pph, at 265 psia (saturated steam), although the average steam load is approximately 30,000 pph per boiler (the total steam demand fluctuates over a range of about 30,000 to 100,000 pph, due largely to the pressing cycle in the wet-process hardboard plant); two of the three boilers were in operation during experimentation, for a total average steam demand of 60,000 pph. As seen in Figure 4, the boilers are fed from a fuel storage bunker, and not directly from the external fuel supply or the dryer. Exhaust gas from each boiler may be diverted to either or both of the two exhaust stacks; during the experimental run each boiler exhausted to a separate stack. Gas to be used for drying is withdrawn directly from the side of one exhaust
Figure 4. Process flow diagram of Boiler/Dryer B
stack, relying on the negative pressure differential developed by the induced-draft fan at the exhaust end of the cyclone. The fuel enters the storage bunker in two separate flows; the main fuel stream is split, part of which enters the bunker directly, the remainder passing through the dryer prior to entry into the bunker.

The relative complexity of Boiler/Dryer B made accurate measurement difficult at best. Some of the sources of difficulty in analyzing this system, or similar systems are the following:

1. The possibility exists that the fuel storage bunker was simultaneously filled and emptied at different rates, resulting in a net accumulation or depletion of fuel contained in the bunker, thus contributing to non-steady-state behavior of the system. This would suggest that perhaps a larger data collection period is required (the period of collection was approximately three to four hours, depending on the general behavior of each boiler/dryer studied) to smooth out the data.

2. The possibility exists that the two boilers in operation were not producing steam at the same rate. As a further consequence, the boiler exhaust flows would not have been equal. The case study simulations of Boiler/Dryer B assume equal boiler performance, and also assume equal boiler exhaust flow rates.

3. Related to Item 2, the possibility exists that each boiler used different levels of combustion excess air.

4. Another source of confusion in the analysis of Boiler/Dryer B stems from the fact that the ductwork to the dryer exits directly
from the exhaust stack. This in itself presents two possibilities: one being the potential loss of part of the exhaust gas stream to the atmosphere via the exhaust stack, the other possibility being the leaking of air into the exhaust stream, again via the exhaust stack. One would assume the latter possibility to be the more likely, primarily due to the favorable (for flow) pressure differential established by the induced-draft fan. In addition, in the event that air enters the gas stream through the exhaust stack, the combustion excess air, as calculated in Appendix D, would be greater than one would expect. Note that the value of excess air reported for Boiler/Dryer B in Table 2 is 380 percent, considerably higher than one would expect for a wood waste-fired boiler, and is much higher than either of the other two systems analyzed. Since the gas stream composition, used in evaluating the excess air, was measured downstream from the exhaust stack/dryer duct junction, no difference would be noted in apparent combustion excess air if part of the exhaust gas stream escaped to the atmosphere at the junction.

**Plant C.** Plant C was by far the easiest boiler/dryer system to analyze. The automated fuel cell of Plant C produces steam for use in veneer-bolt conditioning kilns, and is rated at a maximum steaming capacity of 20,000 pph, at 11.5 psia and 320 °F (superheat). As seen in Figure 5, Boiler/Dryer C is quite simple in layout. All of the fuel that enters the boiler, or fuel cell, passes first through the dryer. The fines entrained in the dryer exhaust stream are captured
Figure 5 Process flow diagram of Boiler/Dryer C
in a cyclone and are recombined with the coarse material prior to entry into the boiler.

Boiler/Dryer Systems of a Broad Size Range Studied

As noted in the previous plant descriptions, the boiler/dryer systems encountered throughout the course of this study were various in size and function. The operational parameters of each system, as well as some of the gas and fuel stream flow rates and conditions, were summarized in Table 2.

As may be seen in Table 2, the dryer exhaust humidity ratios of Plants B and C are lower than the accompanying dryer inlet (boiler exhaust) humidity ratios, implying at first glance that the gas stream loses water. This phenomenon is explained by noting the high values of air leakage into Dryers B and C; material balances around the dryer with air leakage in mind do indeed confirm that the gas stream does indeed pick up water as it passes through the dryer.

Simulation-predicted Quantities Agree Well with Actual Measured Values

Simulation-predicted quantities are contrasted to the corresponding measured quantities in Tables 3-5, for Plants A through C, respectively. The format of presentation is as follows:

Column 1 Measured Values
Column 2 Predicted Values - SIM1
Column 3 Predicted Values - SIM2
Column 4 Predicted Values, "Best Guess" - SIM1
Column 5 Predicted Values, "Best Guess" - SIM2

The predicted values found in Columns 2 and 3 were calculated using the actual measured or calculated parameters of each system, where applicable, including the calculated dryer thermodynamic, or heating efficiency.

Columns 4 and 5 are presented to illustrate the predicted system performance under the "best guess" conditions of: 50 percent dryer thermodynamic (heating) efficiency (SIM2), 2.5 percent (of available energy input to the dryer) fuel stream sensible heat requirement (SIM2), and 10 percent dryer air leakage (SIM1 and SIM2); the dryer exhaust temperature used for the "best guess" case simulations (SIM1) is set at 200 F, and all fuel is assumed to pass through the dryer. Also, these same conditions are used as the dryer-related "standard" conditions in the ensuing Performance Trends Section of this report.

The "best guess" cases are presented primarily as approximations of the changes in boiler performance expected from the addition of a rotary dryer. For example, should the owner of a wood waste-fired boiler similar to those encountered in this study consider the purchase of a rotary dryer, the "best guess" cases provide estimates of boiler efficiency increases and fuel savings resulting from dryer installation, using the operating conditions of the boiler in question, and are offered for comparison. The "best guess" conditions are those that could be expected from a well-designed and operated dryer, with proper attention to air leakage and dryer
loading. Although two of the boiler/dryer systems examined in this study were equipped to split the fuel flow, the "best guess" cases assume that all the fuel passes through the dryer; certain boiler facilities may not have the space required to erect the additional equipment required to split the fuel flow. The rationale behind the choice of the fore-mentioned "best guess" and "standard" conditions is largely substantiated by referring to the experimental data of Dryer A, which is presented in Table 3.

By referring to the respective case studies, one notes that the simulation-predicted values of the various quantities of interest agree fairly well with the corresponding experimentally-measured values, particularly for Plants A and C. A brief discussion of each plant is presented below.

Plant A (Table 3). The predicted values of all the major quantities of interest are in good agreement with the measured values, differing on average by roughly five percent. The predicted quantities tend to be lower in value than the measured quantities, yet are well in the range of estimated experimental error (5-10%). Note that the predicted quantities are based on a carbon loss (carry-over) of 8.66 percent of the ultimate analysis carbon, corresponding to approximately five percent, by weight, of the fuel. In addition, both simulation programs assumed a boiler heat loss of five percent of the higher heating value of the fuel. In the event that essentially all of the charcoal carryover was eventually returned to the boiler, either entrained in the dryer exhaust and collected with the
<table>
<thead>
<tr>
<th>Category</th>
<th>1 Measured</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler steam demand (lb\text{m}/hr)</td>
<td>170,000</td>
<td>170,000</td>
<td>170,000</td>
<td>170,000</td>
<td>170,000</td>
</tr>
<tr>
<td>Boiler steam demand (MBTU/hr)</td>
<td>189.3</td>
<td>189.3</td>
<td>189.3</td>
<td>189.3</td>
<td>189.3</td>
</tr>
<tr>
<td>Combustion excess air (%)</td>
<td>86.1</td>
<td>86.1</td>
<td>86.1</td>
<td>86.1</td>
<td>86.1</td>
</tr>
<tr>
<td>Boiler exhaust temperature (°F)</td>
<td>373</td>
<td>373</td>
<td>373</td>
<td>373</td>
<td>373</td>
</tr>
<tr>
<td>Feed ratio</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>% Total fuel passing through dryer</td>
<td>90\text{1}</td>
<td>90</td>
<td>90</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Stockpile fuel moisture content; MC_{d}/MC_{w}</td>
<td>65.2/39.5</td>
<td>65.2/39.5</td>
<td>65.2/39.5</td>
<td>65.2/39.5</td>
<td>65.2/39.5</td>
</tr>
<tr>
<td>Dryer exit fuel moisture content; MC_{d}/MC_{w}</td>
<td>39.4/28.3</td>
<td>34.9/27.5</td>
<td>34.4/27.3</td>
<td>37.3/27.1</td>
<td>36.7/28.3</td>
</tr>
<tr>
<td>Dryer air leakage (%)</td>
<td>11.75</td>
<td>11.75</td>
<td>11.75</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Dryer exhaust temperature (°F)</td>
<td>20\text{3}</td>
<td>20\text{3}</td>
<td>20\text{1}</td>
<td>20\text{3}</td>
<td>213</td>
</tr>
<tr>
<td>Dryer heating efficiency (%)</td>
<td>53.4</td>
<td>-</td>
<td>53.4</td>
<td>-</td>
<td>50.0</td>
</tr>
<tr>
<td>Sensible heat requirement of fuel (%)</td>
<td>2.4</td>
<td>-</td>
<td>2.4</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Fuel flow rate through dryer (lb\text{m}D.W./hr.)</td>
<td>26,280\text{2}</td>
<td>26,787</td>
<td>26,771</td>
<td>29,718</td>
<td>29,850</td>
</tr>
<tr>
<td>Category</td>
<td>Measured</td>
<td>Predicted (SIM 1)</td>
<td>Predicted (SIM 2)</td>
<td>&quot;Guess&quot; (SIM 1)</td>
<td>&quot;Guess&quot; (SIM 2)</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (lbm D.W./hr)</td>
<td>31,800³</td>
<td>29,763</td>
<td>29,745</td>
<td>29,718</td>
<td>29,850</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (without dryer) (lbm D.W./hr)</td>
<td>31,343</td>
<td>31,343</td>
<td>31,343</td>
<td>31,343</td>
<td>31,343</td>
</tr>
<tr>
<td>Fuel savings with dryer (lbm D.W./hr)</td>
<td>-</td>
<td>1,579</td>
<td>1,598</td>
<td>1,626</td>
<td>1,493</td>
</tr>
<tr>
<td>Percent decrease in fuel using dryer (%)</td>
<td>-</td>
<td>5.04</td>
<td>5.10</td>
<td>5.19</td>
<td>4.76</td>
</tr>
<tr>
<td>Boiler efficiency (%)</td>
<td>65.78⁴</td>
<td>70.28</td>
<td>70.32</td>
<td>70.39</td>
<td>70.08</td>
</tr>
<tr>
<td>Boiler efficiency (without dryer) (%)</td>
<td>-</td>
<td>66.74</td>
<td>66.74</td>
<td>66.74</td>
<td>66.74</td>
</tr>
<tr>
<td>Percent increase in boiler efficiency using dryer (%)</td>
<td>-</td>
<td>5.31</td>
<td>5.37</td>
<td>5.47</td>
<td>5.00</td>
</tr>
<tr>
<td>Boiler exhaust rate; dry (lbm D.G./hr)</td>
<td>380,350</td>
<td>367,358</td>
<td>367,133</td>
<td>366,793</td>
<td>368,428</td>
</tr>
<tr>
<td>Humidity ratio, dryer inlet (lbm H2O/ lbm D.G.)</td>
<td>0.1053</td>
<td>0.0882</td>
<td>0.0878</td>
<td>0.0876</td>
<td>0.0895</td>
</tr>
<tr>
<td>Humidity ratio, dryer exhaust (lbm H2O/ lbm D.G.)</td>
<td>0.1181</td>
<td>0.1003</td>
<td>0.1003</td>
<td>0.1017</td>
<td>0.1017</td>
</tr>
<tr>
<td>Fuel ultimate analysis carbon (lbm C/lbm D.W.)</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
</tr>
<tr>
<td>Fuel ultimate analysis hydrogen (lbm H/lbm D.W.)</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
</tr>
</tbody>
</table>
TABLE 3 (Continued)

<table>
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<tr>
<th>Category</th>
<th>1</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel ultimate analysis oxygen (lb_m O / lb_m D.W.)</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
</tr>
<tr>
<td>Fuel higher heating value (BTU/lb_m D.W.)</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
</tr>
</tbody>
</table>

1 Estimated by visual inspection
2 Dryer fed flow rate determined using "calibration" method developed by plant personnel
3 Fuel consumption determined from carbon balance
4 Boiler efficiency determined using carbon balance fuel consumption
5 (Leonard, 1978)
6 (Arola, 1976)
fines, or trapped by impaction with the larger fuel particles in the dryer, the various flows would be very close to the predicted values.

The conditions used for "best guess" simulations did not radically differ from the actual measured performance of the dryer. Consequently, the predicted flows, etc., of both "best guess" cases presented agree quite well with the "actual case" predictions. Of final note, the close agreement of the corresponding values predicted by each simulation program demonstrates the equivalency of the two models.

Plant B (Table 4). As previously illustrated, the complexity of Boiler/Dryer B made accurate measurement and evaluation of the system difficult. The hardboard press-induced swings in the steam demand added to this difficulty, and contributed to the non-steady-state behavior of the entire system (both Plants A and C experienced relatively constant levels of steam demand and consequently tended to be very nearly steady-state).

When all of this is taken into account, it is not surprising that the predicted and measured quantities presented in Table 4 are not in as close agreement as the other two cases. Nevertheless, the predicted values are in the same ballpark, so to speak, as the measured values, especially the dryer exit fuel moisture contents.

Contrasting the "best guess" with the "actual" simulation conditions, it is readily apparent that significant improvement could be made in the overall performance of Boiler/Dryer B by limiting the
<table>
<thead>
<tr>
<th>Category</th>
<th>1 Measured</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler steam demand (lbm/hr)</td>
<td>60,000</td>
<td>60,000</td>
<td>60,000</td>
<td>60,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Boiler steam demand (MBTU/hr)</td>
<td>62.32</td>
<td>62.32</td>
<td>62.32</td>
<td>62.32</td>
<td>62.32</td>
</tr>
<tr>
<td>Combustion excess air (%)</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>Boiler exhaust temperature (°F)</td>
<td>478</td>
<td>478</td>
<td>478</td>
<td>478</td>
<td>478</td>
</tr>
<tr>
<td>Feed ratio</td>
<td>2/3</td>
<td>2/3</td>
<td>2/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Total fuel passing through dryer</td>
<td>40(^1)</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Stockpile fuel moisture content; (\text{MC}<em>{d}/\text{MC}</em>{w}) (%)</td>
<td>106.3/</td>
<td>106.3/</td>
<td>106.3/</td>
<td>106.3/</td>
<td>106.3/</td>
</tr>
<tr>
<td></td>
<td>51.5</td>
<td>51.5</td>
<td>51.5</td>
<td>51.5</td>
<td>51.5</td>
</tr>
<tr>
<td>Dryer exit fuel moisture content; (\text{MC}<em>{d}/\text{MC}</em>{w}) (%)</td>
<td>30.9/</td>
<td>32.9/</td>
<td>29.7/</td>
<td>4.3/</td>
<td>24.1/</td>
</tr>
<tr>
<td></td>
<td>23.6</td>
<td>24.8</td>
<td>22.9</td>
<td>4.1</td>
<td>19.4</td>
</tr>
<tr>
<td>Dryer air leakage (%)</td>
<td>64.3</td>
<td>64.3</td>
<td>64.3</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Dryer exhaust temperature (°F)</td>
<td>238</td>
<td>238</td>
<td>232</td>
<td>200</td>
<td>249</td>
</tr>
<tr>
<td>Dryer heating efficiency (%)</td>
<td>36.1</td>
<td>-</td>
<td>36.1</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Sensible heat requirement of fuel (%)</td>
<td>1.6</td>
<td>-</td>
<td>1.6</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Category</td>
<td>1 Measured</td>
<td>2 Predicted (SIM 1)</td>
<td>3 Predicted (SIM 2)</td>
<td>4 &quot;Guess&quot; (SIM 1)</td>
<td>5 &quot;Guess&quot; (SIM 2)</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Fuel flow rate through dryer (lb\textsubscript{m} D.W. /hr)</td>
<td>7,500</td>
<td>5,415</td>
<td>5,389</td>
<td>11,307</td>
<td>11,837</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (lb\textsubscript{m} D.W. /hr)</td>
<td>8,820</td>
<td>13,533</td>
<td>13,469</td>
<td>11,307</td>
<td>11,837</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (without dryer) (lb\textsubscript{m} D.W. /hr)</td>
<td>-</td>
<td>14,651</td>
<td>14,651</td>
<td>14,651</td>
<td>14,651</td>
</tr>
<tr>
<td>Fuel savings with dryer (lb\textsubscript{m} D.W/hr)</td>
<td>-</td>
<td>1,118</td>
<td>1,182</td>
<td>3,344</td>
<td>2,814</td>
</tr>
<tr>
<td>Percent decrease in fuel using dryer (%)</td>
<td>-</td>
<td>7.63</td>
<td>8.07</td>
<td>22.82</td>
<td>19.21</td>
</tr>
<tr>
<td>Boiler efficiency (%)</td>
<td>78.17</td>
<td>50.9</td>
<td>51.1</td>
<td>60.9</td>
<td>58.2</td>
</tr>
<tr>
<td>Boiler efficiency (without dryer) (%)</td>
<td>-</td>
<td>47.0</td>
<td>47.0</td>
<td>47.0</td>
<td>47.0</td>
</tr>
<tr>
<td>Percent increase in boiler efficiency using dryer (%)</td>
<td>-</td>
<td>8.26</td>
<td>8.77</td>
<td>29.58</td>
<td>23.78</td>
</tr>
<tr>
<td>Boiler exhaust flow rate; dry (lb\textsubscript{m} D.G./hr)</td>
<td>272,520</td>
<td>422,537</td>
<td>420,534</td>
<td>353,026</td>
<td>369,566</td>
</tr>
<tr>
<td>Humidity ratio, dryer inlet (lb\textsubscript{m} H\textsubscript{2}O / lb\textsubscript{m} D.G.)</td>
<td>0.0638</td>
<td>0.0480</td>
<td>0.0476</td>
<td>0.0247</td>
<td>0.0311</td>
</tr>
<tr>
<td>Humidity ratio, dryer exhaust (lb\textsubscript{m} H\textsubscript{2}O / lb\textsubscript{m} D.G.)</td>
<td>0.0580</td>
<td>0.0430</td>
<td>0.0432</td>
<td>0.0527</td>
<td>0.0527</td>
</tr>
<tr>
<td>Fuel ultimate\textsuperscript{4} analysis carbon (lb\textsubscript{m} C/lb\textsubscript{m} D.W.)</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
<td>0.523</td>
</tr>
</tbody>
</table>
TABLE 4 (Continued)

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel ultimate analysis hydrogen (lb$_m$H/lbm D.W.)</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
</tr>
<tr>
<td>Fuel ultimate analysis oxygen (lb$_m$O/lbm D.W.)</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
<td>0.405</td>
</tr>
<tr>
<td>Fuel higher heating value (BTU/lbm D.W.)</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
<td>9,050</td>
</tr>
</tbody>
</table>

1 Estimated by visual inspection
2 Fuel consumption determined by carbon balance
3 Boiler efficiency determined from carbon balance
4 (Leonard, 1978)
5 (Arola, 1976)
air leakage into the dryer, thereby increasing the dryer heating efficiency.

Plant C (Table 5). Plant C was, as noted previously, a well-contained system; there was little doubt in the fuel and boiler exhaust flows. As shown in Table 5, predicted values are in relatively good agreement with those measured, although, as in the case of Boiler/Dryer A, the flows, both gas and fuel, tend to be low relative to the measured values. Similar to the reasoning in the case of Boiler/Dryer A, the possibility of different levels of boiler heat loss and carbon carryover than were assumed in each simulation program, as well as the inherent experimental error, could easily account for the minor (5-10%) differences in the various flow rates.

Case Studies Substantiate Reliability of SIM1 and SIM2

It has been shown that SIM1 and SIM2 generate fuel and gas stream flow rates and dryer performances (in terms of dryer exit fuel moisture content), that are in fairly good agreement with corresponding experimentally-determined values. It is thus concluded that the models and programs developed in this study may be used for reasonably accurate predictions of boiler/dryer performance, allowing plant personnel to make reliable estimates of the overall economic feasibility of using a rotary dryer in conjunction with a wood waste-fired boiler.
### TABLE 5. Predicted vs. Actual Boiler/Dryer Performance - Boiler/Dryer C

<table>
<thead>
<tr>
<th>Category</th>
<th>1</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler steam demand (lbm/hr)</td>
<td>9,000</td>
<td>9,000</td>
<td>9,000</td>
<td>9,000</td>
<td>9,000</td>
</tr>
<tr>
<td>Boiler steam demand (MBTU/hr)</td>
<td>9.31</td>
<td>9.31</td>
<td>9.31</td>
<td>9.31</td>
<td>9.31</td>
</tr>
<tr>
<td>Combustion excess air (%)</td>
<td>189</td>
<td>189</td>
<td>189</td>
<td>189</td>
<td>189</td>
</tr>
<tr>
<td>Boiler exhaust temperature (°F)</td>
<td>340</td>
<td>340</td>
<td>340</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>Feed Ratio</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>% Total fuel passing through dryer (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Stockpile fuel moisture content; MC&lt;sub&gt;D&lt;/sub&gt;/MC&lt;sub&gt;W&lt;/sub&gt; (%)</td>
<td>154.3/60.7</td>
<td>154.3/60.7</td>
<td>154.3/60.7</td>
<td>154.3/60.7</td>
<td>154.3/60.7</td>
</tr>
<tr>
<td>Dryer exit fuel moisture content; MC&lt;sub&gt;D&lt;/sub&gt;/MC&lt;sub&gt;W&lt;/sub&gt; (%)</td>
<td>104.2/51.0</td>
<td>118.6/54.3</td>
<td>117.7/54.1</td>
<td>120.8/51.4</td>
<td>114.3/53.3</td>
</tr>
<tr>
<td>Dryer air leakage (%)</td>
<td>67.1</td>
<td>67.1</td>
<td>67.1</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Dryer exhaust temperature (°F)</td>
<td>150</td>
<td>150</td>
<td>148</td>
<td>200</td>
<td>178</td>
</tr>
<tr>
<td>Dryer heating efficiency (%)</td>
<td>45.37</td>
<td>-</td>
<td>45.37</td>
<td>-</td>
<td>50.0</td>
</tr>
<tr>
<td>Sensible heat requirement of fuel (%)</td>
<td>2.31</td>
<td>-</td>
<td>2.31</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Fuel flow rate through dryer (lbm D.W./hr)</td>
<td>1,963</td>
<td>1,787</td>
<td>1,783</td>
<td>1,795</td>
<td>1,770</td>
</tr>
<tr>
<td>Category</td>
<td>1 Measured</td>
<td>2 Predicted (SIM 1)</td>
<td>3 Predicted (SIM 2)</td>
<td>4 &quot;Guess&quot; (SIM 1)</td>
<td>5 &quot;Guess&quot; (SIM 2)</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (lb\textsubscript{m} D.W./hr)</td>
<td>1,963</td>
<td>1,787</td>
<td>1,783</td>
<td>1,795</td>
<td>1,770</td>
</tr>
<tr>
<td>Fuel flow rate through boiler (without dryer) (lb\textsubscript{m} D.W./hr)</td>
<td>-</td>
<td>1,945</td>
<td>1,945</td>
<td>1,945</td>
<td>1,945</td>
</tr>
<tr>
<td>Fuel savings with dryer (lb\textsubscript{m} D.W./hr)</td>
<td>-</td>
<td>158</td>
<td>161</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>Percent decrease in fuel using dryer (%)</td>
<td>-</td>
<td>8.12</td>
<td>8.30</td>
<td>7.71</td>
<td>8.98</td>
</tr>
<tr>
<td>Boiler efficiency (%)</td>
<td>52.48\textsuperscript{1}</td>
<td>57.67</td>
<td>57.77</td>
<td>57.40</td>
<td>58.20</td>
</tr>
<tr>
<td>Boiler efficiency (without dryer) (%)</td>
<td>-</td>
<td>52.97</td>
<td>52.97</td>
<td>52.97</td>
<td>52.97</td>
</tr>
<tr>
<td>Percent increase in boiler efficiency using dryer (%)</td>
<td>-</td>
<td>8.86</td>
<td>9.05</td>
<td>8.35</td>
<td>9.87</td>
</tr>
<tr>
<td>Boiler exhaust flow rate; dry (lb\textsubscript{m}/hr)</td>
<td>34,402</td>
<td>33,933</td>
<td>33,874</td>
<td>34,092</td>
<td>33,621</td>
</tr>
<tr>
<td>Humidity ratio, dryer inlet (lb\textsubscript{m} H\textsubscript{2}O/ lb\textsubscript{m} D.G.)</td>
<td>0.1145</td>
<td>0.0967</td>
<td>0.0962</td>
<td>0.0978</td>
<td>0.0944</td>
</tr>
<tr>
<td>Humidity ratio, dryer exhaust (lb\textsubscript{m} H\textsubscript{2}O/ lb D.G.)</td>
<td>0.0868</td>
<td>0.0725</td>
<td>0.0725</td>
<td>0.1058</td>
<td>0.1058</td>
</tr>
<tr>
<td>Fuel ultimate\textsuperscript{2} analysis carbon (lb\textsubscript{m} C/lb\textsubscript{m} D.W.)</td>
<td>0.535</td>
<td>0.535</td>
<td>0.535</td>
<td>0.535</td>
<td>0.535</td>
</tr>
<tr>
<td>Fuel ultimate\textsuperscript{2} analysis hydrogen (lb\textsubscript{m} H/lb\textsubscript{m} D.W.)</td>
<td>0.059</td>
<td>0.059</td>
<td>0.059</td>
<td>0.059</td>
<td>0.059</td>
</tr>
</tbody>
</table>

\textsuperscript{1} \textsuperscript{2}
<table>
<thead>
<tr>
<th>Category</th>
<th>1 Measured</th>
<th>2 Predicted (SIM 1)</th>
<th>3 Predicted (SIM 2)</th>
<th>4 &quot;Guess&quot; (SIM 1)</th>
<th>5 &quot;Guess&quot; (SIM 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel ultimate(^2) analysis oxygen ((1b_{m}) (0/1b_{m}) D.W.)</td>
<td>0.403</td>
<td>0.403</td>
<td>0.403</td>
<td>0.403</td>
<td>0.403</td>
</tr>
<tr>
<td>Fuel higher(^2) heating value (BTU/(1b_{m}) D.W.)</td>
<td>9,040</td>
<td>9,040</td>
<td>9,040</td>
<td>9,040</td>
<td>9,040</td>
</tr>
</tbody>
</table>

\(^1\) Boiler efficiency determining using measured fuel flow rate

\(^2\) (Leonard, 1978)
IV. COMPUTER-SIMULATED BOILER/DRYER PERFORMANCE TRENDS

Use of the Computer Aids in Engineering and Management Decisions

Computer-aided process simulation is a versatile tool to the engineer or the manager. It allows one to predict the behavior of a system, or process under a variety of operating constraints and/or conditions, and greatly simplifies the tasks of equipment design, process optimization, and economic feasibility studies. In addition, computer simulation of a process may be used for process control, by using process information (flows, temperatures, etc.) as input data from monitoring devices, evaluating the necessary quantities, and thus ultimately controlling the process by sending the appropriate signals to control devices (valves, motors, etc.).

The predicted performance trends of a wood waste-fired boiler/rotary dryer system are evaluated in the following pages. The evaluation of these trends involved the selection of operating conditions, or parameters that were considered to have major impact on boiler/dryer performance. Once selected, each parameter was varied over a specific range of interest, holding the remaining parameters constant at "standard" conditions, thus evaluating the system's sensitivity to variation in the particular parameter in question.

The parameters used to evaluate the boiler/dryer performance trends are listed below; the "standard" values of each parameter are shown in parenthesis.
* Stockpile fuel moisture content (100%, dry basis; 50%, wet basis)
* Boiler exhaust temperature, after last heating surface (400 °F)
* Combustion excess air (100%)
* Dryer exhaust temperature - input variable; SIM1 (200 °F)
* Dryer air leakage (10%)
* Dryer thermodynamic, or heating efficiency - input variable; SIM2 (50%)
* Feed ratio/percentage of total fuel that passes through dryer (100%)

The major indicators of boiler/dryer performance are listed below; these are considered to be those quantities that would be of primary interest in the evaluation of the feasibility of rotary dryer installation.

* Boiler efficiency
* Boiler fuel consumption (wood waste fuel)
* Fuel savings resulting from the installation of the rotary dryer
* Dryer performance, as indicated by dryer exit fuel moisture

Each of the above indicators is evaluated, where applicable, for both the case of the boiler alone and the case of the boiler/dryer system as a whole; both are presented together as functions of the particular operating parameter in question, allowing direct
comparison of the two. Should the owner of a wood waste-fired boiler consider installing a rotary fuel dryer, the plots presented in the ensuring pages should provide a quick estimate of the expected changes in boiler performance resulting from the installation of said equipment (assuming that the owner has knowledge of the operating parameters and characteristics peculiar to the boiler in question).

The assumptions used in the evaluation of the following performance trend analyses are the following:

* Ambient temperature of 60 °F
* Ambient humidity of 0.00757 lbm water/lbm dry air (50% relative humidity at 60 °F)
* Boiler heat loss of five percent of fuel higher heating value
* Carbon loss (carryover) of five percent of fuel (corresponds to 8.66 percent of ultimate analysis carbon, assuming 90 percent carbon in carryover (Junge, 1977).
* Boiler steam demand of 100,000 pph (106 MBTU/hr)
* Fuel composed entirely of wood waste, with a higher heating value of 9050 BTU/lbm dry wood
* No drop in temperature from boiler exhaust to dryer inlet

Fuel Moisture Content has a Great Effect on Boiler Efficiency

Figure 6 illustrates the marked effect of fuel moisture content on boiler efficiency, as defined by:
Figure 6. Predicted boiler/dryer response to changes in stockpile fuel moisture content; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit fuel moisture content.
Figure 6 (Continued)
Boiler efficiency = \( 100 \times \frac{\text{Steam Demand} \, (\text{BTU/hr})}{\text{Fuel Higher Heating Value} \, (\text{BTU/lbm dry wood}) \times \text{Fuel Flow to Boiler} \, (\text{lbm dry wood/hr})} \)

It is readily apparent that boiler efficiency decreases with increasing fuel moisture content; conversely, fuel consumption increases. Also apparent is the significant increase in boiler efficiency resulting from the installation of a rotary dryer, with an accompanying decrease in fuel consumption. At a stockpile fuel moisture content of 100%, dry basis, the midpoint of the range of moisture contents considered, the addition of the dryer increased boiler efficiency by 7.2%, from 60.6% (without dryer) to 65.0%. The predicted fuel savings under these conditions (recall the "standard" conditions listed previously) was 1,291 oven-dry pounds per hour, from 19,310 to 18,019 oven-dry pounds per hour, a decrease in fuel consumption of 6.7%.

Dryer exit fuel moisture content is largely a function of dryer inlet fuel moisture content. Figure 6.c is presented not only to illustrate dryer performance as a function of stockpile fuel moisture content, but to also enable the reader to estimate the expected reduction in moisture content resulting from the installation of a rotary dryer, using the fuel moisture content of interest to the reader.

Boiler Exhaust Temperature Another Major Factor in Boiler Efficiency

The boiler efficiency is generally considered to be inversely proportional to boiler exhaust temperature. This phenomenon is well
illustrated by Figure 7 (the curves were generated using Program SIM2, which fixes the dryer heating efficiency and allows the dryer exhaust temperature to float in response to air leakage.) Again it is noted that the addition of a dryer resulted in a predicted increased boiler efficiency accompanied by decreased fuel consumption. At a boiler exhaust temperature of 450 °F, the midpoint of the range considered, the addition of the dryer increased the boiler efficiency by 8.4%, from 59.5% to 64.4%. The predicted fuel savings at these conditions was 1,518 oven-dry pounds per hour, from 19,693 to 18,175 oven-dry pounds per hour, a decrease in fuel consumption by 7.7%.

Although it is advisable to maintain the boiler exhaust temperature at a reasonable (in terms of boiler operation) minimum, the "benefit" from a higher exhaust temperature is the additional evaporative capacity of the stack gas. This is readily apparent in Figure 7.c, where one may observe a pronounced decrease in dryer exit fuel moisture content with increasing boiler exhaust (dryer inlet) temperature. The additional evaporative capacity at higher temperature is implied by noting the relative rates of decrease of the boiler efficiencies shown in Figure 7.a; the curves in this figure reveal that the efficiency is less sensitive to boiler exhaust temperature with a dryer in use than with the boiler alone.
Figure 7. Predicted boiler/dryer response to changes in boiler exhaust temperatures; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit fuel moisture content; (d) percent changes in boiler efficiency, fuel consumption and fuel moisture content resulting from dryer installation.
Figure 7 (Continued)
As With High Boiler Exhaust Temperature, High Excess Air Has "Hidden Benefit"

The effect of combustion excess air on boiler efficiency is illustrated by Figure 8; the curves appearing in these figures were generated using Program SIM2. These figures show a decrease in boiler efficiency, combined with an increase in fuel consumption, with an increase in excess air. This is largely a factor of the high concentration of nitrogen, which plays no role in the combustion process, in air; in the event that boilers could be fired with pure oxygen one would note a considerable decrease in the sensitivity of boiler efficiency to excess air (or in this case, excess oxygen). Once again it is noted that the use of the dryer resulted in predicted increased boiler efficiency combined with decreased fuel consumption. The midpoint of the range of excess air levels considered was 100%; the values of boiler efficiency and fuel consumption are coincident with those reported for a boiler exhaust temperature of 400 °F (coincident "standard" conditions), and have been presented previously.

Similar to the hidden "benefit" encountered with high boiler exhaust temperatures when using a rotary dryer, there is some "benefit" to be garnered from high levels of combustion excess air. This benefit is not the result of evaporative capacity in terms of additional thermal (temperature) energy, but is the result of increased evaporative capacity in terms of higher gas flow rates through the dryer, which in turn produces a decrease in dryer exit fuel moisture con-
Figure 8. Predicted boiler/dryer response to changes in combustion excess air; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit fuel moisture content; (d) percent change in boiler efficiency, fuel consumption and fuel moisture content resulting from dryer installation.
Figure 8 (Continued)
tent. Also similar to the behavior manifested by high stack temperatures, the boiler efficiency tends to be less sensitive to excess air levels with the dryer in use than with the boiler alone.

**High Dryer Exhaust Temperatures Imply Lower Thermodynamics or Heating Efficiencies**

Dryer exhaust temperature has significant impact on the thermodynamic efficiency of the dryer, as may be noted by referring to Table 2 in the Case Studies Section of this report. This impact is further illustrated by the dryer performance trends presented in Figure 9. (These curves were generated using Program SIM1, which fixes the dryer exhaust temperature, and although the decrease in dryer thermodynamic efficiency is merely implied by increasing dryer exhaust temperature, SIM1 better illustrates the overall effect than does SIM2.)

Figure 9.a shows a decrease in boiler efficiency from roughly 67% to 63% in the dryer exhaust temperature range of 150 to 300 °F. The decrease in boiler efficiency is largely due to the loss (in the dryer exhaust) of available energy for drying, or a decrease in dryer thermodynamic or heating efficiency, resulting in an increase in dryer exit fuel moisture content. (An alternative way to view the dryer is as an additional heat transfer unit attached to the boiler, resulting in an effective decrease in boiler exhaust temperature, ergo an increase in boiler efficiency.) Even so, the boiler efficiency is higher with the addition of the dryer. At the midpoint of the range of dryer exhaust temperatures considered (225 °F), the
Figure 9. Predicted boiler/dryer response to changes in dryer exit temperatures; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit fuel moisture content; (d) percent change in boiler efficiency, fuel consumption and fuel moisture content resulting from dryer installation.
Figure 9 (Continued)
addition of the dryer increased the boiler efficiency by 6.6%, from 60.6% to 64.6%. The predicted fuel savings at these conditions was 1,189 oven-dry pounds per hour, from 19,310 to 18,121 oven-dry pounds per hour, a decrease in fuel consumption by 6.2%.

**Dryer Air Leakage Decreases Dryer Thermodynamic Efficiency**

Dryer air leakage decreases the amount of energy available for drying by capturing part of that energy, which is taken up in the sensible heat required to heat the incoming air from its initial (ambient) temperature to the temperature of the dryer exhaust, thus resulting in a decrease in a dryer thermodynamic efficiency. This effect is illustrated by Figure 10, which were generated using Program SIM1. (SIM1 was used to evaluate the effects of dryer air leakage for the same reason that it was used to evaluate the effects of dryer exhaust temperature; the thermodynamic efficiency is implied.) Regardless of the amount of air leakage, the use of the dryer results in greater values of boiler efficiency than with the boiler alone. Even at 40% air leakage, near the upper end of the range considered, the addition of the dryer yielded a predicted increase in boiler efficiency of 7.1% (at a dryer exhaust temperature of 200 °F), from 60.7% to 65.1%, with an accompanying fuel savings of 1,289 oven-dry pounds per hour, from 19,292 to 18,004 oven-dry pounds per hour.

Figure 11 is presented simply to illustrate the effects of dryer thermodynamic, or heating efficiency on dryer performance, as
Figure 10. Predicted boiler/dryer response to changes in dryer air leakage; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit moisture content; (d) percent change in boiler efficiency, fuel consumption and fuel moisture content resulting from dryer installation.
Figure 10 (Continued)
Figure 11. Predicted boiler/dryer response to changes in dryer heating efficiency; (a) boiler efficiency, with and without dryer; (b) fuel consumption, with and without dryer; (c) dryer exit fuel moisture content; (d) percent change in boiler efficiency, fuel consumption and fuel moisture content resulting from installation of dryer.
Figure 11 (Continued)

Dryer Exit Fuel Moisture Content, % dry basis

Dryer Heating Efficiency, %

(d)

boiler efficiency

fuel consumption

fuel moisture content

% Change

Dryer Heating Efficiency, %
indicated by dryer exit fuel moisture content, and on overall boiler efficiency. As one would assume, a decrease in drying efficiency is manifested by an increase in dryer exit fuel moisture content, ultimately resulting in a decrease in boiler efficiency.

**Dryer Feed/Dryer Bypass Ratio Apparently Has Little Effect on Overall Boiler Efficiency or Gross fuel Moisture Content**

Variation in the dryer feed/dryer bypass ratio yields rather interesting results, as shown by Figure 12. At first glance it appears that the feed ratio has minimal effect on the overall boiler efficiency or the gross fuel moisture content; the gross fuel moisture content is the weighted average of the dryer exit and bypass stream fuel moisture contents. This phenomenon may be explained by recalling that the dryer thermodynamic, or heating efficiency is set at 50% (Program SIM2 was used to generate the curves found in Figure 12), and subsequently assumes that half of the available energy in the boiler exhaust is used for drying. At lower feed ratios (less fuel passing through the dryer) greater changes in the dryer exit fuel moisture content are observed simply because there is less fuel in the dryer, consequently the ratio of available energy to dryer fuel flow rate increases; the total available energy in the boiler remains essentially constant. The final result is seen by noting that although the dryer exit fuel moisture content is lower, the dry wood flow rate through the dryer is also lower, and hence contributes less to the gross (weighted average) moisture content of the fuel entering the boiler.
Figure 12. Predicted boiler/dryer response to changes in the percentage of total fuel flow rate to the boiler that passes through the dryer; (a) boiler efficiency, with and without dryer; (b) fuel moisture content, boiler inlet and dryer exit.
The curves found in Figure 12.b may at first seem a bit anomalous; negative dryer exit fuel moisture contents are observed when less than roughly 30% of the total fuel passes through the dryer. Conceptually this is impossible, although mathematically feasible. However, there is some value to Figure 12.b, providing that one ignores the region of negative moisture content. It is a recognized fact that energy greater than the latent heat of vaporization is required to evaporate water from wood at moisture contents lower than the fiber saturation point. The additional energy required to dry below the fiber saturation point is not justified by the incremental reduction in moisture content; the drying process becomes less effective (and less efficient). In addition, the danger of fire in the dryer (and cyclones) increases with reduced moisture content, especially below the fiber saturation point. If the gross fuel moisture content in the dryer falls below the fiber saturation point, it can be assumed that the fines will be nearly bone-dry; a spark from tramp metal in the dryer could ignite the fines, resulting in a dryer fire or explosion. Thus the value of Figure 12.b is that it allows one to predict the minimum percentage of the total fuel that passes through the dryer, in terms of efficient drying and safety, by specifying a minimum acceptable dryer exit fuel moisture content, reading the percentage of total fuel that passes through the dryer directly from the graph.
Overall, the Addition of a Rotary Dryer Increases Boiler Efficiency

The performance trends analyses presented in this section indicate that the addition of a rotary dryer to a wood waste-fired boiler results in decreased fuel consumption and increased boiler efficiency, or alternatively, boiler capacity. In addition, the use of a rotary dryer results in a stabilization of the actual operation of the boiler (in terms of the operating conditions listed previously; additional stabilizing influences resulting from the addition of said dryer are discussed in the Introduction of this report). This stability is manifested in a boiler/dryer system that is less sensitive to fluctuations in boiler exhaust temperature and combustion excess air than the case of the boiler alone; the losses in the boiler are partially compensated by gains in the dryer.

Of further note, it appears that the performance of the dryer itself is more sensitive to the dryer exhaust temperature than to dryer air leakage, as indicated by the relative rates of change in boiler efficiency (which is a function of dryer exit fuel moisture content) with respect to each parameter. An increase in air leakage from zero to 50% has roughly the same effect on boiler efficiency as an increase in dryer exhaust temperature from 190 to 230 °F (the range considered was from 150 to 300 °F, corresponding to the ranges observed in the field). This is further substantiated by experimental data (see Energy Partitioning in Appendix D).
The underlying trend exhibited here is one that has been repeated many times in the course of this section - the use of a rotary dryer in conjunction with a wood waste-fired boiler results in substantial increases in boiler efficiency and decreases in fuel consumption. For the operating conditions listed in the beginning of this section (100,000 pph boiler, 100% excess air, 400°F boiler exhaust temperature, etc.) the average increase in boiler efficiency resulting from the addition of the dryer was roughly 7%, accompanied by a decreased fuel consumption of approximately 1,300 oven-dry pounds per hour.

It is important to note that boiler efficiency is a function of all the parameters presented in this section; the 7% increase in boiler efficiency represents that which could be expected for boiler/dryer systems operating at moderate conditions (roughly the midpoints of the ranges of each parameter considered). One could expect the boiler efficiency increases to differ at the extreme ends of the ranges considered. For example, one would realize a significantly greater increase in boiler efficiency resulting from the addition of a dryer at stack temperatures greater than 400°F. As illustrated by Figure 7, the percent increase in boiler efficiency is approximately 12% at a stack temperature of 600°F, with an accompanying decrease in fuel consumption of approximately 11%.
V. ECONOMIC ANALYSIS

The case studies and the performance trends analyses have well illustrated the potential benefits of installing a rotary dryer for use with a wood waste-fired boiler. These benefits have largely been in terms of decreased fuel consumption and increased boiler efficiency and/or boiler capacity. What remains is essentially the "bottom line" in all industrial decisions -- can the installation of a rotary dryer be justified in terms of the overall economics involved?

Rotary Dryers - Two Capital Cost Options

The economic analyses presented here consider two options: (1) on the less expensive end of the scale is the case where a used rotary dryer is purchased and all engineering and contracting is done "in-house" by staff personnel (however, this staff cost is included), and, (2) on the more expensive side is the case where new equipment is purchased, and all engineering design and associated contracting is done by consulting engineering or dryer manufacturing firms. These two options provide a realistic range of dryer installation costs.

The overall economic feasibility of dryer installation is examined in the following pages, in terms of both cash flow and income bases payback periods. In each case (used dryer and new dryer), the payback periods (years) are in terms of wood fuel savings alone, and
then are contrasted with the payback periods determined using the wood fuel savings BTU-equivalents of natural gas and No. 6 heating oil, using the capital cost of the drying equipment.

It is appropriate to contrast the wood fuel savings with equivalent savings of natural gas and oil for several reasons. In the event that the stockpile fuel moisture content approaches or exceeds the limits of combustion (roughly 68%, wet basis (Johnson, 1975)), it becomes necessary to overfire the boiler with an alternate fuel source, usually oil, just to sustain combustion; additional (oil) is required to maintain the steaming rate at acceptable levels. This is the situation at Plant C; the fuel as delivered is simply too wet to burn. Originally Plant C used an oil-fired burner to generate steam. As fossil fuel prices increased, the oil burner was replaced with a fuel cell equipped with a rotary fuel dryer. The new system has proven satisfactory; the management at Plant C is quite happy with their choice.

An analogous situation existed at Plant B. During the winter months (and periods of heavy rain) the stockpile fuel moisture content increased to the point that it became difficult to maintain fire in the boiler, necessitating overfiring with oil. The choice was made to retrofit the boilers with a rotary dryer, and resulted in decreased oil consumption during the winter and eliminated it entirely in the summer. In addition to minimized oil consumption, actual wood waste fuel savings were realized during the summer months.
Occasionally there exists the situation in which the wood waste moisture content is low enough to sustain combustion and produce steam, yet high enough to reduce the desired steaming rate of the boiler. As with the previous cases, the boiler may be overfired with oil, or, as in the case of Plant A, the difference between required and produced steam must be displaced using auxiliary boilers that are fired with gas or oil. In this event, oil and/or gas must replace an equivalent amount of wood fuel in order to compensate for the difference in steam load and steam production (by the wood waste-fired boiler), ergo it is reasonable to contrast the two alternative fuel sources with wood waste, in terms of fuel savings.

Performance Trends Suggest Seven Percent Fuel Savings Following Installation of Dryer

The performance trends presented in the previous section indicate a conservative 7.19 percent fuel savings resulting from the installation of a rotary dryer. The boiler operating parameters used to evaluate this savings fell in approximately the middle of the performance trend parameter ranges, and are as follow:

* Boiler steam demand - 100,000 pph (106 MBTU/hr)
* Combustion excess air - 100%
* Boiler heat loss - 5% of fuel higher heating value
* Boiler exhaust temperature (after last heating surface) - 400°F
* Fuel moisture content - 100% (dry basis); 50% (wet basis)
* Fuel higher heating value - 9,050 BTU/lbm dry wood

* Predicted fuel consumption, boiler alone - 18,019 lbm dry wood/hr

The seven percent fuel savings indicated by the performance trend analyses tends to be conservative in contrast to other reported values of fuel savings, yet falls within the fuel savings predicted for each plant evaluated in the Case Studies Section of this report, as seen in Table 6.

Table 6 - Predicted Boiler Efficiencies and Fuel Savings from Case Studies Analysis

<table>
<thead>
<tr>
<th>Plant</th>
<th>Boiler Efficiency (%)</th>
<th>Fuel Consumption lbm o.d. wood/hr</th>
<th>w/o dryer</th>
<th>w/dryer</th>
<th>% change w/o dryer</th>
<th>w/dryer</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>66.7</td>
<td>31,343</td>
<td>70.3</td>
<td>29,745</td>
<td>-5.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>47.0</td>
<td>14,651</td>
<td>50.9</td>
<td>13,467</td>
<td>-8.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>53.0</td>
<td>1,945</td>
<td>57.8</td>
<td>1,783</td>
<td>-8.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>7.56</td>
<td></td>
<td></td>
<td></td>
<td>-7.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The economic analysis that follows is a bit more on the conservative side, and rounds-off 7.19 percent fuel savings to 7.0 percent, and 18,019 pounds fuel per hour to 18,000. The predicted hourly fuel savings is then:

\[
\text{Fuel Savings} = 0.07 \times 18,000 \ \text{lbm dry wood/hr}
\]

or \[
\text{Fuel Savings} = 1,260 \ \text{lbm dry wood/hr}
\]
If one assumes a load factor of 0.92 (boiler in operation 92% of the time), the annual fuel savings may be calculated as:

Annual fuel savings =

\[(1,260 \text{ lb}_m \text{ dry wood/hr})(24 \text{ hr/day})(365 \text{ day/yr})(0.902 \text{ load factor})\]

or

Annual fuel savings = 10,154,592 \text{ lb}_m \text{ dry wood/year}

Assuming 2,160 pounds of dry material in one unit (Brown, 1973), the annual fuel savings in terms of units is equal to:

\[\text{Fuel savings, units} = \frac{10,154,592 \text{ lb}_m \text{ dry wood/yr}}{2160 \text{ lb}_m \text{ dry wood/unit}}\]

or

Annual fuel savings, units = 4,701.2 \text{ units/year}

Throughout the course of this study unit costs for fuel were encountered in a range from a low of $4.00/unit for a very high moisture content fuel in a low demand area, to a high of $70.00/unit in a high demand area (local competition by horticultural firms for bark mulch and landscaping bark). A value of $30.00/unit was suggested by a leading forest products manufacturer as a representative unit cost in the local forest products manufacturing sector. Using this representative value, the annual fuel savings in dollars may be calculated as:

\[\text{Fuel savings, dollars} = (4,701.2 \text{ units/year})(30.00 \text{$/unit})\]

Thus:

Annual fuel savings, hog fuel = $141,036/year

As they will be used in the ensuing economic analysis, it is appropriate at this time to determine the BTU and dollar equivalents of the fuel savings listed above, both for natural gas and No. 6 heating oil.
Wood-fired, gas-fired, and oil-fired burners each have different average values of combustion efficiency (Curtis, 1978). They are: (1) 61.2 percent (at 45 percent moisture content, wet basis) for wood-fired burners, (2) 77.8 percent for natural gas-fired burners, and (3) 82.5 percent for oil-fired burners. These differences in combustion efficiency must be taken into account when comparing each fuel, as seen below.

**Natural Gas**

Natural gas is commonly sold in units of therms (1 therm = 100,000 BTU). The therm equivalent to the fuel savings given above is calculated as:

\[
\text{Annual fuel savings, natural gas} = (10,154,529 \text{ lbm dry wood/yr})(9050/\text{lbm dry wood})(61.2\% \text{ efficiency/77.8\% efficiency}) \times (1 \text{ therm/100,000 BTU})
\]

Thus: **Annual fuel savings, natural gas = 722,908 therms/year**

At $0.490/therm (phone quotation - interruptible rate), this fuel savings corresponds to:

\[
\text{Annual fuel savings, therms} = (722,908 \text{ therms/yr})(0.490/\text{therm})
\]

Thus: **Annual fuel savings, natural gas = $354,225/yr**

**No. 6 Heating Oil**

No. 6 heating oil is sold on a per barrel basis, at a current price (May 1983) of $29.00/barrel. The heating value of No. 6
heating oil is given as 6.14 MBTU (MacCallum, et al., 1982). Thus the barrel equivalent of the wood fuel savings is calculated as:

\[
\text{Fuel savings, No. 6 heating oil} = (10,154,592 \text{ lbm dry wood/yr})(9050 \text{ BTU/lbm dry wood})(61.2\% \text{ efficiency}/82.5\% \text{ efficiency}) \times (1 \text{ barrel/6.14 MBTU})
\]

Thus:

\[
\text{Annual fuel savings, No. 6 heating oil} = 11,103 \text{ barrels/year}
\]

And:

\[
\text{Annual fuel savings, No. 6 heating oil} = $321,987/\text{year}
\]

**Capitalized Cost of Rotary Dryer Installation**

The capitalized cost includes the following:

* Foundation costs
* Construction costs
* Labor costs
* Drying equipment (rotary dryer, cyclones, fans, etc.)
* Electrical costs
* Control and instrumentation equipment costs
* Engineering and DEQ (State of Oregon Department of Environmental Quality) testing
* Fire suppression equipment costs
* Insulation costs

plus 15 percent contingency costs.

The capitalized cost of rotary dryer installation as a function of boiler capacity is presented in Figure 13. The curve representing new equipment and external engineering was developed using data presented by MacCallum, et al. (1982) for rotary dryer capitalized
Figure 13. Capital cost of rotary dryers as a function of boiler capacity; new dryer/external engineering and used dryer/in-house engineering options.
cost, and is normalized with respect to currency exchange and inflation (both curves are presented in May 1983 dollars). The curve representing used equipment and in-house engineering was adopted from a leading forest products manufacturer's capitalized cost estimates.

**Payout Calculation - Used Dryer/In-house Engineering**

The following payout calculations are for a 100,000 pph boiler. The capitalized cost of rotary dryer installation may be read from Figure 13 as approximately 1.1 million dollars. The payout calculations are summarized on the following page.
<table>
<thead>
<tr>
<th>Cash Flow Balance Sheet</th>
<th>Hog Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Investment</td>
<td>$1,100,000</td>
</tr>
<tr>
<td>Federal Tax Credits:</td>
<td></td>
</tr>
<tr>
<td>Investment (10%)</td>
<td>$110,000</td>
</tr>
<tr>
<td>Energy (10%)</td>
<td>110,000</td>
</tr>
<tr>
<td>State of Oregon Energy Tax Credits</td>
<td></td>
</tr>
<tr>
<td>(35% over five years, taken in annual increments of 10,10,5,5,5 %, and assuming 10% interest)</td>
<td>334,343</td>
</tr>
<tr>
<td></td>
<td>$554,343</td>
</tr>
<tr>
<td>Adjusted Capital Investment</td>
<td>$545,657</td>
</tr>
<tr>
<td>Annual Fuel Savings, hog fuel</td>
<td>$141,036</td>
</tr>
<tr>
<td>less operating costs</td>
<td>(20,520)</td>
</tr>
<tr>
<td>less depreciation (straight-line; 10 years)</td>
<td>(110,000)</td>
</tr>
<tr>
<td>Net Profit Before Taxes</td>
<td>$10,516</td>
</tr>
<tr>
<td>Income Tax (@ 50%)</td>
<td>5,258</td>
</tr>
<tr>
<td>Net Profit</td>
<td>5,258</td>
</tr>
<tr>
<td>Depreciation</td>
<td>110,000</td>
</tr>
<tr>
<td>Cash Flow</td>
<td>$115,250</td>
</tr>
</tbody>
</table>

Payback Period, cash flow basis = ($545,657/$115,250) = 4.73 years
Payback Period, income basis = ($545,657/$5,258) = 103.8 years
The previous cash flow assuming wood as the fuel source is contrasted to the following cash flows assuming the equivalent BTU savings of natural gas and No. 6 heating oil as the fuel sources and also assuming the same adjusted capital investment as for the hog fuel dryer.

<table>
<thead>
<tr>
<th>Cash Flow Balance Sheet</th>
<th>Natural Gas</th>
<th>No. 6 Heating Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted Capital Investment</td>
<td>$ 545,657</td>
<td>$ 545,657</td>
</tr>
<tr>
<td>Annual Fuel Savings</td>
<td>$ 354,225</td>
<td>$ 321,987</td>
</tr>
<tr>
<td>less operating costs</td>
<td>(20,520)</td>
<td>(20,520)</td>
</tr>
<tr>
<td>less depreciation</td>
<td>(110,000)</td>
<td>(110,000)</td>
</tr>
<tr>
<td>Net Profit Before Taxes</td>
<td>$ 223,705</td>
<td>$ 191,467</td>
</tr>
<tr>
<td>Income Tax (@ 50%)</td>
<td>(111,852)</td>
<td>(95,733)</td>
</tr>
<tr>
<td>Net Profit</td>
<td>$ 111,853</td>
<td>$ 95,734</td>
</tr>
<tr>
<td>Depreciation (straight-line; 10 years)</td>
<td>110,000</td>
<td>110,000</td>
</tr>
<tr>
<td>Cash Flow</td>
<td>$ 221,853</td>
<td>$ 205,734</td>
</tr>
<tr>
<td>Payback Period, cash flow basis</td>
<td>2.46 years</td>
<td>2.65 years</td>
</tr>
<tr>
<td>Payback Period, income basis</td>
<td>4.88 years</td>
<td>5.70 years</td>
</tr>
</tbody>
</table>

**Payout Calculations - New Dryer/External Engineering**

The following payout calculations are those for new equipment and external engineering and contracting. The capitalized cost may be read from Figure 13 as 1.9 million dollars. The ensuing calculations are identical to the previous calculations, and are summarized below.
### Cash Flow Balance Sheet

#### Hog Fuel

**Capital Investment**

- Federal Tax Credits:
  - Investment (10%) $190,000
  - Energy (10%) 190,000
- State of Oregon Energy Tax Credits (35% over 5 years) $575,890
- Adjusted Capital Investment $955,890

**Annual Fuel Savings, hog fuel**

- less operating costs (20,520)
- less depreciation (190,000)

**Net Profit Before Taxes** (69,484)

**Income Tax (@ 50%)**

**Net Profit** (69,484)

**Depreciation** 190,000

**Cash Flow** $120,516

**Payback Period, cash flow basis** 7.83 years

**Payback Period, income basis** Never
The cash flow assuming wood as the fuel source is contrasted to the cash flows assuming natural gas and No. 6 heating oil as the fuel sources in the following summary.

<table>
<thead>
<tr>
<th>Cash Flow Balance Sheet</th>
<th>Natural Gas</th>
<th>No. 6 Heating Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted Capital Investment</td>
<td>$ 944,110</td>
<td>$ 944,110</td>
</tr>
<tr>
<td>Annual Fuel Savings</td>
<td>354,225</td>
<td>321,987</td>
</tr>
<tr>
<td>less operating costs</td>
<td>(20,520)</td>
<td>(20,520)</td>
</tr>
<tr>
<td>less depreciation</td>
<td>(190,000)</td>
<td>(190,000)</td>
</tr>
<tr>
<td>Net Profit Before Taxes</td>
<td>$ 143,705</td>
<td>$ 111,467</td>
</tr>
<tr>
<td>Income Tax (@ 50%)</td>
<td>(71,852)</td>
<td>(55,733)</td>
</tr>
<tr>
<td>Net Profit</td>
<td>$ 71,853</td>
<td>$ 55,734</td>
</tr>
<tr>
<td>Depreciation</td>
<td>190,000</td>
<td>190,000</td>
</tr>
<tr>
<td>Cash Flow</td>
<td>$ 261,853</td>
<td>$ 245,734</td>
</tr>
<tr>
<td>Payback Period, cash flow basis</td>
<td>3.61 years</td>
<td>3.84 years</td>
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<tr>
<td>Payback Period, income basis</td>
<td>13.14 years</td>
<td>16.94 years</td>
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</table>

**Economic Analysis Indicates Cost Effectiveness of Rotary Dryer Installation**

In summary, the economic feasibility of the installation of a rotary dryer was evaluated assuming the following: a federal investment tax credit of 10%, a 10% federal energy tax credit, a State of Oregon energy tax credit of 35%, taken over five years in yearly increments of 10, 10, 5, 5, 5%, and an interest rate of 10%. The capital cost estimates for the retrofitting of a rotary dryer to an
existing boiler were obtained from forest products and dryer manufacturers, and are illustrated in Figure 13.

The payback periods were evaluated assuming a 100,000 pph boiler with a 7% fuel savings resulting from the installation of a rotary dryer, (using a boiler exhaust temperature of 400°F), corresponding to a fuel savings of 4,701 units per year. At a per-unit cost of $30.00, the annual hog fuel savings was calculated to be $141,036 per year. The corresponding BTU equivalent savings of natural gas and No. 6 heating oil, corrected for differences in combustion efficiency, were calculated as, respectively, $354,225 per year (722,908 therms/year @ $0.490/therm) and $321,987 per year (11,103 barrels/year @ $29.00/barrel); the preceding fuel costs are current to May 1983. The capitalized costs of rotary dryer retrofit were taken to be 1.1 million dollars for a used dryer, with all engineering and contracting done by plant personnel (staff costs are included in the capital cost estimates), and 1.9 million dollars for a new dryer, with all engineering done by external consulting or dryer manufacturing firms.

The respective payback periods are summarized in Table 7, which contrasts the cash flow and income bases payback periods of the BTU equivalent savings of each fuel source considered. The payback periods were evaluated assuming the same dryer installation capital investment.
TABLE 7 Summary of the Economic Evaluation of Rotary Dryer Installation

<table>
<thead>
<tr>
<th>Equipment Option</th>
<th>Equivalent BTU Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural</td>
</tr>
<tr>
<td>Used Dryer</td>
<td></td>
</tr>
<tr>
<td>Payback Period, cash flow basis (yrs)</td>
<td>4.73</td>
</tr>
<tr>
<td>Payback Period, income basis (yrs)</td>
<td>103.8</td>
</tr>
<tr>
<td>New Dryer</td>
<td></td>
</tr>
<tr>
<td>Payback Period, cash flow basis (yrs)</td>
<td>7.83</td>
</tr>
<tr>
<td>Payback Period, income basis (yrs)</td>
<td>Never</td>
</tr>
</tbody>
</table>

The payback periods summarized in Table 7 suggest that the retro-fitting of a rotary dryer to an existing boiler is cost effective, especially when considering the equivalent fossil fuel savings. It is worthy to note again that the preceding economic analysis were based on a 7% fuel savings for a boiler operating at the relatively moderate conditions of approximately 100% excess air and a 400 F boiler exhaust temperature. The 7% fuel savings at these conditions was suggested by both the Case Studies and the Performance Trends. As noted in both sections, a greater fuel savings would be realized at conditions more favorable for drying which may not be true for boiler operation. For example, the Performance Trends predict a fuel savings of approximate-
ly 11% at a boiler exhaust temperature of 600 F. (Note that the total fuel consumption increases with increasing boiler exhaust temperature, yet the percent decrease in fuel consumption, relative to the boiler alone, also increases.) If the calculations presented in this section were repeated using 11% fuel savings, the economics of rotary dryer retrofit would be even more attractive.

In conclusion, this study contends that the installation of a rotary can be economically feasible.
VI. CONCLUSIONS

The focal point of this study was the evaluation of the feasibility of the use of a rotary dryer to dry wood waste fuel using boiler exhaust gases as the drying medium. The accomplishments of this study are summarized below.

(1) The development of a boiler/dryer simulation model that accurately predicts the behavior of the system using site-specific operating and fuel conditions.

(2) The evaluation of boiler/dryer systems currently in operation in the forest products industry. The data obtained from these studies were used to validate the accuracy of the simulation model and to establish typical boiler/dryer operating conditions in the field.

(3) The subsequent economic evaluation of the retrofitting of a rotary dryer to an existing boiler.

Programs SIM1 and SIM2 Reliably Model the Boiler/Dryer System

Two boiler/dryer simulation models were developed in this study, differing only in the treatment of the energy balances around the dryer. Program SIM1 fixes the dryer exhaust temperature and the dryer exit fuel temperature, and is useful in modeling those systems that use a feedback control system to maintain the dryer exhaust temperature at a specified value by regulating the fuel flow rate.
through the dryer, diverting part of the fuel directly to the boiler. Program SIM2 fixes the dryer thermodynamic, or heating efficiency, and the sensible heat requirement of the fuel and the water remaining in the fuel at the dryer exit, each as percentages of the total available energy in the boiler exhaust gas. Program SIM2 is useful as a general model of the boiler/dryer system. Both models use site-specific boiler/dryer operating parameters and conditions, and yield values of the associated flows and properties that are comparable to those actually measured, as substantiated by experimental data.

The simulation models were used to evaluate the general boiler/dryer system's sensitivity to variation in the associated operating conditions. These sensitivity studies, found in the Performance Trends Section of this report, predict a fuel savings of approximately 7% for the moderate operating conditions of 100% excess air, 100% fuel moisture content (dry basis) and a boiler exhaust temperature of 400°F. The performance trends also predict that greater fuel savings may be realized at higher exhaust temperatures. For example, a decrease a fuel consumption of approximately 11% may be realized at a stack temperature of 600°F. It is important to note, however, that the total fuel consumption increases with increasing boiler exhaust temperature, and the percent decrease in fuel consumption, relative to the boiler alone, also increases with increasing boiler exhaust temperature.
Case Studies Show a Wide Range of Boiler/Dryer Operating Conditions

Three boiler/dryer systems currently in operation in the forest products industry were evaluated in this study. The data obtained from these field studies were used to validate the reliability of the two simulation programs developed, as previously mentioned. The data for each system is presented in Tables 2-5 in the Case Studies Section of this report.

Wide ranges of boiler size and boiler/dryer operating conditions were observed in the field. Significant drying was noted at each facility for moderate stack temperatures (340-500 °F; two plants exhibited boiler exhaust temperatures under 400 °F), further suggesting the potential for drying under similarly moderate conditions. A fuel savings of approximately 7% (the average of all three systems considered) was predicted using the simulation models; percent changes in boiler efficiency and fuel consumption resulting from the use of a rotary dryer are summarized for each system in Table 6.

Of further note, the dryer exhaust humidities observed in the field tended to be significantly lower than the saturated conditions at the same dryer exhaust temperature. This suggests the possibility of maintaining the dryer exhaust temperature a lower values than were observed, yet greater than the dew point temperature, in effect increasing the thermodynamic, or heating efficiency of the dryer.
Economic Analysis Suggests the Feasibility of Dryer Installation

The economic feasibility of the retrofitting of a rotary dryer to an existing hog fuel boiler was evaluated based on hog fuel savings and the equivalent BTU savings of natural gas and No. 6 heating oil. Capital cost estimates of dryer installation were established for two options: (1) the purchase of a used dryer, with all engineering and contracting done by plant personnel (staff cost was considered in the capital cost), and (2) the purchase of a new dryer, with all engineering and contracting done by external consulting or dryer manufacturing firms.

Using current (May 1983) market prices for hog fuel, natural gas and No. 6 heating oil, and assuming a 7% fuel savings resulting from dryer installation for a 100,000 pph boiler, cash flow and income bases payback periods were calculated for the two options mentioned above. The payback calculations also consider current federal and state (Oregon) tax policies. The payback periods are summarized in Table 7. Briefly, the cash flow basis payback period based on hog fuel savings ranged from 4.7 years for a used dryer to 7.8 years for a new dryer. The cash flow payback periods for equivalent BTU savings of natural gas and No. 6 heating oil ranged from, respectively, 2.5 to 3.6 years for natural gas and from 2.7 to 3.8 years for heating oil.

Once again it is of value to note that the economic feasibility of dryer installation was based on a fuel savings of 7%. As stated previously, the 7% figure was predicted for moderate boiler operating
conditions, i.e., a boiler exhaust temperature of 400 F. The fuel savings realized at higher stack temperatures has been shown to be as high as 11% for a stack temperature of 600 F. Calculations based on 11% fuel savings would yield payback periods even more favorable than those presented in this study. As a caution to the reader, it must be noted that each state has different tax policies. Should the reader wish to carry out cash flow calculations similar to those presented in this study, it is absolutely necessary to familiarize oneself with the tax policies of the state in question.

The overall conclusion of this study is that the retrofitting of a rotary dryer to an existing boiler can be cost effective in terms of fuel savings, both for hog fuel and fossil fuels, and presents an attractive option to the forest products industry.
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APPENDICES
# APPENDIX A

## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>Air leakage flow rate (lb-moles air/pound dry wood)</td>
</tr>
<tr>
<td>AIRFED</td>
<td>Combustion air flow rate (lb-moles air/pound dry wood entering boiler)</td>
</tr>
<tr>
<td>ALF</td>
<td>Air leakage factor, expressed as decimal percent of the dry gas that enters the dryer in the boiler exhaust</td>
</tr>
<tr>
<td>AVAILEN</td>
<td>Total available energy in the boiler exhaust, relative to the ambient temperature (BTU/hour)</td>
</tr>
<tr>
<td>AVDRY</td>
<td>The energy used to dry the fuel (BTU/hour)</td>
</tr>
<tr>
<td>EA</td>
<td>Combustion excess air (decimal percent)</td>
</tr>
<tr>
<td>EINB</td>
<td>Total energy contained within the input streams to the boiler, relative to the elements at 77°F (BTU/hour)</td>
</tr>
<tr>
<td>EIND</td>
<td>Total energy contained within the input streams of the dryer, relative to the elements at 77°F (BTU/hour)</td>
</tr>
<tr>
<td>EOUTB</td>
<td>Total energy contained in the output streams of the boiler, relative to the elements at 77°F (BTU/hour)</td>
</tr>
<tr>
<td>EOUTD</td>
<td>Total energy contained within the output streams of the dryer, relative to the elements at 77°F (BTU/hour)</td>
</tr>
<tr>
<td>FFRD1</td>
<td>Fuel flow rate, bone-dry, stream 1 (dryer feed) (lbs/hour)</td>
</tr>
</tbody>
</table>
FFRD2 Fuel flow rate, bone-dry, stream 2 (dryer bypass) (lbs/hour)

FFRD3 Fuel flow rate, bone-dry, stream 3 (dryer exit); note that FFRD3 = FFRD1 (lbs/hour)

FFRDT Total fuel flow rate to boiler (bone-dry lbs/hour)

FHR Ambient humidity ratio (lbs water/lb dry air)

FMCD1 Fuel moisture content (dry basis), stream 1 (dryer inlet) (decimal percent)

FMCD2 Fuel moisture content (dry basis), stream 2 (dryer bypass) (decimal percent)

FMCD3 Fuel moisture content (dry basis), stream 3 (dryer exit) (decimal percent)

FMCDT Fuel moisture content (dry basis) to boiler (weighted average of FMCD2 and FMCD3) (decimal percent)

FR Feed ratio, defined as the ratio of the dryer feed flow rate to the dryer bypass flow rate; FR = FFRD3/FFRD2

HHV Fuel higher heating value (BTU/pound dry wood)

HTLF Boiler heat loss factor, expressed as a percentage of the fuel higher heating value

HTLOSSB Boiler heat loss (BTU/hour)

H2OFED Flow rate of water in combustion air (lbs-moles water/lb dry wood fed to boiler)

N2FED Flow rate of nitrogen in combustion air (lb-moles nitrogen/lb dry wood fed to boiler)
O2FED  Flow rate of oxygen in combustion air (lb-moles oxygen/lb dry wood fed to boiler)
O2REQ  Oxygen consumed in combustion (lb-moles oxygen/lb dry wood fed to boiler)
PCTCL  Percent carbon loss, expressed as a percentage of the fuel ultimate analysis carbon
PCT1   Percent of the total available energy in the boiler exhaust that is used for drying
PCT2   Percent of the total available energy in the boiler exhaust that is used to heat the fuel, and the water contained in the fuel at the dryer exit, from the entrance to the exit temperature of the dryer
TAM    Ambient temperature (°F)
TBE    Boiler exhaust temperature (°F)
TDE    Dryer exhaust temperature (°F)
TDI    Dryer inlet (gas) temperature (°F)
TF1    Dryer inlet fuel temperature (°F)
TF2    Bypass stream fuel temperature (°F)
TF3    Dryer exit fuel temperature (°F)
TREF   Reference temperature (77 °F)
QHTL   Energy lost to air leakage and atmosphere in dryer exhaust (BTU/hour)
QSENS  Energy taken up in sensible heat of fuel and water contained in fuel at dryer exit (BTU/hour)
QSTEAM Boiler steam demand (BTU/hour)
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULTC</td>
<td>Ultimate analysis carbon (lbs carbon/lb dry wood)</td>
</tr>
<tr>
<td>ULTH</td>
<td>Ultimate analysis hydrogen (lbs hydrogen/lb dry wood)</td>
</tr>
<tr>
<td>ULTO</td>
<td>Ultimate analysis oxygen (lbs oxygen/lb dry wood)</td>
</tr>
<tr>
<td>X</td>
<td>&quot;Quasi&quot;-Ultimate analysis carbon (lb-moles carbon/lb dry wood)</td>
</tr>
<tr>
<td>Y</td>
<td>&quot;Quasi&quot;-Ultimate analysis hydrogen (lb-moles hydrogen/lb dry wood)</td>
</tr>
<tr>
<td>Z</td>
<td>&quot;Quasi&quot;-Ultimate analysis oxygen (lb-moles oxygen/lb dry wood)</td>
</tr>
</tbody>
</table>
APPENDIX B

"WOOD AND BARK AS FUEL"

by

Stanley E. Corder

Stan Corder's "Wood and Bark as Fuel" is an excellent treatise on the use of wood residue as a boiler fuel in the forest products industry. It covers topics ranging from wood and bark characteristics to the various types of boilers currently in use in the industry. Ultimate analysis and higher heating value data for a variety of wood species is presented along with some of the aspects of boiler operating conditions on boiler performance. It is currently (May 1983) out of print, and is presented in this report as a useful reference to the reader.
Wood and Bark as Fuel

Stanley E. Corder
Mechanical Engineer

Research Bulletin 14
August 1973

Forest Research Laboratory
School of Forestry
OREGON STATE UNIVERSITY
Corvallis, Oregon 97331
A characteristic of an industrial society is its enormous consumption of energy. Until recently, the "energy barrel" available in the United States seemed to have no bottom, and most people were little concerned with energy supply. But now, our news media constantly remind us of the problem. We are told to expect shortages of fuel and electricity; curtailments for some users have occurred already, and rising costs for energy seem assured.

Wood—a fuel that once supplied most of this country's energy, but now is of commercial importance mainly at or near forest industry plants—is the subject of this report. It includes some information on historical trends in the use of wood and bark fuels, summarizes fuel properties, and discusses technical and economic considerations in using such fuels. Sometimes, wood and bark residues are the lowest cost fuel for providing heat and power for a plant—and their use as fuel can solve the problem of disposal.

Our laboratory published a report in 1963 by George H. Atherton, "Burning West Coast Hemlock Hogged Fuel in Boiler Furnaces." This report is now out of print, but some information from it is included here and it was most helpful in preparing the present report.
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   Historical Uses ............................................................................................. 1
       Domestic .................................................................................................. 2
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The usual response to the question, “What single use, world wide, consumes the greatest quantity of wood?” is “Construction.” Not so—the largest single use of wood is still the oldest one—fuel!

In 1969, 43 percent of the wood cut was for fuel (35), and 34 percent of the world’s roundwood production was for sawlogs, veneer logs, and railroad ties. Much variation of roundwood use for fuel occurred among various countries. The more industrialized countries used less and the less industrialized countries used more of their roundwood for fuel. In 1969, Latin American countries used 83 percent; Africa, 89 percent; Mainland China, 77 percent; Western Europe, 20 percent; and the United States only 6 percent.

In 1952, the latest year for which we have complete national statistics for roundwood and residues, the Forest Service reports that 25 percent of the timber output of the highly industrialized United States was used for fuel (36). The amount of wood used for fuel was greater than that for lumber.

The quantity of wood burned for fuel in this country has been decreasing continually since the late 1800’s. Sixteen percent of the roundwood cut in 1952 was for fuelwood (36) but, in 1969, it was only 6 percent (35). Reasons for the decrease are easy to find. Increasing value for other uses of roundwood and expanding uses of wood residues for pulp and board manufacture, as well as the convenience and low cost (at least until recently) of other fuels, have been major reasons.

**Historical Production**

Less than a century ago, the United States was well into the Industrial Revolution, and wood was the major source of energy for industrial expansion. In 1850, about 90 percent of the energy was supplied by fuelwood (Figure 1); by 1875, two-thirds of the energy still came from fuelwood. In the 1880’s, coal supplanted wood as the major supplier of energy.

Fuelwood consumption reached a peak of about 140 million cords in 1875 and has declined steadily to about 40 million cords in 1970 (Figure 2). Fuelwood now accounts for about 1 percent of the national use of energy (Figure 1).

**Historical Uses**

**Domestic.** More than 90 percent of the 100 million cords of firewood consumed in 1850 was used domestically for heating and cooking, and about 75 percent of the total was burned in open fireplaces. An American family in the 1850’s used about 18 cords of wood per year for home heating (32).

George B. Abdill² noted:

> Residential needs of people in Western Oregon from pioneer days up to fairly recent times must have consumed mountains of fuel wood. It staggers the imagination to think how many cords of wood went into the cookstoves, furnaces and fireplaces over the years. Train load after train load was hauled into Portland every year; . . . . Curbside parking strips in every residential area were stacked with cordwood and the hum of buzz saws filled the air as cutting crews moved through the neighborhoods, cutting 4-foot stacks of cord and mill slab wood into stovewood or furnace lengths.

¹This includes only roundwood used for fuel. If residues were considered, the use would be greater.

As recently as 1940, 20 percent of occupied dwellings used wood fuel for central heating or cooking, but these uses dropped to about 10 percent by 1950 (32, 36). A further decrease in domestic use of wood fuel has occurred since 1950. Stanford Research Institute (33) predicted a decrease in consumption for all except industrial uses of about 50 percent between 1952 and 1975. Similar decreases were predicted by the U.S. Forest Service (36).

One domestic use of wood fuel has not declined—for fireplaces (Figure 3). Stanford Research Institute reported (33) 14 million cords of wood used in fireplaces in 1950 and projected use of 17 million cords in 1975. Indeed, what 100 years ago was an enormous use of fireplace fuel by necessity has become a small, steady, luxury use today.

**Industrial and Transportation Uses.** The first railroads and steamboats in this country were fired with wood fuel. Wood was the principal fuel for railroads nationally until about 1870, when about 6 million cords were burned annually (32). Wood continued to be the principal fuel for Oregon's locomotives until the early 1900’s, as illustrated in Figures 4 and 5.

George Abdill told me that wood contractors received about $2.75 per cord for 2-foot lengths of wood delivered to the railroad right-of-way, and that Oregon and California railroad engines burned as much as 18 cords of wood on the 144-mile trip from Roseburg to Ashland, Oregon.

Wood fuel was commonly the energy source for early day lumbering as well. Figures 6 and 7 show Pacific Northwest operations where steam produced from wood fuel provided power to yard and saw logs into lumber.

Although coal and oil replaced wood for rail and water transport in this country at about the turn of the century, wood fuel has continued to supply heat and power for many industrial, commercial, institutional, and utility operations. Most industrial use of wood fuel is now at forest industry plants, where it supplies heat and power for their own operations.

In Oregon, 32 forest industry operations generated electricity with wood and bark residues in 1949 and 21 in 1968, according to maps issued by the Federal Power Commission.
Installed generating capacity of the plants was about 90 megawatts. Many more forest industry companies were using wood and bark residues to produce steam, mainly for drying lumber and veneer.

Two of the largest users of wood and bark fuel in Oregon are at Eugene. The Eugene Water and Electric Board uses about 125,000 units3 of wood and bark fuel a year to generate electricity and to produce steam for distribution to the Eugene business area. The University of Oregon uses about 75,000 units of fuel annually to supply heat and power to its campus (Figure 8). Wood and bark residues from forest industry operations still provide the cheapest source of heat and power at many installations.

WOOD-BARK RESIDUES

Most logs harvested in this country go into the manufacture of lumber, plywood, or pulp. Less than half the volume of a log ends up as lumber or plywood; the rest is such items as bark, slabs, edgings, sawdust, shavings, veneer and plywood trim, cores, and sander dust. Although

3A unit is a bulk volume of 200 cubic feet.
more of this residue, in recent years, has been used as a raw material for pulp and composition board manufacture, large amounts still are available for other uses, such as fuel.

In Oregon, most of the raw material for pulp plants is obtained from wood residues of sawmills and plywood plants, but, in the eastern part of the country, much pulp is made from roundwood. Before processing, the bark normally is removed from the roundwood and remains as a residue.

A variety of uses can be made of these wood and bark residues. If a plant does not have sufficient uses and markets for residues, however, then it has a disposal problem. Use as fuel could be a solution.

Characteristics

One term that best describes residues is variable. Residues range in size from fine sander dust up to large slabs. Moisture ranges from a small amount in sander dust and plywood trim up to where it exceeds the amount of dry material in wood and bark for some species. And bark looks different from wood (Figure 9).

To reduce many kinds of residue to a particle size that can be more conveniently handled, it frequently is put through a machine called a "hog." The name probably originated because...
of the voracious capacity of the equipment to consume residue. The processed residue commonly is called hogged fuel or hog fuel, a term that is not specific; it can include wood or bark material, in any proportion, that has been reduced to a particular size. Sometimes sawdust and shavings are added to the hogged material, and the mixture still is called hogged fuel. After bark (Figure 9) is hogged, it is called hogged bark or, again, hogged fuel (Figure 10).

Marketing Measure

In the Pacific Northwest, hogged fuel, as well as other types of residue, usually is sold by bulk volume, or unit. A unit is the amount of material contained in a volume of 200 cubic feet.

A unit of hogged fuel frequently contains about a ton of dry substance (excluding the weight of moisture). The dry weight might range from 1,200 pounds for Douglas fir shavings to 1,900 pounds for sawdust and up to 2,600 pounds for hogged Douglas fir bark (8).

The amount of moisture in hogged fuel varies with the species, time of year, type of hogged fuel, and whether the logs were handled on a dry deck or in a pond. Douglas fir bark from ponded logs frequently contains an amount of moisture about equal to the dry weight. Thus, the weight of a unit of hogged Douglas fir bark from such logs might have a wet weight of about 5,200 pounds.

Amounts

To estimate the amount of different types of residue produced from lumber and plywood manufacture, average conversion factors are given in Tables 1 and 2 (8). I emphasize that these values are intended only as averages for Oregon mills, and much variation occurs between mills and within mills depending on such factors as size of log, quality of log, species, equipment, and kind and size of product, as well as quality control within the mill. To assess the residue for a particular mill, that plant should study its own conditions.

About 4 million dry tons of residues from Oregon sawmills and plywood plants, or 27 percent of the total residues produced, were used for fuel in 1967 (8). The \( 70 \times 10^{12} \) Btu of heat contained in that amount of residues used for fuel was about equal to the heat from the

| Table 1. Average Conversion Factors for Estimating Residues from the Manufacture of a Thousand Board Feet of Lumber in Oregon (8). |
|---|---|---|---|
| Item | Solid | Proportion | Dry weight |
|     | volume | by volume | Western | Eastern |
|     | Cu ft  | Percent  | Oregon | Oregon |
| Coarse wood residue \(^2\) | 43     | 26.0     | 0.580  | 0.516  |
| Sawdust       | 22     | 13.4     | 0.297  | 0.264  |
| Planer shavings | 16     | 9.7      | 0.216  | 0.192  |
| Total wood residue | 81     | 49.1     | 1.093  | 0.972  |
| Bark residue  | 19     | 11.5     | 0.285  | 0.228  |
| Lumber       | 65     | 39.4     | 0.878  | 0.780  |
| Total log    | 165    | 100.0    | 2.256  | 1.980  |

\(^1\)Equivalent undried solid volume.

\(^2\)Includes slabs, edgings, and lumber trim.
Table 2. Average Conversion Factors for Estimating Residues Developed from the Manufacture of a Thousand Square Feet of Equivalent 3/8-Inch Plywood (Rough Basis) in Oregon (8).

<table>
<thead>
<tr>
<th>Item</th>
<th>Solid volume(^1)</th>
<th>Proportion by volume</th>
<th>Dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu ft</td>
<td>Percent</td>
<td>Tons</td>
</tr>
<tr>
<td>Log trim</td>
<td>5.4</td>
<td>4.4</td>
<td>0.046</td>
</tr>
<tr>
<td>Cores</td>
<td>3.7</td>
<td>4.8</td>
<td>0.050</td>
</tr>
<tr>
<td>Undried veneer(^2)</td>
<td>18.5</td>
<td>24.1</td>
<td>0.250</td>
</tr>
<tr>
<td>Dried veneer(^3)</td>
<td>6.5</td>
<td>8.5</td>
<td>0.088</td>
</tr>
<tr>
<td>Sander dust</td>
<td>1.6</td>
<td>2.1</td>
<td>0.021</td>
</tr>
<tr>
<td>Total wood residue</td>
<td>33.7</td>
<td>43.9</td>
<td>0.455</td>
</tr>
<tr>
<td>Bark residue</td>
<td>8.8</td>
<td>11.5</td>
<td>0.132</td>
</tr>
<tr>
<td>Plywood</td>
<td>34.3</td>
<td>44.6</td>
<td>0.463</td>
</tr>
<tr>
<td>Total log</td>
<td>76.8</td>
<td>100.0</td>
<td>1.050</td>
</tr>
</tbody>
</table>

\(^1\) Volumes are based on equivalent undried solid volume.
\(^2\) Undried veneer residue includes veneer clippings, roundup, and spur trim.
\(^3\) Dried veneer residue includes dry veneer loss and panel trim.

Total sales in 1967 of the Northwest Natural Gas Company—which supplies most of the natural gas to western Oregon, as well as some areas along the Columbia River in Washington. Incidentally, while 4 million dry tons of wood and bark were used for fuel in Oregon in 1967, India burned about 100 million tons of cow dung for cooking and heat (38). Indeed, not everyone is cooking with gas!

FUEL PROPERTIES

Ultimate Analysis

Different species of wood show remarkable uniformity in their elemental composition (27), which also is not greatly different for wood and bark (2, 7, 20, 24). Typical, moisture-free, elemental composition of Douglas fir and western hemlock bark is shown in Table 3. The samples were hogged bark from a sawmill (7), so they also contained some wood—a normal component of hogged bark fuel. Ultimate analysis of 14 different species of eastern Canadian barks (24) gave compositions similar to those listed in Table 3.

Bark and wood fuels contain negligible sulfur, and do not, therefore, cause air pollution from sulfur compounds. Most coals and some heavy oils have sufficient sulfur to cause some problems.

Ash is the noncombustible part of fuel that often becomes entrained in the combustion gases and usually is removed in part by some separating device. Wood has a low ash content, generally less than 1 percent of dry weight (2, 15, 25). The ash content of bark is usually greater than that of wood. Handling and harvesting of logs frequently causes dirt and sand to cling to the bark, which adds to the noncombustible content. Table 4 gives reported ash contents for some western species. Chang and Mitchell (5) reported ash content on a dry-weight basis for nine species of softwood barks, which ranged from 0.6 for sugar pine up
Table 3. Typical Ultimate Analysis of Two Bark Fuels on a Dry-Weight Basis (7).

<table>
<thead>
<tr>
<th>Component</th>
<th>Douglas fir bark</th>
<th>Western hemlock bark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td>Percent</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.2</td>
<td>5.8</td>
</tr>
<tr>
<td>Carbon</td>
<td>53.0</td>
<td>51.2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>39.3</td>
<td>39.2</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Ash</td>
<td>1.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

to 2.5 percent for Engelmann spruce. Fifteen species of hardwood barks had ash contents ranging from 1.5 for paper birch up to 10.7 percent for white oak. Millikin (24) reported ash contents of several coniferous eastern Canadian barks ranging from 2.0 percent for jack pine up to 4.2 percent for tamarack.

Proximate Analysis

The proximate analysis of a solid fuel is a standard test for determining the relative amount of volatile material it contains. Results usually are reported as a percentage of dry weight for volatile matter, fixed carbon, and ash. Volatile matter for Douglas fir wood generally has been reported (2, 15, 25) at about 85 percent and fixed carbon at about 15 percent. Most other western species of wood were similar in composition (25).

Barks generally have less volatile material and therefore a higher percentage of fixed carbon than does wood. Mingie and Boubel (25) indicated Douglas fir bark contained about 72

Table 4. Reported Ash Contents on a Dry-Weight Basis of Some Western Species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Reference</th>
<th>Ash content, dry basis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wood</td>
</tr>
<tr>
<td></td>
<td>Percent</td>
<td>Percent</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(25)</td>
<td>0.1</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(15)</td>
<td>0.3</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(7)</td>
<td>---</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(2)</td>
<td>0.8</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(25)</td>
<td>0.2</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(7)</td>
<td>---</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(2)</td>
<td>2.1</td>
</tr>
<tr>
<td>White fir</td>
<td>(25)</td>
<td>0.5</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td>(25)</td>
<td>0.2</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>(5)</td>
<td>---</td>
</tr>
<tr>
<td>Sugar pine</td>
<td>(5)</td>
<td>---</td>
</tr>
<tr>
<td>Red alder</td>
<td>(5)</td>
<td>---</td>
</tr>
<tr>
<td>Red alder</td>
<td>(25)</td>
<td>---</td>
</tr>
<tr>
<td>Engelmann spruce</td>
<td>(5)</td>
<td>---</td>
</tr>
<tr>
<td>Western larch</td>
<td>(5)</td>
<td>---</td>
</tr>
</tbody>
</table>
percent volatiles and about 26 percent fixed carbon. They concluded that bark consistently
has about 10 percent less volatile matter than does wood. A similar conclusion was made by
Koch and Mullen (20) for southern pine. Millikin (24) reported volatile matter from bark of
seven coniferous and five hardwood species from eastern Canada ranged between about 70 and
80 percent.

Heating Value
One of the most important properties of a fuel is its heating value. The heating value
usually is obtained by burning a known quantity of fuel and measuring the heat released.
Because the water vapor from the products of combustion is condensed by the laboratory
procedure, the higher heating value usually is reported. When fuel actually is utilized, the water
vapor normally is not condensed, so the heat of condensation is not available. This loss, as well
as others, is taken into consideration when combustion efficiencies are calculated.

Not much difference in the heating value of moisture and resin-free wood of different
species has been found. It is about 8,300 Btu per pound. Resin has a value of about 16,900
Btu per pound (2), so resinous woods have heating values higher than those of nonresinous
woods. A summary of published heating values for wood and bark of some western species is
given in Table 5. Bark, in general, has higher values than does wood. A higher proportion of
resin-like compounds in barks probably accounts for the difference. Chang and Mitchell (5)
indicated that the heating value of hardwood barks was lower than that of softwood barks. All
softwood barks evaluated (eight species) had values greater than 8,500 Btu per dry pound, but
nine of the twelve hardwood barks had lower values.

Because wood fuel often is marketed by volume rather than weight, the heating value of
some western woods is shown by volume in Table 6. The volumetric heating values are
compared to that of Douglas fir. I would like to emphasize that heating values given in Table 6
are based on the heat contained in dry wood and do not take into account different moisture
contents that might occur in the different kinds of wood.

Moisture
An important characteristic of a fuel—especially wood and bark—is the amount of
moisture or water included with the dry substance. Moisture has a negative heating value,
because heat is required to evaporate it, and the heat in the evaporated moisture is lost up the
stake.

The amount of moisture in a material can be expressed in several ways. In the forest
products field, moisture content is given usually in terms of the weight of water in a material
divided by the weight of dry substance, and then this proportion is expressed as a percentage.
A material with equal weights of water and dry substance would have a moisture content of
1/1 = 1.0 or 100 percent, reported on the dry basis.

Another way of reporting moisture content—the one more common in the field of fuels
and combustion—is to express moisture as the weight of water in a material divided by the
total wet weight of the material, with this ratio then expressed as a percentage. A material with
equal weights of water and dry substance would have a moisture content of 1/2 = 0.5 or 50
percent, reported on the wet basis.

If the moisture content on either the wet or the dry basis is known, it can be converted to
the other by the following:

\[
M.C. (\text{wet}) = \frac{100 \times M.C. (\text{dry})}{100 + M.C. (\text{dry})}
\]

\[
M.C. (\text{dry}) = \frac{100 \times M.C. (\text{wet})}{100 - M.C. (\text{wet})}
\]
where M.C. = moisture content in percent, either wet or dry basis, as designated.

The relations of moisture contents on wet and dry bases are shown for the normal ranges of wood and bark fuels in Figure 11.

In this paper, I will express moisture content on the dry basis for two reasons. First, it is the expression most familiar to persons in the forest products industry. Second, it gives a more understandable concept of the relative amount of water compared to the dry weight of wood, which is directly related to heat supplied. For example, if we had 1 pound of dry wood at a moisture content of 50 percent, wet basis, and then added enough water to have 60 percent moisture on the wet basis, the moisture increase on the wet basis is from 50 to 60 percent—that is, 10 percentage points—an apparently small increase. The actual water

<table>
<thead>
<tr>
<th>Species</th>
<th>Reference</th>
<th>Higher heating value, per dry pound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wood: Btu</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(7)</td>
<td>...</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(9)</td>
<td>9,200</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(15)</td>
<td>8,860</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(41)</td>
<td>8,800</td>
</tr>
<tr>
<td>Douglas fir</td>
<td>(2)</td>
<td>8,910</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(7)</td>
<td>...</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(9)</td>
<td>8,500</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(41)</td>
<td>8,000</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>(2)</td>
<td>8,620</td>
</tr>
<tr>
<td>True firs</td>
<td>(9)</td>
<td>8,500</td>
</tr>
<tr>
<td>(White fir)</td>
<td>(41)</td>
<td>8,000</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td>(9)</td>
<td>9,100</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td>(41)</td>
<td>9,140</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>(9)</td>
<td>8,600</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>(5)</td>
<td>...</td>
</tr>
<tr>
<td>Sitka spruce</td>
<td>(9)</td>
<td>8,100</td>
</tr>
<tr>
<td>Engelmann spruce</td>
<td>(5)</td>
<td>...</td>
</tr>
<tr>
<td>Western larch</td>
<td>(5)</td>
<td>...</td>
</tr>
<tr>
<td>Western redcedar</td>
<td>(9)</td>
<td>9,700</td>
</tr>
<tr>
<td>Western redcedar</td>
<td>(41)</td>
<td>9,700</td>
</tr>
<tr>
<td>Redwood</td>
<td>(2)</td>
<td>9,210</td>
</tr>
<tr>
<td>Red alder</td>
<td>(9)</td>
<td>8,000</td>
</tr>
<tr>
<td>Red alder</td>
<td>(41)</td>
<td>8,000</td>
</tr>
<tr>
<td>Red alder</td>
<td>(5)</td>
<td>...</td>
</tr>
<tr>
<td>Oregon ash</td>
<td>(41)</td>
<td>8,200</td>
</tr>
<tr>
<td>Bigleaf maple</td>
<td>(41)</td>
<td>8,410</td>
</tr>
<tr>
<td>Bigleaf maple</td>
<td>(9)</td>
<td>8,400</td>
</tr>
<tr>
<td>Black cottonwood</td>
<td>(9)</td>
<td>8,800</td>
</tr>
<tr>
<td>Oregon white oak</td>
<td>(41)</td>
<td>8,110</td>
</tr>
</tbody>
</table>

1Hogged bark as obtained from a mechanical debarker had some wood included.
2Sawdust.
Table 6. A Comparison of the Densities and Heating Values on a Volume Basis of Some West Coast Species of Wood.

<table>
<thead>
<tr>
<th>Kind of wood</th>
<th>Density dry</th>
<th>Higher heating value, dry</th>
<th>Heating value reference</th>
<th>Higher heating value</th>
<th>Relative heating value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas fir</td>
<td>28</td>
<td>8,900</td>
<td>(2)</td>
<td>249,000</td>
<td>1.00</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>24</td>
<td>8,500</td>
<td>(9)</td>
<td>204,000</td>
<td>0.82</td>
</tr>
<tr>
<td>Ponderosa pine</td>
<td>24</td>
<td>9,100</td>
<td>(9)</td>
<td>218,000</td>
<td>0.88</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>24</td>
<td>8,600</td>
<td>(9)</td>
<td>206,000</td>
<td>0.85</td>
</tr>
<tr>
<td>Sitka spruce</td>
<td>23</td>
<td>8,100</td>
<td>(9)</td>
<td>186,000</td>
<td>0.75</td>
</tr>
<tr>
<td>Western redcedar</td>
<td>19</td>
<td>9,700</td>
<td>(9)</td>
<td>184,000</td>
<td>0.74</td>
</tr>
<tr>
<td>Redwood</td>
<td>24</td>
<td>9,210</td>
<td>(2)</td>
<td>221,000</td>
<td>0.89</td>
</tr>
<tr>
<td>Red alder</td>
<td>23</td>
<td>8,000</td>
<td>(9)</td>
<td>184,000</td>
<td>0.74</td>
</tr>
<tr>
<td>Black cottonwood</td>
<td>20</td>
<td>8,800</td>
<td>(9)</td>
<td>176,000</td>
<td>0.71</td>
</tr>
<tr>
<td>Bigleaf maple</td>
<td>27</td>
<td>8,400</td>
<td>(9)</td>
<td>227,000</td>
<td>0.91</td>
</tr>
<tr>
<td>Oregon ash</td>
<td>31</td>
<td>8,200</td>
<td>(41)</td>
<td>254,000</td>
<td>1.02</td>
</tr>
<tr>
<td>Oregon white oak</td>
<td>37</td>
<td>8,110</td>
<td>(41)</td>
<td>300,000</td>
<td>1.20</td>
</tr>
</tbody>
</table>

1Volume based on green condition, solid volume.
2Relative basis, Douglas fir equal 1.0, different fuel moisture not considered.

Associated with that 1 pound of dry wood is 1 pound at 50 percent moisture, wet basis, and 1.5 pounds of water at 60 percent moisture, wet basis—a 50-percent increase in the amount of water. The dry-basis moisture reflects this 50-percent increase in water by going from 100-percent moisture, dry basis, to 150-percent moisture, dry basis.

Wood and bark fuels vary widely in moisture content; the range for commercial hogged fuels in the Northwest is usually between 75 and 125 percent (2, 4, 12, 15, 17, 22, 31). It is generally lower in summer than in winter and is higher for some species than others. Douglas fir hogged fuel is usually less than 100 percent moisture (2, 7, 15), but western hemlock hogged fuels are frequently over 100 percent (2, 17). Some species, such as sugar pine, might have moisture contents of nearly 200 percent.

Certain types of wood residues used for fuel might have extremely high or extremely low moisture contents. Sander dust, for example, would be low—perhaps, 10 percent—but sawdust coming from water-cooled saws could have in excess of 200 percent moisture. When the moisture exceeds about 150 percent, the fuel is difficult to burn in most commercial installations.

**COMBUSTION**

Combustion is a chemical combination of hydrogen and carbon in the fuel with oxygen in the air, in which heat is evolved. If combustion is complete, hydrogen combines with oxygen to form water vapor, and the carbon combines with oxygen to form carbon dioxide. Small amounts of carbon monoxide, hydrocarbons, and other gases usually form because some of the carbon and hydrogen does not react completely with oxygen. The ash is noncombustible, so it either falls to the grate or is entrained with combustion gases.
Three successive, overlapping steps occur in the combustion of wood and bark: water evaporation, distillation and combustion of volatile matter, and reaction of fixed carbon with oxygen. Before combustion can occur, water first must be evaporated from the fuel, and this step requires heat. In the second step, volatile hydrocarbon gases are evolved and mixed with oxygen, which releases heat. In the final step, the fixed carbon combines with oxygen at high temperature to produce carbon dioxide, which also releases heat.

Air Requirements

The amount of air theoretically needed for combustion can be calculated if the fuel analysis is known and the carbon and hydrogen in the fuel are assumed to burn completely to carbon dioxide and water. This amount is called "theoretical air." In practice, a quantity of air greater than the amount indicated by theoretical calculations must be supplied to insure adequate mixing and to have optimum conditions for combustion. Air supplied in excess of theoretical air is defined as "excess air."

Using the fuel analysis for Douglas fir bark given in Table 3, about 6.5 pounds of air theoretically are required to burn 1 pound of dry fuel. The quantity of air required for complete burning of 1 dry pound of this Douglas fir bark fuel with up to 100 percent excess air is shown in Figure 12. Air quantities are given in both weight and volume, assuming air is at standard atmospheric pressure and at a temperature of 70 F. The curve should help in determining capacity for forced-draft fans.

Stack Gases

When 1 pound of dry Douglas fir bark fuel at 100 percent moisture (2 pounds of fuel including moisture) is burned completely with theoretical air, about 8.5 pounds of stack gas

![Figure 11. The relation between moisture contents as expressed on percentages of wet and dry weights.](image)

![Figure 12. Air required for complete burning of 1 pound of dry Douglas fir bark fuel. Volume in cubic feet is calculated for standard air at 70 F with a density of 0.075 of a pound per cubic foot.](image)
are produced. The weight of stack gases from complete burning of 1 pound of dry Douglas fir bark with a range of moisture content and amounts of excess air is given in Figure 13.

The volume of stack gases produced in burning fuel increases with the temperature of the gases. Figure 14 indicates the volume of stack gases produced in burning 1 pound of dry Douglas fir bark with 40-percent excess air and with a range of stack temperatures and fuel moistures that might occur with this fuel. An air supply of 40-percent excess was selected because it represents a condition that might exist in a boiler plant using such fuel. The curve could assist in determining size of induced-draft fans.

The main components of the stack gases are carbon dioxide, nitrogen, oxygen, and water vapor. To determine excess air in a combustion process, a sample of stack gases is analyzed for carbon dioxide or oxygen on a dry volumetric basis. An indication of excess air used for combustion can be determined by assuming complete combustion. Such a relation of carbon dioxide and oxygen to excess air is shown for Douglas fir bark in Figure 15. Because most wood and bark fuels are similar in composition, their relation would be similar.

STEAM PLANTS

Wood and bark residue fuels are used extensively for producing steam. They also are burned in stoves, furnaces, and fireplaces for home heating. Sander dust is used to supply heat directly to veneer dryers (37, 39) and to dryers for wood particles (21), as well as to fire steam plants. The biggest industrial application of wood and bark fuels, however, is burning them in furnaces to produce steam, which is then used for heating, processing, power, or the generation of electricity. Steam plants burning hogged fuel range in capacity from small plants producing 10,000 pounds of steam per hour up to plants at large paper mills producing over 500,000 pounds.
Figure 15. Carbon dioxide and oxygen as volumetric percentages of dry stack gases when Douglas fir bark fuel is burned completely with various amounts of excess air.

Burning Methods

Dutch Oven. A common way of burning wood and bark hogged fuel has been a two-stage furnace consisting of a dutch oven in which moisture is evaporated and fuel gasified, and a secondary furnace where combustion is completed (Figure 16). The fuel is fed by gravity through an opening in the primary furnace and forms a conical fuel pile. Although the dutch-oven furnace has been used widely in the past (2), and almost exclusively until the late 1940’s, most newer installations follow other burning methods.

Figure 16. Boiler with a dutch-oven furnace.
Fuel Cell. Another two-stage furnace is called a fuel cell. The fuel drops from above onto a water-cooled grate in the primary furnace, and the gases pass into a secondary combustion chamber where burning is completed (Figure 17). Many boilers of this type have been installed in the western United States. The steam plants are automated so that little labor is required for their operation. They operate at low pressure (below 25 psi) with capacities usually ranging between 10,000 and 30,000 pounds of steam per hour. Most of them are at lumber plants.

Figure 17. Automatically controlled steam plant that uses wood and bark residues for fuel (from Larry Wellons and Associates, Inc.).
Figure 18. Automatically fired steam plant at a lumber mill in Grant’s Pass, Oregon, that uses sawdust to produce steam for dry kilns.

where the steam is used in kilns for drying lumber (10). Some units (Figure 18) incorporate fuel dryers, which become necessary if the fuel moisture is much above 100 percent.

*Spreaders Stoker.* Many recently installed steam plants fueled by wood and bark have been the spreader-stoker type (4, 12, 13, 16, 17, 22, 29, 31, 40). With the spreader stoker, fuel is introduced above the grate into the furnace by either a pneumatic or mechanical spreader. Part of the fuel is burned in suspension, and the remainder drops to the grates where burning is completed. Spreaders stokers are used with small boilers that have capacities as low as 25,000 pounds of steam per hour up to large plants with capacities in excess of 500,000 pounds. The general arrangement of such plants is illustrated in Figures 19 and 20.

Figure 19. Recent steam-plant installation in Idaho, designed to produce 180,000 pounds of steam per hour using hogged fuel. The fuel is spread by pneumatic spreaders (drawing courtesy of Riley Stoker Corporation).
Figure 20. Steam boiler at a Louisiana paper company, designed to burn hogged bark with a spreader stoker. The plant can generate 450,000 pounds of steam per hour (drawing courtesy of Combustion Engineering, Inc.).

**Inclined Grate.** The inclined grate furnace is shown in Figure 21. Fuel enters the furnace at the top part of the grate in a continuous ribbon, passes over the upper drying section where moisture is removed, and then descends into the lower burning section. Finally, the ash is removed at the lowest part of the grate.

**Boiler Performance**

When boiler performance is examined, a heat balance is made to see where the heat in the fuel is distributed. Energy supplied by the fuel is distributed among the following items:

a. Heat absorbed by boiler fluid (to steam),
b. Heat loss to dry stack gases,
c. Heat loss to moisture in the fuel.
d. Heat loss from formation of moisture from hydrogen in the fuel,
e. Heat loss from incomplete combustion, and
f. Heat loss from radiation and unaccounted for.

Figure 21. Inclined, water-cooled grate boiler at a British Columbia pulp and paper company, designed to produce 250,000 pounds of steam per hour. The fuel is hogged bark and wood refuse combined with oil or natural gas (drawing courtesy of Foster Wheeler Limited).
The most important performance parameter for a boiler is the overall efficiency, which is item a above divided by the total heat supplied by the fuel. To arrive at overall efficiency, evaluating the various heat losses (items b through f above) and then calculating overall efficiency, or item a, by difference, often is simpler.

The last two items of heat loss (e and f) are small and might be assumed to be about 4 percent (23). Heat loss from formation of moisture from hydrogen in the fuel (item d) will vary from about 7 to 8 percent for Douglas fir bark fuel depending on stack temperature.

Fuel Moisture. Because most wood and bark fuels have high moisture contents, heat loss from fuel moisture is correspondingly high. Figure 22 shows heat loss from a range of fuel moisture contents for Douglas fir bark. About 13 percent of the total heat in the fuel is required for moisture evaporation at 100 percent fuel moisture, and about 26 percent of the fuel heat is needed at a fuel moisture of 200 percent.

Not only does increasing fuel moisture content increase heat losses and thereby reduce overall efficiency, but an increasing moisture content also retards combustion and lowers flame temperature, which reduces steam rate capacity. At a point between about 180 and 230 percent moisture, a stable fire no longer can be maintained (23).

Preliminary treatments might aid in burning excessively wet fuels. A moisture press or a fuel dryer (Figure 18) might remove enough moisture so the fuel will burn satisfactorily in the furnace, or auxiliary oil or gas firing can be used.

Dry Stack Gases. The heat loss in a boiler from dry stack gases depends on the amount of excess air used for combustion and also on the stack gas temperature. Figure 23 shows heat loss because of dry stack gases as a percentage of the heating value for Douglas fir bark fuel. Complete combustion was assumed and entering air was assumed to be at 70 F.
loss from dry stack gases for different values of excess air and stack gas temperature. Heat loss to stack gases can be reduced by minimizing excess air into the furnace and by passing stack gases through an air preheater after they have passed through the boiler (Figures 19 and 21).

**Overall Efficiency.** When various items of heat loss have been evaluated, the overall efficiency of a steam plant can be predicted. Figure 24 indicates overall efficiencies for a steam plant using Douglas fir bark fuel with 40-percent excess air. Excess air amounting to 40 percent was chosen as a value that might be expected with hogged fuel firing. Because the main effect of excess air is on losses of dry stack gas, corrections for other values of excess air could be obtained by referring to Figure 23.

With stack temperatures of 400-500°F and fuel with 100 percent moisture, a boiler efficiency of 65-68 percent is indicated from Figure 24. Reported efficiencies of operating plants (4, 22, 23, 31) also indicate similar values for boiler efficiencies with fuel of about 100 percent moisture. To obtain above efficiencies, heat-recovery equipment such as air heaters or economizers usually is required.

**Air-Pollution Control**

One of the most important considerations for any plant now in operation or being planned is, "Will it meet air-pollution-control regulations?" Wood and bark fuels have negligible amounts of sulfur so emissions of sulfur compounds are not a problem. The regulations most applicable to wood and bark-fired steam plants pertain to visible smoke and particulate loading from the stack. Oregon's laws are among the most stringent in this country.
and limit particulate emissions from new boilers to 0.1 grain per standard cubic foot of gas corrected to 12 percent carbon dioxide (1).

Dust loading from bark-burning furnaces has been reported (3) to range from 0.5 to 5.0 grains per standard cubic foot. Dust concentration increases with the second or third power of the boiler load (3, 22). Therefore, reducing the boiler output reduces the particulate concentration of stack gases.

**Fly Ash Characteristics.** Particulate emissions from hogged-fuel boilers depend on the nature of the hogged fuel. Bark has a higher ash content than wood and it also has significant amounts of dirt or sand that result from log handling. Because most hogged fuels contain bark, they also contain various amounts of dirt and sand.

Particulate emissions from hogged fuel or hogged bark-burning boiler stacks are, therefore, usually a mixture of two separate kinds of material, sand (or dirt) and char. Sand is fine, dense, or heavy, highly abrasive, and not a highly visible component of stack emission (3). Char is small, incompletely burned fuel particles that are mainly unburned carbon. This unburned carbon, or char, has low density and is irregular in shape, extremely fragile, and highly visible (3).

**Fly Ash Collectors.** Normally, mechanical fly ash collectors are installed on most hogged-fuel stoker-fired boilers, although not on dutch-oven installations. The usual type of mechanical collector consists of multiple small-diameter cyclones. Barron (3) gives a good description and discussion of the operation of mechanical collectors with bark-fired boilers.

**Reinjection.** Because unburned char contains appreciable combustible material, the fly ash obtained from mechanical collectors frequently is reinjected into the furnace for further combustion. The noncombustible fraction, however, will not be burned, so that complete reinjection causes an increase in dust concentration coming from the furnace. Particulate emissions from stacks, therefore, will be reduced by installing a screening system to separate the char from the sand or ash (3, 26, 29). The screened portion high in ash and sand then is discarded, and that portion having a large amount of char is reinjected into the furnace.

**Two-Stage Particulate Removal.** To meet present regulations for particulate emissions, two-stage collection may be required (1, 3, 12, 18, 30, 34). A two-stage, mechanical, dust-collection system is reported (3, 18) to increase efficiency of overall particulate collection to about 95 percent as compared to about 90 for a single stage.

Another system of two-stage particulate collection has a mechanical collector for the first stage and a wet scrubber for the second stage. Such two-stage systems (Figure 25) have been installed on hogged-fuel boilers (12, 30), and are reported (1, 12, 18) able to meet present emission regulations. The wet scrubber has several disadvantages: a visible steam plume is discharged from the stack; water supply to the scrubbers is required; and the ash slurry requires disposal (12).

Another possibility for two-stage collection is mechanical collectors followed by electrostatic collectors. The use of electrostatic collectors, however, has not been proven with hogged-fuel boilers (1).

**ECONOMICS**

**Fuel-Cost Comparison**

Three principal industrial fuels in Oregon are oil, natural gas, and hogged fuel: oil is sold by the barrel, natural gas by the therm (equivalent to 100,000 Btu's), and hogged fuel by the unit (200 cubic feet of volume).
To compare fuels, the costs should be for equivalent heat output. The last column of Table 7 and Figure 26 show costs in dollars per million Btu of fuel utilized in a steam plant with assumptions as given in the table. Costs listed are those that prevailed in the Willamette Valley of Oregon in December, 1972. Other fuel costs or assumptions could be used for different conditions. For a plant with unused wood and bark residues available for which they have no market, no direct cost for fuel would be incurred if the residues were used for fuel at the plant site.

Table 7 and Figure 26 show that costs for hogged fuel are considerably lower than for oil or natural gas. Fuel is a big item in steam generation, but overall costs must take into account the higher costs of capital and fuel handling associated with hogged fuel.

Although costs appear lower for natural gas than for oil, industrial use of natural gas for steam plants is one of lowest priority. If natural gas were in limited supply, large steam plants would be among those customers first curtailed. Customers on interruptible gas service have to use other fuels when natural gas is interrupted. For example, natural gas at the Oregon State University's heating plant, which uses it on an interruptible schedule, was curtailed over 3 months in the 1971-1972 heating season and about 2½ months in the 1972-1973 heating season.

We are reminded constantly of an energy crisis, impending fuel shortages, and expected rising fuel prices. Indeed, most fuel prices have increased significantly in the past few years. For example, the price of No. 5 fuel oil used by Corvallis schools increased 55 percent in the 3-year period from 1969 to 1972. Natural gas prices in the Willamette Valley, on an interruptible schedule with a usage of 500,000 therms per month, increased 23 percent for the same period, with another increase of 13 percent effective April 1, 1973. Along with higher prices have been longer periods of interruption of service. Prices for hogged fuel depend markedly on location and on local conditions of supply and demand. In January 1973, the University of Oregon paid half the price for hogged fuel that they had paid 10 years previously although prices of most fuels generally were increasing.

![Figure 26. A comparison of costs of some industrial fuels for steam generation from data in Table 7. Natural gas usage assumed was 100,000 therms per month, and the cost of hogged Douglas fir bark assumed was $4.00 per unit.](image)
Hogged Fuel Comparisons

For a given heat content, hogged fuel is heavier and bulkier than oil. For example, 4.3 pounds of Douglas fir bark are needed for the same heat output as 1 pound of oil (Figure 27) with the assumptions given in Table 7. By volume, about 11 cubic feet of hogged Douglas fir bark supply about the same heat as 1 cubic foot of oil (Figure 27). Transportation costs are therefore higher (Figure 28), and much larger storage volumes are needed for hogged fuel than for oil.

A comparison of how much oil or gas is needed to supply the same heat as a unit of hogged fuel would be of interest. Table 8 and Figure 29 show the quantities of oil and gas that have the same heat output as a unit of hogged fuel, based on assumptions given in Table 7.

Using information for western hemlock bark given in Table 7 and generating steam at 600 psi and 750°F from water at 212°F, we find that one unit of hemlock bark will produce about 10,800 pounds of steam.

Steam-Plant Costs

Because hogged fuel is bulky and has high moisture content, steam plants that use it cost more than steam plants that use oil or gas. Koch and Mullen (20) reported that a steam boiler for burning bark and oil would cost about twice that for a boiler burning oil only. J. Donald Kroeker and Associates* indicated that a hogged fuel boiler with capacity for 100,000 pounds of steam per hour would cost about twice as much as one that burns oil and gas only. Dost (11) indicated that a small, automated, wood or bark-fired boiler of the type illustrated in Figure 18, complete with fuel-storage silo, would cost about four times as much as the same size oil-fired boiler.

To give an indication of costs for steam plants fired with hogged fuel, Haley (17) reported a bark-fired steam plant with a capacity of 27,000 pounds of steam per hour had an installed cost of $340,000. Evanson (14) indicated a boiler fired with hogged fuel, with a capacity of 100,000 pounds of steam per hour, would cost about $650,000. For an automated,

\[ \text{Figure 27. Weight and volume comparison of equivalent heat for oil and hogged Douglas fir bark with 80-percent moisture.} \]

\[ \text{Figure 28. Truck hauling cost for Douglas fir hogged bark with 80-percent moisture. Costs shown are 15 percent higher than those reported (19) because of estimated cost increase. Hogged bark weight is assumed to be 4,700 pounds per unit.} \]

Table 7. Fuel Cost Comparison of Some Industrial Fuels Used for Steam Generation.

<table>
<thead>
<tr>
<th>Kind of fuel</th>
<th>Quantity of measure</th>
<th>Cost per quantity</th>
<th>Heating value per quantity</th>
<th>Assumed steam gen. efficiency</th>
<th>Fuel cost $ per million Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 5 fuel oil</td>
<td>Barrel</td>
<td>4.80</td>
<td>6.3</td>
<td>80</td>
<td>0.95</td>
</tr>
<tr>
<td>No. 6 fuel oil</td>
<td>Barrel</td>
<td>4.20</td>
<td>6.3</td>
<td>80</td>
<td>0.83</td>
</tr>
<tr>
<td>Natural gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial firm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,000 therms per month</td>
<td>Therm</td>
<td>0.0661</td>
<td>0.1</td>
<td>76</td>
<td>0.87</td>
</tr>
<tr>
<td>500,000 therms per month</td>
<td>Therm</td>
<td>0.0612</td>
<td>0.1</td>
<td>76</td>
<td>0.81</td>
</tr>
<tr>
<td>Industrial interruptible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100,000 therms per month</td>
<td>Therm</td>
<td>0.0480</td>
<td>0.1</td>
<td>76</td>
<td>0.63</td>
</tr>
<tr>
<td>500,000 therms per month</td>
<td>Therm</td>
<td>0.0444</td>
<td>0.1</td>
<td>76</td>
<td>0.58</td>
</tr>
<tr>
<td>Wood-bark residues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Douglas fir sawdust</td>
<td>Unit</td>
<td>2.0-4.0</td>
<td>16.9$</td>
<td>66$</td>
<td>0.18-0.36</td>
</tr>
<tr>
<td>Western hemlock sawdust</td>
<td>Unit</td>
<td>2.0-4.0</td>
<td>14.3$</td>
<td>58$</td>
<td>0.24-0.48</td>
</tr>
<tr>
<td>Douglas fir hogged bark</td>
<td>Unit</td>
<td>2.0-4.0</td>
<td>24.4$</td>
<td>67$</td>
<td>0.12-0.24</td>
</tr>
<tr>
<td>Western hemlock hogged bark</td>
<td>Unit</td>
<td>2.0-4.0</td>
<td>19.6$</td>
<td>66$</td>
<td>0.16-0.31</td>
</tr>
</tbody>
</table>

3. A unit is 200 cubic feet of bulk volume assumed to contain 1,900 pounds of dry Douglas fir sawdust, 1,700 of western hemlock sawdust, 2,600 of Douglas fir bark, and 2,200 pounds of dry western hemlock bark.
4. Higher heating values per pound, dry, assumed; Douglas fir sawdust, 8,900; western hemlock sawdust, 8,400; Douglas fir bark, 9,400; and western hemlock bark, 8,900.
5. Efficiencies assumed 40-percent excess air, 500°F stack temperature, fuel moisture 80 percent for Douglas fir sawdust and bark and western hemlock bark, 120 percent for western hemlock sawdust.
ONE UNIT OF
DOUGLAS FIR
HOGGED BARK

PRODUCES
HEAT OF

WHICH COSTS

3 1/4 BARRELS
NO. 5 FUEL OIL

$15.60

OR

215 THERMS
OF NATURAL GAS

$14.20

Figure 29. Comparison of heat produced from different fuels. Cost of oil is assumed to be $4.80 per barrel; natural gas is assumed to be 6.61 cents per therm by Northwest Natural Gas Company Schedule 21—Firm High Load Factor—100,000 therms per month. Other assumptions are listed in Table 7.

Table 8. A Comparison of the Quantity of Oil or Natural Gas Required to Provide the Heat Equivalent to One Unit (200 cu ft) of Wood-bark Residues for Steam Generation. Assumptions Given in Table 7.

<table>
<thead>
<tr>
<th>Kind of residue</th>
<th>Heat equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oil</td>
</tr>
<tr>
<td>Douglas fir sawdust</td>
<td>2.21</td>
</tr>
<tr>
<td>Western hemlock sawdust</td>
<td>1.65</td>
</tr>
<tr>
<td>Douglas fir hogged bark</td>
<td>3.24</td>
</tr>
<tr>
<td>Western hemlock hogged bark</td>
<td>2.57</td>
</tr>
</tbody>
</table>

Overall Economics

As I mentioned before, where hogged fuel is available, it is frequently the lowest cost fuel, but capital and operational costs are greater for a steam plant fired with hogged fuel than for one that uses oil or gas. An indication of the overall economics of steam generation with hogged fuel compared to oil or gas can be obtained from reported plant operations or studies.

Dost (11) reported that for a sawmill kiln-drying about 18 million board feet of white fir and pine annually, the fuel savings for a wood-fired steam plant would be about $41,000 annually over that of an oil-fired plant. Fuel savings would pay for the added cost of the wood-fired plant in about 2 years, assuming that wood fuel was available at the plant at no cost.

Pratt (28) indicated that the fuel savings for a wood-fired steam plant supplying heat to 17 double-track dry kilns (each with a capacity of 55,000 board feet of lumber) was about $65,000 annually, as compared with natural gas. The added cost of the wood-fired plant could be repaid in slightly over 3 years with the fuel savings.

Haley (17) reported that a bark-fired steam plant (27,000 pounds of steam per hour) to dry from 50 to 60 million board feet of western hemlock lumber annually would have a payout period of 3.3 years. The payout period considered not only savings on fuel, but also
others, such as elimination of costs associated with operating a wigwam burner. Annual fuel savings were given as $60,000.

In 1963, J. Donald Kroeker and Associates (unpublished report) compared the economics of using hogged fuel or natural gas for the heating and power plant at the University of Oregon in Eugene. An additional boiler with a capacity of 110,000 pounds of steam per hour was being considered. The analysis indicated the cost for a boiler using hogged fuel was $184,000 greater than for a gas-fueled boiler, but an annual net savings of about $92,000 could be made using hogged fuel. The added cost of the hogged-fuel installation would be recovered in 2 years. The report recommended that the additional boiler use hogged fuel, with oil as a standby. The conclusions were based on a price of $3.35 per unit for hogged fuel: since the study, interruptible gas prices increased 25-30 percent, but the price now paid for hogged fuel is only about half of what it was in 1963. The savings by using hogged fuel, therefore, are greater than anticipated.

Another example of savings using wood fuel is an installation at Eugene, Oregon, where sander dust supplies heat to a veneer dryer. It uses about 1,500 pounds of sander dust to heat the dryer, with a monthly fuel savings of $2,300 (39). The fuel savings is expected to pay for the cost of the installation in less than 3 years (37).

CONCLUSIONS

Wood and bark fuels, at one time, supplied most of the energy used in this country. Marked changes have occurred in patterns of energy use in the last 100 years. Although total energy use has grown tremendously, use of wood for fuel has declined. Still, wood and bark are commercially important fuels in some areas. Most of the wood and bark fuel used in this country today comes from residues at forest industry plants. Because wood and bark fuels have a relatively low heating value per unit of volume as well as per pound, transportation costs are high. Such fuels are therefore economical only near or at mills where the residue is produced. Use of wood and bark residues for fuel sometimes can provide the cheapest source of heat and power for a plant, and also can help solve a troublesome and expensive disposal problem. As other fuels increase in price and become less plentiful, even more incentive to use residues for fuel will exist.

LITERATURE CITED


APPENDIX C

EXPERIMENTAL METHOD

As with any process simulation, the underlying concern in this study was the reliability of the simulation predictions. In order to establish the relative accuracy and reliability of the boiler/dryer simulations presented in this paper, experimental case studies were undertaken at existing industrial facilities. These case studies involved the gathering and reduction of process data, followed by the comparison with simulation program-generated values. A total of three cases were studied, at three different plant sites.

The desired measurements were the typical flow measurements required for material and energy balances, i.e., stream flow rates, compositions, and temperatures. These measurements are categorized as follows, and are covered in detail in this section:

1. Gas Stream Measurements
2. Fuel (wood and bark) Stream Measurements
3. Ambient Condition Measurements
4. Operational Parameter Measurement

Gas Stream Measurements

The parameters of interest pertaining to the various gas streams found in conjunction with the boiler/dryer tandem are the following:
Gas stream temperatures. Of particular interest to this study were the dryer inlet temperature and the dryer exhaust temperature. Of supplemental interest were the boiler exhaust temperature (following the final heating surface of the boiler, such as an air heater) and the cyclone exhaust temperature.

Two methods of temperature measurement were used in this study. Semi-continuous temperature measurements were made using thermocouples in conjunction with a multi-channel temperature recorder. Thermocouple placement varied from facility to facility, although in each case, probes were placed in the ductwork before and after the dryer. In each case an attempt was made to place each of the respective probes as close to the dryer as possible. In certain situations the downstream probe was placed in the exhaust stream of the cyclone. Depending on access or interest, a third thermocouple probe was placed at points such as the boiler exhaust upstream from the air heater, or in the exhaust stream of the cyclone (assuming that probe access prior to the cyclone was also available). Occasionally the third probe was used as a utility probe to measure ambient temperature or fuel sample temperature.

The second method used was coincidental with gas stream moisture content determination. This method involved the periodic wet bulb and dry bulb temperature measurement of the various gas streams, particularly the dryer inlet and exhaust streams. These measurements were made approximately every thirty minutes during the experimental run (the total length of each run was approximately three to four
hours), and were made using a hand-held temperature monitor with its accompanying thermocouple probe. Both methods were found to be in relative agreement.

(b) Gas stream composition. The gas stream components in question here are those normally associated with combustion processes: carbon dioxide, carbon monoxide, oxygen, and nitrogen. The oxides of sulfur and nitrogen occur in such small amounts that their contribution to the overall material and energy balances are negligible, consequently they were ignored in this study. Again, two methods of measurement were used in this study. Continuous measurements of carbon monoxide, carbon dioxide, and oxygen concentrations were made using a series of infrared gas analyzers. This involved the continuous withdrawal of gas from the various ducts, condensing the water vapor present in the gas, ultimately passing the sample gas through the IR cells. The levels of each species were recorded by strip chart recorders. The strip chart data were reduced using calibration charts, yielding concentrations as percentage of dry gas. Nitrogen concentrations were determined by difference from one-hundred percent.

The second method of gas stream composition involved the use of Fyrite-type gas analyzers, in which a sample of gas is withdrawn from the gas stream, absorbed chemically into a specific solution, the concentration of the gas then read directly as percent dry gas. Carbon dioxide and oxygen concentrations were measured in this manner; carbon monoxide was assumed to be negligible in contribution
to the overall material and energy balances. These measurements were made approximately every thirty minutes during the experimental run.

In both of the above cases samples were taken at points preceding and following the dryer. In addition to the typical material and energy balances, the data obtained from such measurements allowed calculation of air leakage into the dryer, based on the relative concentrations of carbon dioxide before and after the dryer, and also allowed the calculation of combustion excess air (see Appendix D.)

(c) Gas stream flow rates. The gas flow through the system was easily measured by standard pitot traverse. The pitot traverse involved measuring the velocity pressure, which is the difference between the total pressure within the duct and the static pressure, at the centers of equal concentric areas. This implies, and such was indeed the case, that the ducts encountered during the case studies were circular in cross section. (Rectangular ducts require a slightly different treatment.) Velocity pressure readings were taken at ten points along the diameter of each duct, and when possible, along a second diameter ninety degrees from the first. The gas stream velocities were then evaluated using Bernoulli's Equation:

$$\frac{\Delta P}{\rho} + \frac{1}{2}v^2 = 0$$

Upon rearranging, this equation can be used to solve for velocity as:

$$v = (2\Delta P/\rho)^{1/2}$$
Once the average flow velocity is established it becomes a simple matter to calculate the gas stream volumetric and mass flow rates. The volumetric flow rate is simply the product of the cross-sectional area of the duct in question, and the average velocity at that point in the duct:

\[ \dot{V} = A \times v = \pi \left( \frac{D}{2} \right)^2 v \]

The mass flow rate is then the product of the volumetric flow rate and the gas density at the point (and temperature) of measurement:

\[ M = \dot{V}_D \]

(d) Gas stream moisture content. This study used two different methods to determine gas stream moisture content. The predominant method used was the standard wet bulb/dry bulb method of determining moisture content or humidities from wet bulb depression measurements.

As a point of general interest, the wick used to measure the wet bulb temperature was saturated with hot water at a temperature above the expected wet bulb temperature. This technique allowed the observation of a minimum temperature, which was taken as the wet bulb temperature. (The temperature was observed to decrease from the initial (wick) temperature, stabilize momentarily at the wet bulb temperature, and then increase as the wick dried. The use of cold water to saturate the wick resulted in temperature readings that increased continually, with a plateau at the wet bulb temperature. It was decidedly easier to observe a minimum temperature than to note a plateau temperature.)
The second method involved the continuous collection of a gas sample of known total volume, condensing the water vapor in impingers in an ice bath, and thus noting the total amount of water condensed. Once values for the volume of dry gas and the mass of water condensed are known, the ensuing calculation of humidity ratios and concentrations is straightforward, and will not be presented here (see Appendix D.) This second method, henceforth termed the impinger method, was used primarily as a check on the wet bulb/dry bulb method, and was used in two of the three runs. It was discovered that the wet bulb/dry bulb method yielded values for the gas stream moisture content that were relatively consistent with the impinger method. Additionally, although the impinger method is allegedly more reliable than the wet bulb/dry bulb method, it is more cumbersome in use, and requires much more equipment.

The wet bulb/dry bulb method of determining stream moisture content is a bit more involved in terms of the calculations required, especially if the system in question is not an air/water system, or cannot be accurately modeled as such. In the event that the system in question is indeed air/water, and is at moderately low temperatures (210°F and below) and pressures of roughly one atmosphere, the gas stream moisture content may be readily determined from psychrometric charts. The humidity of an air/water system in the temperature range of 210-300°F may be evaluated using the methods summarized by Rosen (1981).
The assumption in this study was that the boiler exhaust gas could not be modeled as an air/water system. Consequently a more rigorous series of calculations is required to evaluate moisture content. The fact that the system under study consisted of a mixture of primarily four gases (carbon dioxide, water, nitrogen, and oxygen) further compounded the calculations required.

Gas stream moisture content in terms of absolute humidity may be determined from a rearrangement of the following equation (Treybal, 1980):

\[ t_G - t_W = \frac{\lambda_W(Y'_W - Y'_f)}{(h_G/k_Y)} \]

where:
- \( t_G \) = the dry bulb temperature (°F)
- \( t_W \) = the wet bulb temperature (°F)
- \( \lambda_W \) = the latent heat of vaporization at \( t_W \) (BTU/lbm H\(_2\)O)
- \( Y'_f \) = the absolute humidity (lbm H\(_2\)O/lbm dry gas)
- \( Y'_W \) = the absolute humidity at saturated conditions (t\(_W\))
- \( h_G \) = the convective heat transfer coefficient (BTU/ft\(^2\)hr °F)
- \( k_Y \) = the convective mass transfer coefficient (lbm/ft\(^2\) hr)

The ratio \( (h_G/k_Y) \), sometimes termed the "psychometric ratio" may be determined using the following empirical equation (Henry and Epstein, 1970.)

\[ (h_G/k_Y) = C_S(Sc/Pr)^{0.567} \]

where:
- \( C_S = C_P^{Dry \ gas} + Y'C_P^{H_2O} \) (BTU/lbm Dry Gas °F)
- \( Sc = Schmidt \ Number = \mu/\rho D_{AB} \) (dimensionless)
- \( Pr = Prandtl \ Number = \mu C_P/k \) (dimensionless)
Cp = the heat capacity of the species in question
(BTU/lbm °F)
μ = the viscosity of the gas (lbm/ft sec)
ρ = the density of the gas (lbm/ft³)
k = the thermal conductivity of the gas (BTU/ft hr)
D_AB = the mass diffusivity (ft²/hr)

The properties listed above tend to be somewhat dependent on temperature; it is standard convention to evaluate them at the arithmetic mean of the wet bulb and dry bulb temperatures, termed the "film temperature". Values for the various properties listed above may be found in any good engineering handbook, or thermodynamics reference (Perry and Chilton, 1973; Smith and Van Ness, 1975).

As stated previously, the system under study here is considered to be a mixture of combustion gases. As a result it is necessary to evaluate several of the properties above using thermodynamic mixing rules, or variations thereof. The properties in question, and the methods of evaluation for mixtures follow.

**Density of a gas mixture**

The density of a gas mixture may be evaluated most easily using the assumption of ideal solutions. This assumption is quite valid at the temperatures and pressures encountered in this study. The assumption of ideal solutions states:

\[ V \text{ (molar volume of mixture)} = \sum_{i=1}^{n} y_i v_i \]

where \( y_i \) is the mole fraction of species \( i \) in the mixture and \( v_i \) is
the molar volume of species \( i \) at the pressure and temperature of the mixture. The density of species \( i \) is then defined as:

\[
\rho_i = \frac{1}{V_i} \text{ (molar density - lb-moles/ft}^3)\]

Similarly: \( \bar{\rho} = \frac{1}{V} \) (molar density of mixture - lb-moles mixture/ft\(^3)\)

Rearrangement and substitution of these latter relationships into the first equation listed yields the average density of the gas mixture as:

\[
\bar{\rho} = \frac{1}{\Sigma y_i(1/\rho_i)}
\]

The relationship used in this study for the evaluation of the gas stream moisture content yields a value of mass water per mass dry gas, hence it is necessary that the gas properties involved are presented on the same mass basis. This requirement is easily accommodated through the use of the following relationships:

\[
\rho_{m,i} = \rho_i MW_i \text{ (mass density - lb}_m/ft^3)\]

Likewise:

\[
\bar{\rho}_m = \bar{\rho}_{m,ave} \text{ (mass density of mixture - lb}_m \text{ mixture/ft}^3)\]

where: \( MW = \text{the molecular weight of the species in question (lb}_m/\text{lb-mole)}\)

These two relationships may be substituted into the expression for the density of a gas mixture to yield the following relationships:

\[
\bar{\rho}_m = \Sigma y_i MW_i / \Sigma y_i (MW_i / \rho_{m,i})
\]

\[
\bar{\rho}_m = \Sigma y_i MW_i / \Sigma y_i (1/\rho_i)
\]

The first of these two expressions is used in the event that the various gas densities are reported on a mass basis; the second if density is reported on a molar basis.
Thermal conductivity of a gas mixture

The thermal conductivity of a gas mixture is given as (Perry and Chilton, 1973)

\[
\bar{k} = \frac{\sum y_i k_i (MW_i)^{1/3}}{\sum y_i (MW_i)^{1/3}}
\]

Heat capacity of a gas mixture

The heat capacity of a gas mixture again assumes the state of ideal solutions. With this assumption in mind, the heat capacity of a gas mixture is given as:

\[
\overline{C_p} = \sum y_i C_{pi} \quad \text{(Molar heat capacity - BTU/lb-mole mixture)}
\]

In a manner similar to the treatment of the gas mixture density, the gas heat capacity is presented on a mass basis as shown below:

\[
\overline{C_{pm}} = \frac{\sum y_i MW_i C_{pm,i}}{\sum y_i MW_i}
\]

Again, the first relationship is used in the event that heat capacity data is presented on a mass basis; the second is used when heat capacity data is presented on a molar basis.

Diffusivity of a gas mixture

The diffusivity, or diffusion coefficient, of a gas mixture is found by first calculating (or locating in the literature) a value of the diffusivity of each of the binary mixtures formed by the species of concern, in this case water, and each of the remaining component
gases. Following the calculation of the binary diffusivities, the diffusivity of the mixture may be found using the following mixing relationship (Welty, et al., 1976):

\[ D_{A-mix} = \frac{1}{\sum y_i^{-1}} D_{A-i} \]

where: \( y_i \) = the mole fraction of component i on an "A-free" basis

The binary diffusivities may be readily calculated using the following Gilliland-like equation (Fuller, et al., 1966)

\[ D_{AB} = \frac{10^{-3} T^{1.75} (1/MW_A + 1/MW_B)^{1/2}}{P (\nu_A^{1/3} + \nu_B^{1/3})^2} \]

where: \( D_{AB} \) is given as cm²/s
\( P \) is given as atmospheres
\( T \) is given as degrees Kelvin (absolute temperature)
\( \nu \) is the molal volume, given in cm³/mole

A table of the molal volumes of the species of interest in this study is shown below:

<table>
<thead>
<tr>
<th>Species</th>
<th>( \nu ) (cm³/mole)</th>
<th>Species</th>
<th>( \nu ) (cm³/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>12.7</td>
<td>CO</td>
<td>18.9</td>
</tr>
<tr>
<td>N₂</td>
<td>17.9</td>
<td>CO₂</td>
<td>26.9</td>
</tr>
<tr>
<td>O₂</td>
<td>16.6</td>
<td>Air</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Once the methods of determining the gas mixture properties have been established, it is a relatively simple matter to calculate the gas stream moisture content. The method of solution is iterative in
nature, noting that the average properties are dependent on composition as well as temperature. One of the many methods of solution involves the "guesstimating" of the humidity ratio, evaluating the properties using this estimated value in conjunction with the dry gas composition, ultimately calculating a "new" value of $Y'$. The solution is reached when the calculated value is in relative agreement with the initial estimate. If the estimated and calculated values are not in agreement, the entire process is repeated, using the latest calculated value as the new estimate. (The method described is termed the "Method of Successive Substitution".)

**Fuel (Wood) Stream Measurements**

The parameters of interest which pertain to the various fuel streams throughout the boiler/dryer tandem are the following:

(a) Fuel stream flow rates. Fuel stream flow rates were obtained by collecting the total flow passing a given point in a specified time interval, usually thirty seconds to one minute. The collected fuel was then weighed. Flow rate measurements were made approximately every thirty minutes throughout the course of the run. The particular streams of interest were primarily the total flow to the dryer, the coarse fuel flow rate at the dryer exit, and the fines flow rate at the cyclone exit.

In one particular case, the fuel flow rate to the dryer was established using a calibration method which had been previously developed at the facility in question. This calibration method cor-
related the flow rate (oven-dry wood) with the rpm of the dryer feed screw.

As a check, flow rates of dry wood were calculated from experimental data using an overall carbon balance on the system. In most cases the carbon balance yielded values in relatively good agreement with the measured flow rates.

(b) Fuel composition. Fuel composition was established by first determining the species of wood used as a fuel source, then consulting the literature to establish both the dry wood composition (ultimate analysis) and the higher heating value of the particular species (Corder, 1973; see Appendix B.)

(c) Fuel moisture content. Individual fuel samples for moisture content determination were collected on the same schedule as the flow measurement. These samples were collected at the following points: (1) At the entrance to the dryer (or the conveyor to the dryer); (2) At the exit of the dryer (coarse fuel); (3) At the exit of the cyclone (fines); (4) At a point on the conveyor to the boiler (gross (dry) fuel). These samples were collected, catalogued, and sealed in plastic bags for later analysis in the lab. Fuel moisture contents were determined by placing a known amount of fuel in a convection oven at 220°F for a period of twenty-four hours. The samples were then removed from the oven, cooled, and weighed. The moisture contents were then calculated using the following relationship:
$$MC_d, \% = 100 \times \frac{\text{Mass Sample, initial} - \text{Mass Sample, final}}{\text{Mass Sample, final}}$$

thus

$$MC_d, \% = 100 \times \frac{\text{Mass of water in initial sample}}{\text{Mass of oven-dry wood in sample}}$$

(d) Fuel temperature. Fuel temperatures were measured coincidentally with the fuel flow rate and moisture content samples using a hand-held temperature monitor. The fuel stream temperatures of primary interest were the dryer entrance and dryer exit (gross fuel) temperatures.

Ambient Condition Measurements

The ambient conditions of interest to this study were the ambient temperature and the ambient humidity. These were determined through the use of a sling psychrometer in conjunction with atmospheric psychrometric charts. Ambient pressure was assumed to be approximately one atmosphere.

Operational Parameters

Operational parameters such as the boiler steam demand and the feedwater and header steam conditions were deduced from daily plant records and from consultation with plant personnel. Other operational parameters such as combustion excess air were established by the analysis of experimental data (see Appendix D.)
Introduction

The data and calculations coincident with this study, are presented in an attempt to summarize the experimental data derived from the analysis of the respective boiler/dryer systems studied. In addition, sample calculations of the various parameters of interest to this study are provided as a template, in the event that the reader wishes to evaluate similar parameters.

The concepts used in the calculation of the various quantities that follow are presented in detail in Appendix C, Experimental Method. Sample calculations using experimental data gathered in this study consist of the following:

* Gas stream moisture content (both wet bulb depression and so-called impinger methods)
* Gas stream flow rate
* Dryer air leakage
* Fuel moisture content
* Heat of formation of dry wood
* Energy "Partitioning" within the dryer
* Combustion excess air from boiler exhaust analysis
* Total fuel flow rate to boiler from boiler exhaust analysis
These calculations make use of simple engineering principles, primarily material and energy balances, and tend to support the validity of the use of the First Law of Thermodynamics in common practice.

**Experimental Data Summary**

Experimentally determined flows and properties of each of the boiler/dryer systems analyzed are presented in Table D.1. A summary of the energy flows (energy "partitioning") within the dryer for each case is presented in Table D.2.

**Thermodynamic Data Summary**

The heat capacity of various gases are commonly expressed as third order equations (established from experimental data through use of curve-fitting techniques) of the form shown below (Felder and Rousseau, 1978):

\[ C_p = A + BT + CT^2 + DT^3 \]

The heat effect, of enthalpy, manifested by a change in temperature, is determined by integrating the heat capacity equation. Thus:

\[ h \frac{T_2}{T_1'} = C_p \int_{T_1}^{T_2} dT = A(T_2 - T_1) + \frac{B}{2}(T_2^2 - T_1^2) + \frac{C}{3}(T_2^3 - T_1^3) + \frac{D}{4}(T_2^4 - T_1^4) \]

The coefficients of the heat capacity equation for species of interest to this study, as well as other thermodynamic values, are listed in Table D.3. Note that the equations were developed assuming temperature units of degrees Centigrade, and even though the heat
TABLE D.1 Boiler/Dryer Flows and Properties

<table>
<thead>
<tr>
<th>Category</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler steam demand during trial (pph)</td>
<td>170,000</td>
<td>60,000</td>
<td>9,000</td>
</tr>
<tr>
<td>Boiler steam demand during trial (MBTU/hr)</td>
<td>189.3</td>
<td>62.32</td>
<td>9.31</td>
</tr>
<tr>
<td>Dry gas flow rate, dryer inlet (lbm dry gas/hr)</td>
<td>380,350</td>
<td>272,520</td>
<td>34,400</td>
</tr>
<tr>
<td>Dryer inlet temperature (°F)</td>
<td>373</td>
<td>478</td>
<td>340</td>
</tr>
<tr>
<td>Dryer exhaust temperature (°F)</td>
<td>203</td>
<td>238</td>
<td>150</td>
</tr>
<tr>
<td>Dryer inlet humidity ratio (lbm H₂O/lbm dry gas)</td>
<td>0.1053</td>
<td>0.0638</td>
<td>0.1145</td>
</tr>
<tr>
<td>Dryer exhaust humidity ratio (lbm H₂O/lbm dry gas)</td>
<td>0.1181</td>
<td>0.0580</td>
<td>0.0868</td>
</tr>
<tr>
<td>% CO₂, Dryer inlet (% dry gas)</td>
<td>10.56</td>
<td>4.24</td>
<td>7.00</td>
</tr>
<tr>
<td>% CO₂, Dryer exit (% dry gas)</td>
<td>9.45</td>
<td>2.58</td>
<td>4.19</td>
</tr>
<tr>
<td>% O₂, dryer inlet (% dry gas)</td>
<td>9.50</td>
<td>16.32</td>
<td>13.31</td>
</tr>
<tr>
<td>% O₂, dryer exit (% dry gas)</td>
<td>11.04</td>
<td>18.44</td>
<td>16.26</td>
</tr>
<tr>
<td>Fuel flow rate through dryer (lbm dry wood/hr)</td>
<td>26,280¹</td>
<td>7,500</td>
<td>1,963</td>
</tr>
<tr>
<td>Fuel moisture content, dryer inlet; MC_d/MC_w (%)</td>
<td>65.2/39.5</td>
<td>106.3/51.5</td>
<td>154.3/60.7</td>
</tr>
<tr>
<td>Fuel moisture content, dryer exit; MC_d/MC_w (%)</td>
<td>39.4/28.3</td>
<td>30.9/23.6</td>
<td>104.2/51.0</td>
</tr>
<tr>
<td>Fuel flow rate to boiler (lbm dry wood/hr)</td>
<td>31,800²</td>
<td>8,820²</td>
<td>1,960</td>
</tr>
</tbody>
</table>

¹ Assuming 100% efficiency
² Assuming 100% efficiency
TABLE D.2  Summary of Dryer Energy Partitioning

<table>
<thead>
<tr>
<th>Category</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total available energy in boiler exhaust, relative to ambient temperature (BTU/hr)</td>
<td>301,994</td>
<td>150,539</td>
<td>27,253</td>
</tr>
<tr>
<td></td>
<td>(100.00)¹</td>
<td>(100.00)¹</td>
<td>(100.00)</td>
</tr>
<tr>
<td>Energy in boiler exhaust that is lost to the atmosphere (BTU/hr)</td>
<td>121,687</td>
<td>61,295</td>
<td>9,261</td>
</tr>
<tr>
<td></td>
<td>(40.29)</td>
<td>(40.72)</td>
<td>(33.98)</td>
</tr>
<tr>
<td>Sensible heat requirement of dryer air leakage (BTU/hr)</td>
<td>11,536</td>
<td>32,551</td>
<td>4,999</td>
</tr>
<tr>
<td></td>
<td>(3.82)</td>
<td>(21.62)</td>
<td>(18.34)</td>
</tr>
<tr>
<td>Sensible heat of wood and water in wood at dryer exit (BTU/hr)</td>
<td>7,413</td>
<td>2,354</td>
<td>630</td>
</tr>
<tr>
<td></td>
<td>(2.45)</td>
<td>(1.56)</td>
<td>(2.31)</td>
</tr>
<tr>
<td>Energy remaining for drying (BTU/hr)</td>
<td>101,358</td>
<td>54,339</td>
<td>12,364</td>
</tr>
<tr>
<td></td>
<td>(53.43)</td>
<td>(36.10)</td>
<td>(45.37)</td>
</tr>
<tr>
<td>Dryer thermodynamic (heating) efficiency (%)</td>
<td>53.43</td>
<td>36.10</td>
<td>45.37</td>
</tr>
</tbody>
</table>

¹Values in parenthesis indicate percent of total available energy.
capacity (presented in terms of (J/mol°C)) may be converted to other units (conversion factors are found in Table D.3), the temperatures of evaluation must remain in terms of degrees Centigrade.

The heat capacity relationship used for dry wood is that determined by Dunlap (Beall, 1968):

\[ C_{p_{\text{Wood}}} = 0.266 + 0.00116 \, T \, (\text{cal/gram °C}) \]

where \( T \) equals temperature over the interval from 0 to 100 °C. Note that although the units of cal/gram °C are equivalent to the units of BTU/lbm °F, the equation above was developed in terms of degrees Centigrade, and consequently requires temperatures evaluated as such.

The heat effects resulting from changes in the temperature of the wood may be determined by integrating the above equation as follows:

\[
\int_{T_1}^{T_2} C_{p_{\text{Wood}}} \, dT = 0.266 (T_2 - T_1) + 0.00058 (T_2^2 - T_1^2)
\]

(a) **Gas Stream Moisture Content**

This study used two independent methods of gas stream moisture content determination: (1) a condensation, or impinger method, in which a known volume of gas is drawn through a set of impingers placed in an ice bath, thus collecting the water contained in the gas sample (the volume was measured downstream from the impingers), and, (2) a wet bulb depression method, which uses standard techniques of psychrometry, wet bulb/dry bulb temperatures, etc.

The impinger method is relatively straightforward. The volume of (dry) gas was measured using an integrating gas meter; the volume is measured at the meter conditions. The water collected in the
<table>
<thead>
<tr>
<th>Formula</th>
<th>Mol. Wt.</th>
<th>$\Delta h_f$ (kJ/mol)$^1$</th>
<th>A</th>
<th>Bx10$^2$</th>
<th>Cx10$^5$</th>
<th>Dx10$^9$</th>
<th>Temp. Unit</th>
<th>Temp. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-</td>
<td>29.0</td>
<td>-</td>
<td>28.94</td>
<td>0.4147</td>
<td>0.3191</td>
<td>-1.965</td>
<td>°C</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO$_2$</td>
<td>44.01</td>
<td>-393.5</td>
<td>36.11</td>
<td>4.233</td>
<td>-2.887</td>
<td>7.464</td>
<td>°C</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>28.01</td>
<td>-110.52</td>
<td>28.95</td>
<td>0.4110</td>
<td>0.3548</td>
<td>-2.220</td>
<td>°C</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N$_2$</td>
<td>28.02</td>
<td>-</td>
<td>29.00</td>
<td>0.2199</td>
<td>0.5723</td>
<td>-2.871</td>
<td>°C</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O$_2$</td>
<td>32.00</td>
<td>-</td>
<td>29.10</td>
<td>1.158</td>
<td>-0.6076</td>
<td>1.311</td>
<td>°C</td>
</tr>
<tr>
<td>Water (1)</td>
<td>H$_2$O</td>
<td>18.016</td>
<td>-285.84</td>
<td>75.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>°C</td>
</tr>
<tr>
<td>Water (g)</td>
<td>H$_2$O</td>
<td>18.016</td>
<td>-241.83</td>
<td>33.46</td>
<td>0.6880</td>
<td>0.7604</td>
<td>-3.593</td>
<td>°C</td>
</tr>
</tbody>
</table>

Example: $C_p$$_{CO_2} = 36.11 + (4.233\times10^{-2})T + (-2.887\times10^{-5})T^2 + (7.464\times10^{-9})T^3$, where $T$ is in deg. C, $C_p$ in (J/mol. C)

To calculate $C_p$ in (cal/mol. C) or (BTU/lb. mole.F), divide all coefficients by 4.184
To convert $h_f$ to kcal/mol, divide given value by 4.184; to convert to BTU/lb. mol, multiply by 430.28

$^1$(adapted from Felder and Rousseau, "Elementary Principles of Chemical Processes", 1978, John Wiley & Sons)
impingers was measured using initial and final weights of the impingers.

The total flow rate of dry gas passing through the meter is determined assuming ideal gases, as follows:

\[ PV = nRT \]

This equation, upon rearranging, yields:

\[ n = \frac{PV}{RT} \]

where:
- \( P \) = pressure (psia)
- \( V \) = volume (ft\(^3\))
- \( R \) = gas law constant (10.73 ft\(^3\)-psia/lb-mole R)
- \( T \) = absolute temperature (R)

Upon substituting experimental data for Case A for the dryer inlet stream into the above expression yields the total molar flow rate of the dry gas as:

\[ n = \frac{(11.56 \text{ psia}) (11.93 \text{ ft}^3)}{(11.56 \text{ psia}) (11.93 \text{ ft}^3) - (10.73 \text{ ft}^3 \text{- psia/lb-mole-R})(565.8 \text{ R})} \]

Thus: \( n = 0.0227 \text{ lb-mole dry gas} \)

The mass of the water condensed in the impingers was determined to be 14.7 grams.

Thus: \( \text{Mass } H_2O \text{ condensed} = 14.7 \text{ gram} = 0.03421 \text{ lbm } H_2O \)

\[ = 0.00180 \text{ lb-mole } H_2O \]

The gas stream moisture content may then be expressed in several forms, both on a molar and mass basis. These various forms are illustrated as follows:
Mole fraction, H₂O-free basis

The H₂O-free basis, sometimes referred to as the "solute-free" basis is defined in the relationship shown below as:

\[ \frac{1 \text{ lb-moles H}_2\text{O}}{0.00180 \text{ lb-moles H}_2\text{O}} = \frac{0.02272 \text{ lb-moles dry gas}}{1 \text{ lb-moles dry gas}} \]

Thus: \[ Y_{H_2O} = 0.079 \text{ lb-moles H}_2\text{O}/\text{lb-moles dry gas} \]

(7.9% on an H₂O-free basis)

Mole fraction, total basis

The mole fraction on a total basis is a common method of reporting gas or liquid concentrations. It is defined in this case as:

\[ \frac{1 \text{ lb-moles H}_2\text{O}}{0.00180 \text{ lb-moles H}_2\text{O}} = \frac{0.02272 \text{ lb-moles Dry Gas} + 0.00180 \text{ lb-moles H}_2\text{O}}{1 \text{ lb-moles wet gas}} \]

Thus: \[ Y_{H_2O} = 0.073 \text{ lb-moles H}_2\text{O}/\text{lb-mole wet gas} \]

(or 7.3% H₂O on a total basis)

Mass fraction, H₂O-free basis

The H₂O-free basis mass fraction is the common basis of representing the absolute humidity of a gas stream. It is defined as:

\[ \frac{1 \text{ lb}_m \text{ H}_2\text{O}}{1 \text{ lb}_m \text{ dry gas}} \cdot \frac{\text{lb-moles H}_2\text{O}}{\text{lb-moles dry gas}} \cdot \frac{\text{MW H}_2\text{O}}{\text{MW dry gas}} \]

and is easily calculated from the H₂O-free basis mole fraction as:

\[ Y'_{H_2O} = Y_{H_2O} \left( \frac{\text{MW H}_2\text{O}}{\text{MW dry gas}} \right) = \left(0.079 \frac{\text{lb}_m \text{ H}_2\text{O}}{\text{lb}_m \text{ dry gas}} \right) \left( \frac{18.016 \text{ lb}_m \text{ H}_2\text{O}/\text{lb-mole H}_2\text{O}}{30.101 \text{ lb}_m/\text{lb-mole dry gas}} \right) \]

Thus: \[ Y'_{H_2O} = 0.0474 \text{ lb}_m \text{ H}_2\text{O}/\text{lb}_m \text{ dry gas} \]

(or 4.74% on an H₂O-free mass basis)
(Note that the molecular weight of the dry gas is given as 30.10 lbm/lb-mole dry gas. This value was calculated from the dry gas compositions and molecular weights presented in Table D.4, using the following expression:

\[ MW_{\text{dry gas}} = \Sigma y_i MW_i \]

**Mass fraction, total basis**

The mass fraction on a total basis is defined as:

\[ Y_{H_2O} = \frac{1b_m H_2O}{1b_m \text{ wet gas}} \]

and may easily be determined from the total basis mole fraction as:

\[ Y_{H_2O} = y_{H_2O} \frac{MW H_2O}{MW \text{ wet gas}} \]

or

\[ Y_{H_2O} = y_{H_2O} \left( \frac{MW H_2O}{y_{H_2O} (MW H_2O) + (1 - y_{H_2O}) (MW \text{ dry gas})} \right) \]

Substituting the appropriate values into this expression yields:

\[ Y_{H_2O} = 0.0453 \text{ lbm H}_2\text{O}/\text{lbm wet gas} \]

(or 4.53% on a total mass basis)

The wet bulb depression method of moisture content determination uses the system of equations presented in Appendix C (Experimental Method). Although the method is a bit tedious (the assumption of this study was that the boiler exhaust could not be accurately modeled as an air/water system), the calculations involved are
relatively straight-forward. As stated in the Experimental Method, the calculation of the gas stream moisture content is an iterative process; it is helpful to have a programmable calculator or a mini-computer to aid in the process.

Recall from the experimental method discussion the fundamental equation of wet bulb depression:

$$t_G - t_W = \frac{\lambda_w(Y_W' - Y')}{(h_G/k_Y)}$$

Recall also that the properties used in the above expressions are evaluated at the film temperature, or the arithmetic mean of the wet bulb and the dry bulb temperatures, and that several of the properties require evaluation using mixing rules.

The calculation of the gas stream moisture content for the exhaust stream of Boiler/Dryer A is as follows. Table D.4 summarizes the various boiler exhaust components and their respective properties (Welty, et al., 1976) evaluated at the film temperature. Although the ensuing calculations are iterative in nature, the following development will circumvent iteration by selecting as the initial guess value of the moisture content the solution value. As follows:

**Calculation of gas mixture diffusivity**

The diffusivity of a gas mixture is determined by first calculating the diffusivities of each of the binaries formed by water and each of the remaining components using the following equation:

$$D_{AB} = \frac{10^{-3} T^{1.75}(1/MW_A + 1/MW_B)^{1/2}}{P (v_A^{1/3} + v_B^{1/3})^2}$$
**TABLE D.4**  Boiler Exhaust Gas Components and Respective Properties Evaluated at the Film Temperature

<table>
<thead>
<tr>
<th>Species</th>
<th>MW&lt;sub&gt;i&lt;/sub&gt;</th>
<th>y&lt;sub&gt;i&lt;/sub&gt;</th>
<th>y&lt;sub&gt;i&lt;/sub&gt;'</th>
<th>k&lt;sub&gt;i&lt;/sub&gt; (BTU/hr-ft-F)</th>
<th>ρ&lt;sub&gt;i&lt;/sub&gt; (lb&lt;sub&gt;m&lt;/sub&gt;/ft&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>C&lt;sub&gt;p m,i&lt;/sub&gt; (BTU/lb&lt;sub&gt;m&lt;/sub&gt;-F)</th>
<th>v&lt;sub&gt;i&lt;/sub&gt;(cm&lt;sup&gt;3&lt;/sup&gt;/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>28.01</td>
<td>0.0005</td>
<td>0.0006</td>
<td>0.0185</td>
<td>0.0534</td>
<td>0.2501</td>
<td>18.9</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>44.01</td>
<td>0.0873</td>
<td>0.1025</td>
<td>0.0150</td>
<td>0.0843</td>
<td>0.2257</td>
<td>26.9</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>18.02</td>
<td>0.1484</td>
<td>0.1743</td>
<td>0.0157</td>
<td>0.0347</td>
<td>0.4820</td>
<td>12.7</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>28.02</td>
<td>0.6843</td>
<td>0.8036</td>
<td>0.0193</td>
<td>0.0535</td>
<td>0.2491</td>
<td>17.9</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>32.00</td>
<td>0.0795</td>
<td>0.0933</td>
<td>0.0199</td>
<td>0.0612</td>
<td>0.2253</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Wet Bulb Temperature (t<sub>W</sub>): 143 °F
Dry Bulb Temperature (t<sub>G</sub>): 371 °F
Film Temperature (t<sub>f</sub>): 257 °F
Latent Heat of Vaporization at t<sub>W</sub> (λ<sub>W</sub>): 1012.1 BTU/lb<sub>m</sub>
Saturation Moisture Content, at t<sub>W</sub> (Y<sub>W</sub>): 0.1620 lb<sub>m</sub> H<sub>2</sub>O/lb<sub>m</sub> Dry Gas
Duct Pressure: 0.9986 atmospheres

(data adapted from Welty, et al., (1976))
where $D_{AB}$ is given in cm$^2$/s

$P$ is given as atmospheres

$T$ is in degrees Kelvin

$MW$ is the molecular weight

$\nu$ is the molal volume (cm$^3$/mole)

Once the binary diffusivities have been established, the diffusivity of water through the gas mixture is determined through use of the following equation:

$$D_{A-mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{D_{A-i}}}$$

For example, the diffusivity of water in nitrogen for the conditions specified in Table D.4 is calculated as:

$$D_{H_2O-N_2} = \frac{10^{-3} \cdot (398.15)^{1.75} \cdot (1/18.016 + 1/28.02)^{1/2}}{0.9986 \cdot ((12.7)^{1/3} + (17.9)^{1/3})^2}$$

Thus

$$D_{H_2O-N_2} = 0.4382 \text{ cm}^2/\text{s} = 1.6972 \text{ ft}^2/\text{hr}$$

In a similar fashion, the diffusivities of the remaining binaries are:

$$D_{H_2O-CO} = 0.4299 \text{ cm}^2/\text{s} = 1.6648 \text{ ft}^2/\text{hr}$$

$$D_{H_2O-CO_2} = 0.3500 \text{ cm}^2/\text{s} = 1.3554 \text{ ft}^2/\text{hr}$$

$$D_{H_2O-O_2} = 0.4388 \text{ cm}^2/\text{s} = 1.6995 \text{ ft}^2/\text{hr}$$
The diffusivity of the water-dry gas mixture is then evaluated using the expression above for gas mixtures. Thus

\[ D_{\text{H}_2\text{O-mix}} = 1.6546 \text{ ft}^2/\text{hr} \]

Calculation of gas mixture density

The density of a gas mixture may be found using the following expression, which was developed in Appendix C:

\[ \bar{\rho}_m = \frac{\sum y_i MW_i}{\sum y_i \left( \frac{MW_i}{\rho_{m,i}} \right)} \]

Thus the calculation of the average density of the gas mixture yields from the individual gas densities found in Table D.4 the average density of:

\[ \bar{\rho}_m = 0.0540 \text{ lb}_m \text{ mixture/ft}^3 \]

Calculation of gas mixture thermal conductivity

The thermal conductivity of a gas mixture is given by the following equation:

\[ \bar{k} = \frac{\sum y_i k_i (MW_i)^{1/3}}{\sum y_i (MW_i)^{1/3}} \]

Substitution of the respective thermal conductivities presented in Table D.4 into the expression above yields a thermal conductivity of the gas mixture as:

\[ \bar{k} = 0.0184 \text{ BTU/hr-ft-F} \]
**Calculation of gas mixture heat capacity**

The heat capacity of a mixture of gases is determined by using the following expression, which was developed in Appendix C (Experimental Method).

\[
\bar{C}_{P_m} = \frac{\sum y_i MW_i C_{P_m,i}}{\sum y_i MW_i}
\]

Again, substituting the individual gas densities into the equation above yields the heat capacities of the following mixtures:

- \( C_{P_m, \text{ dry gas}} = 0.2432 \text{ BTU/lbm-F} \)
- \( C_{P_m, \text{ wet gas}} = 0.2658 \text{ BTU/lbm-F} \)

**Calculation of the Psychrometric ratio**

The psychrometric ratio is empirically evaluated as:

\[
\left(\frac{h_G}{k_Y}\right) = Cs \left(\frac{Sc}{Pr}\right)^{0.567}
\]

where: \( Cs = C_{P_m, \text{ dry gas}} + Y_{H_2O} C_{P_m, H_2O} \)

and:

\[
\frac{Sc}{Pr} = \frac{k}{\bar{\rho}_m D_{AB} C_{P_m}}
\]

Substitution of the appropriate (wet gas) values calculated above into the expressions shown above yields the psychrometric ratio as a function of the moisture content, as:

\[
\left(\frac{h_G}{k_Y}\right) = 0.2104 + 0.4171 Y_{H_2O}
\]
Calculation of gas stream moisture content

The gas stream moisture content, in a water-free mass basis, may be found using the fundamental equation presented earlier in this development. It is reproduced here for the sake of convenience. Recall that the preceding properties were evaluated assuming the solution value as the initial "guess" of the moisture content.

\[ t_G - t_W = \frac{\lambda_W (Y'_W - Y'_t)}{(h_G/k_\gamma)} \]

Substituting the wet bulb and dry bulb temperature, the latent heat of vaporization at the wet bulb temperature (\(\lambda_W\)), and the saturation moisture content (\(Y\)), presented in Table D.4, as well as the relationship from the psychrometric ratio, into the above equation yields upon solving for \(Y'_t\):

\[ Y_{H_2O} = 0.1048 \text{ lbm}H_2O/\text{lbm dry gas} \]

This value is in good agreement with the (computer-generated) solution value of 0.1046 lbm/lbm dry gas, which was used as the initial "guess" value of the moisture content. The difference in the fourth digit is probably due to round-off errors in hand calculations. Had the calculated moisture content differed from the initial value, the entire process would have been repeated, using the calculated moisture content as the next "guess" value. Convergence is attained quite rapidly in this case, usually within two or three iterations. (As implied above, the experimental gas stream moisture contents were evaluated using a computer. In each case the initial
guess was a moisture content of ten percent, on a water-free mass basis, and in each case convergence was achieved in under five iterations, usually in three.) Consequently, the calculations may be done relatively easily by hand, although it is advantageous to have a programmable calculator or mini-computer available, in terms of accuracy and speed of calculation.

(b) **Gas stream flow rate**

The volumetric and mass flow rates of a gas stream may be readily evaluated from velocity pressure data obtained using a simple pitot traverse, as illustrated in Appendix C (Experimental Method). The average duct velocity is obtained by substituting the average value of velocity pressure, and the gas density at the point of measurement, into the following equation (modified Bernoulli's equation).

\[
\frac{\Delta P}{\rho} + \frac{1}{2}v^2 = 0
\]

Note that accurate evaluation of the gas stream density requires appropriate values of the gas stream temperature and composition.

Upon rearranging, this equation may be used to solve for velocity directly, as:

\[
v = (\frac{2\Delta P}{\rho})^{1/2}
\]

In the event that the units of measurement are English units, the above equations require the use of an additional quantity, the gravitational constant \((g_c)\), which converts pounds force to pounds mass, as shown below.
\[
\frac{\Delta P}{\rho} + \frac{1}{2} \frac{v^2}{g_c} = 0
\]

Thus:

\[
v = \left( \frac{2 \Delta P g_c}{\rho} \right)^{\frac{1}{2}}
\]

The average velocity and density of the gas stream (dryer exhaust; post wet scrubber) at the point of the pitot traverse were 0.705 inches of water and 0.0635 lbm/ft\(^3\), respectively. The value of the gravitational constant is 32.174 (lbm ft/s\(^2\))/lbf. Thus the velocity is calculated as:

\[
v = \left[ 2(0.705 \text{ in H}_2\text{O})(3.613\times10^{-2} \text{ psia/in. H}_2\text{O})(144 \text{ m}^2/\text{ft}^2)/0.0635 \text{ lbm/ft}^2 \right]^{\frac{1}{2}} \times (32.174 \text{ lbm ft/s}^2/\text{lbf})
\]

Or:

\[v = 60.95 \text{ ft/s} = 3657 \text{ ft/min}\]

The volumetric flow rate is found by multiplying the velocity by the cross-sectional area of the duct in question, i.e.,

\[\dot{V} \text{ ft}^3/\text{min} = vA_x = v\pi \left(\frac{D}{2}\right)^2\] (in the case of a circular duct)

The diameter of the wet scrubber exhaust duct of Plant A was 56 inches. Thus:

\[\dot{V} = (3657 \text{ ft/min}) \pi \left(\frac{56/12 \text{ ft}}{2}\right)^2\]

Or:

\[\dot{V} = 62,544 \text{ ft}^3/\text{min}\]

The mass flowrate is easily established by multiplying the volumetric flow rate by the appropriate gas density. Thus:

\[\dot{M}_{\text{wet gas}} = \dot{V} \frac{\rho_{\text{wet gas}}}{\rho_{\text{m,wet gas}}} = (62544 \text{ ft}^3/\text{min})(0.0635 \text{ lbm/ft}^3)\]

Or:

\[\dot{M}_{\text{wet gas}} = 3871 \text{ lbm/min}\]
(c) **Dryer air leakage**

Dryer air leakage is defined in this study in terms of percentage of dry gas flow rate in the boiler exhaust that enters the dryer. It is quite easily determined from the respective carbon dioxide concentrations (on a dry gas basis) of the dryer inlet and exhaust gas streams. Note the following relationship:

\[
\frac{y'_{CO_2, \text{inlet}}}{y'_{CO_2, \text{outlet}}} = \frac{1}{1 + y'_{Air}}
\]

where \(y'\) denotes the mole fraction (or decimal percentage) of carbon dioxide in each gas stream, on a dry-gas or "water-free" basis. This equation may be recast to yield the mole fraction of air in the dryer exhaust, or the decimal percent air leakage into the (dryer) inlet gas stream, as:

\[
y'_{Air} = \frac{y'_{CO_2, \text{inlet}}}{y'_{CO_2, \text{outlet}}} - 1
\]

Using the respective inlet and outlet concentrations for Dryer A from Table D.1, the air leakage into Dryer A may be calculated as:

\[
y'_{Air} = \frac{0.1056 \text{ moles CO}_2/\text{mole Dry Gas; inlet}}{0.0945 \text{ moles CO}_2/\text{mole Dry Gas; outlet}} - 1
\]

Or:

\[
y'_{Air} = 0.1175
\]

Dryer air leakage = 11.75%
(d) **Fuel moisture content**

The dry basis fuel moisture content may be determined using the following relationship:

\[
MC_d = \frac{\text{Mass } H_2O}{\text{Mass bone dry Wood}} \times 100
\]

Using a representative sample from Case A, the dry basis moisture content may be determined as:

\[
MC_d = \frac{86.85 \text{ gr (wet)} - 52.10 \text{ gr (dry)}}{52.10 \text{ gr (dry)}} \times 100
\]

Or: \[MC_d = 66.70\%\]

The wet basis moisture content may be determined through use of either of the following equations shown below.

\[
MC_w = \frac{\text{Mass wet wood} - \text{Mass dry wood}}{\text{Mass dry wood}} \times 100
\]

\[
MC_w = \frac{MC_d}{100 + MC_d}
\]

The conversion of wet basis to dry basis moisture content is shown below for convenience. A plot of MCD versus MCW is presented
in Appendix B, and may be used to convert from one basis to the other.

\[ MC_d = \frac{MC_w}{100 - MC_w} \]

(e) **Heat of formation of dry wood**

The concept of the heat of formation of dry wood is developed in detail in Appendix E, Program Development. The stoichiometric equation for the formation of wood from its constituent elements is written as:

\[ x C(s) + \frac{y}{4} H_2(g) + \frac{z}{2} O_2(g) \rightarrow C_x H_y O_z(s) \]

where \( x, y, \) and \( z \) represent the stoichiometric coefficients derived from the "quasi"-ultimate analysis presented in Appendix E. For the case of Douglas-fir, Leonard (1978), the stoichiometric coefficients are calculated as:

\[
\begin{align*}
\text{x (lb-atoms C/1 lb m dry wood)} &= \frac{0.523 \text{ lb m C/1 lb m D.W.}}{12.01115 \text{ lb m C/1 lb-atom}} = 0.04354 \\
\text{y (lb-atoms H/1 lb m dry wood)} &= \frac{0.063 \text{ lb m H/1 lb m D.W.}}{1.00797 \text{ lb m H/1 lb-atom H}} = 0.06250 \\
\text{y (lb-atoms O/1 lb m dry wood)} &= \frac{0.405 \text{ lb m O/1 lb m D.W.}}{15.9994 \text{ lb m O/1 lb-atom O}} = 0.02531
\end{align*}
\]
The analytical equation developed in Appendix E for the heat of formation of dry wood is as follows:

\[ \Delta h_f \text{ dry wood} = \text{HHV} + \frac{V}{2} (\Delta h_f H_2O(1)) + x (\Delta h_f CO_2(g)) \]

Recall that HHV represents the higher heating value of the fuel as commonly reported in forest products literature. For the case of Douglas fir wood the higher heating value is approximately 9050 BTU/lbm dry wood (Arola 1978). **Note:** The ultimate analyses and higher heating values for various wood species are presented in Appendix B.) Thus the heat of formation may be determined as:

\[ \Delta h_f \text{ dry wood} = 9050 \text{ BTU/lbm dry wood} + \left(\frac{0.06250}{2}\right) \frac{1 \text{ lb-mole } H_2O \text{ formed}}{\text{non dry wood}} \]

\[ \times (-122991.24 \text{ BTU/lb-mole } H_2O(1) \text{ formed}) \]

\[ + (0.04354 \text{ lb-mole } CO_2/\text{lbm dry wood}) \times (-169315.18 \frac{\text{BTU}}{\text{lb-mole } CO_2 \text{ formed}}) \]

\[ \therefore \Delta h_f \text{ dry wood} = -2165.5 \text{ BTU/lbm dry wood} \]

The heat of formation of wet wood, which takes into consideration the heat effects resulting from the sorption of (bound) water, may be determined in a similar manner using the following expression:

\[ \Delta h_f \text{ wet wood} = \Delta h_f \text{ dry wood} + (MC_d)(hsorption) \]

For example, the average heat of sorption for a dry-basis moisture content of 25 percent is -284 BTU/lbm water sorbed, (Smith, 1974). Thus:

\[ \Delta h_f \text{ Wet Wood} = \Delta h_f \text{ Dry Wood} + (0.25 \text{ lbm } H_2O/\text{lbm Dry Wood}) \]

\[ (-284 \text{ BTU/lbm } H_2O \text{ sorbed}) \]
Thus: \[ \Delta h_f \text{ Wet Wood} = -2236.5 \text{ BTU/lb Dry Wood} \]

Note that the difference between the respective heats of formation is minor, on the order of three percent.

(f) Energy "partitioning" within the dryer

The concept of energy "partitioning" within the dryer is a simple accounting procedure used to trace the flow(s) of the energy that enters the dryer in the boiler exhaust gas. This energy may be termed "available energy", and represents that energy contained in the boiler exhaust gas, relative to the ambient temperature; no more energy can be removed from the boiler exhaust, in this case, than that "released" from the gas on cooling it to the ambient temperature. (Likewise, one cannot burn his finger on a cold stove; the fundamental idea is the same.) This accounting of energy "flows" requires the knowledge of fuel and gas stream flows, as well as the ambient temperature and air leakage. Sample calculations of this accounting procedure are summarized in the following pages, using experimental data from Dryer A.

The first step is the determination of the total available energy, relative to the ambient temperature, that is present in the boiler exhaust/dryer inlet stream. This step is summarized in Table D.5. Note that TDI represents the dryer inlet temperature, TAM represents the ambient temperature.

The second step of the evaluation of the respective energy flows is the calculation of the energy that is carried out of the dryer exhaust stream by the boiler exhaust components. Again, the energy is
### TABLE D.5 Total Available Energy in Boiler Exhaust, Relative to the Ambient Temperature

\[ h_i = \frac{\int_{TAM}^{TDI} C_p dT}{TAM} \]

<table>
<thead>
<tr>
<th>Species</th>
<th>(BTU/lb-mole)</th>
<th>( m_i ) (lb-mole/min)</th>
<th>( H_i = m_i h_i ) (BTU/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1122.16</td>
<td>0.11</td>
<td>123.4</td>
</tr>
<tr>
<td>CO₂</td>
<td>600.21</td>
<td>23.08</td>
<td>13,852.9</td>
</tr>
<tr>
<td>H₂O</td>
<td>526.97</td>
<td>38.10</td>
<td>20,077.6</td>
</tr>
<tr>
<td>N₂</td>
<td>453.03</td>
<td>172.55</td>
<td>78,170.3</td>
</tr>
<tr>
<td>O₂</td>
<td>462.93</td>
<td>20.60</td>
<td>9,536.4</td>
</tr>
</tbody>
</table>

Total energy remaining in input gas.....................121,687 BTU/min
Total energy remaining in input gas, as percentage of input...40.29%

### TABLE D.6 Energy Remaining in Input Gas to Dryer at Dryer Exit Conditions

\[ h_i = \frac{\int_{TAM}^{TDE} C_p dT}{TAM} \]

<table>
<thead>
<tr>
<th>Species</th>
<th>(BTU/lb-mole)</th>
<th>( m_i ) (lb-mole/min)</th>
<th>( H_i = m_i h_i ) (BTU/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>453.96</td>
<td>0.11</td>
<td>49.9</td>
</tr>
<tr>
<td>CO₂</td>
<td>600.21</td>
<td>23.08</td>
<td>13,852.9</td>
</tr>
<tr>
<td>H₂O</td>
<td>526.97</td>
<td>38.10</td>
<td>20,077.6</td>
</tr>
<tr>
<td>N₂</td>
<td>453.03</td>
<td>173.55</td>
<td>78,170.3</td>
</tr>
<tr>
<td>O₂</td>
<td>462.93</td>
<td>20.60</td>
<td>9,536.4</td>
</tr>
</tbody>
</table>

Total energy remaining in input gas.....................121,687 BTU/min
Total energy remaining in input gas, as percentage of input...40.29%
relative to the ambient temperature. The energy remaining in the boiler exhaust stream at the dryer exit is summarized in Table D.6. Note that TDE represents the dryer exhaust temperature.

The energy remaining for drying is determined by totalling the energy requirements and losses presented in Tables D.6 and D.7 and subtracting this value from the total available energy shown in Table D.5. The convective, radiative, and conductive losses from the dryer are of minor importance (Blackwell and MacCallum, 1983), and are not considered here. A summary of the energy flows of Dryer A is presented in Table D.8.

The energy actually used for drying, when expressed as the percentage of the total available energy, may be considered to be representative of the thermodynamic efficiency of the drying process, here termed the "drying efficiency". Note that the value of drying efficiency (percent of available energy used for drying) shown in Table D.8 for Dryer A agrees well with literature values of 35 - 65 percent (Sloan, 1967), as do the values presented in Table D.2 for the remaining dryers.
TABLE D.7  Sensible Heat Requirements of Air Leakage and Fuel/Water Streams

\[ h_i = \frac{T_2}{T_1} \int_{T_1}^{T_2} C_p dT \]

<table>
<thead>
<tr>
<th>Species</th>
<th>( h_i ) (BTU/lb-mole)</th>
<th>( m_i ) (lb-moles/min)</th>
<th>( H_i = m_i h_i ) (BTU/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>453.82</td>
<td>25.42</td>
<td>11,536.1</td>
</tr>
<tr>
<td>Wood</td>
<td>5.11</td>
<td>438</td>
<td>2,238.2</td>
</tr>
<tr>
<td>Sorbed</td>
<td>30.00</td>
<td>172.5</td>
<td>5,175.0</td>
</tr>
</tbody>
</table>

Sensible Heat Requirement of air leakage..................11,536.1 BTU/min
Sensible Heat Requirement of air leakage, as percent of input energy.................................3.82%
Sensible Heat Requirement of Wood and Sorbed Water:. 7,413.2 BTU/min
Sensible Heat Requirement of Wood and Sorbed Water, as percent of available energy input to dryer.....2.45%

TABLE D.8  Summary of Energy Flows Within Dryer A

<table>
<thead>
<tr>
<th>Flow</th>
<th>Total Energy of Flow (BTU/min)</th>
<th>% of Available Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available energy in Boiler Exhaust Stream</td>
<td>301,994</td>
<td>100.00</td>
</tr>
<tr>
<td>Energy Remaining in input gas to dryer at dryer exhaust conditions</td>
<td>121,687</td>
<td>40.29</td>
</tr>
<tr>
<td>Sensible heat requirement of dryer air leakage</td>
<td>11,536</td>
<td>3.82</td>
</tr>
<tr>
<td>Sensible heat requirement of wood and sorbed water remaining with wood at dryer exit</td>
<td>7,413</td>
<td>2.45</td>
</tr>
<tr>
<td>Energy remaining for drying</td>
<td>161,358</td>
<td>53.43</td>
</tr>
</tbody>
</table>
Combustion Excess Air from Boiler Exhaust Analysis

As implied by the title of this subsection, the combustion excess air may be determined from the boiler exhaust analysis. In addition, the method presented below also requires the stoichiometric coefficients (from the "quasi"-ultimate analysis) of the combustion equation.

Combustion excess air is most easily defined by noting the following relationship:

$$\text{Excess Air, } \% = \left( \frac{\text{moles } O_2 \text{ fed} - \text{moles } O_2 \text{ theoretically req'd}}{\text{moles } O_2 \text{ theoretically required}} \right)$$

The molar flow rate, on a total basis, of oxygen to the boiler may be calculated using the flow rate of non-reactive nitrogen in the boiler may be calculated using the flow rate of non-reactive nitrogen in the boiler exhaust as a "tie element", and the atmospheric ratio of nitrogen to oxygen. Using the nitrogen flow rate in the boiler exhaust stream of Boiler A (Table D.5), the molar flow rate of oxygen to Boiler A may be calculated as:

$$O_2 \text{ fed} = \frac{172.55 \text{ lb-moles } N_2/\text{min}}{3.7619 \text{ lb-moles } N_2/\text{lb-mole } O_2}$$

Thus: $$O_2 \text{ fed} = 45.87 \text{ lb-moles } O_2/\text{min}.$$  

By noting the molar flow rate or carbon (identical to the molar flow rate of carbon dioxide in the boiler exhaust, if one neglects the minor contribution of carbon monoxide), one may calculate the molar flow rates of the wood component species and the combustion products, thereby accounting for the oxygen, as carbon dioxide, that
originates in the fuel. This involves the use of stoichiometric coefficients as illustrated below.

(i) $\text{lb-moles C fed to boiler} = \text{lb-moles CO}_2 \text{ in boiler exhaust}$

$= 23.08 \text{ lb-moles/min}$

(ii) $\text{lb-moles H fed to boiler in fuel} =$

$(23.08 \text{ lb-atoms C fed}) \times (0.06250 \text{ lb-atom H/lb}_m \text{ dry wood})$

Thus: $\text{lb-moles H fed to boiler in fuel} = 33.13 \text{ lb-moles/min}$

(iii) $\text{lb-moles O fed to boiler in fuel} =$

$(23.08 \text{ lb-atoms C fed}) \times (0.02531 \text{ lb-atoms O/lb}_m \text{ dry wood})$

Thus: $\text{lb-moles O fed to boiler in fuel} = 13.42 \text{ lb-moles/min}$

Through use of the stoichiometric equation shown below, one may calculate the oxygen theoretically required for complete combustion. Note that this approach assumes negligible carbon losses from carry-over (charcoal) and, as previously stated, carbon monoxide. Note also that the coefficients shown below are not precisely those obtained from the "quasi"-ultimate analysis. They are, however, multiples of said coefficients; their relative magnitudes are unchanged.

As follows:

$$C_xH_yO_z(s) + (x + \frac{y}{4} - \frac{z}{2})O_2(g) \rightarrow xCO_2(g) + \frac{y}{2}H_2O$$

Thus: $C_{23.08}H_{33.13}O_{13.42} + n_{\text{th}}O_2 \rightarrow 23.08 \text{CO}_2 + 6.71 \text{H}_2\text{O}$
where \( n_{th} \) is the theoretical molar flow rate of oxygen required for complete combustion, and is equal to:

\[
\begin{align*}
    n_{th} &= (x + \frac{y}{4} - \frac{z}{2}) = (23.08 + \frac{33.13}{4} - \frac{13.42}{2}) \\
    &\quad \text{Thus the theoretical oxygen required is:} \\
    O_2\; th &= 24.65 \text{ lb-moles } O_2/\text{min}
\end{align*}
\]

Thus the combustion excess air is then found by substituting the values of the theoretical oxygen and the actual oxygen fed to the boiler into the defining equation of excess air. Thus:

\[
\text{Excess Air} = 100 \times \frac{\text{45.87 lb-moles } O_2 \text{ fed} - 24.65 \text{ lb-moles } O_2 \text{ req.}}{24.65 \text{ lb-moles } O_2 \text{ req.}}
\]

Thus: Combustion excess air, Boiler A = 86.07%

Note that the numerator of the excess air equation represents the oxygen not used in combustion, and exhausted from the boiler. The value of the numerator above is equal to 21.22 lb-moles oxygen/min, which compares favorably with the flow rate of 20.60 lb-moles oxygen/min found in Table D.5, differing by roughly three percent.

(h) **Total Fuel Flow Rate to Boiler from Boiler Exhaust Exchange Analysis**

The total fuel flow rate to the boiler may be obtained via carbon balance, using the carbon dioxide flow rate in the boiler ex-
haust, assuming negligible contributions from carryover and carbon monoxide.

The flow rate of carbon through Boiler A is determined as follows, using flow rate data presented in Table D.5.

(i) The flow rate of gaseous carbon (as carbon dioxide) is given as 23.08 lb-moles CO₂/min

(ii) The mass flow rate of carbon through the boiler is calculated as:

\[
\text{Mass Flow}_{\text{carbon}} = (23.08 \text{ lb-moles C (CO₂)/min}) \\
\times (12.01115 \text{ lbm C/lb-mole C})
\]

Thus:

\[
\text{Mass Flow}_{\text{carbon}} = 277.22 \text{ lbm C/min}
\]

(iii) By using the ultimate analysis carbon value for a 50/50 wood/bark mixture of Douglas-fir, the total fuel flow rate to the boiler may be calculated as:

\[
\text{Mass Flow}_{\text{dry wood}} = \frac{277.22 \text{ lbm C/min}}{0.523 \text{ lbm C/lb dry wood}}
\]

Thus:

\[
\text{Mass Flow}_{\text{dry wood}} = 530.05 \text{ lbm/min (31800 lbm/hr)}
\]

Remarks

One can learn much about the operation of a process, in this case a boiler/dryer system, from appropriate use of easily-measured
quantities such as flow rates, temperatures and compositions, as illustrated in the examples above. The techniques of measurement and subsequent calculation are relatively straight-forward; the methods are fairly reliable.

The examples shown above also further illustrate the utility in using the concepts of mass and energy conservation fundamental to the first law of thermodynamics so stressed in Appendix E (Program Development) in common engineering practice. The examples also illustrate the usefulness of the "black box" or control volume concept in the analysis of a process system.
APPENDIX E

SIMULATION PROGRAM DEVELOPMENT

Introduction

As stated in the text, one of the objectives of this study was to develop a process simulation model for the boiler/dryer system. Two process simulation models/programs were developed, SIM1 and SIM2, differing only in the treatment of the material and energy balances in the dryer section (these differences are covered in detail later in the development of each program). Both models/programs were used for comparative purposes in the Case Studies Section of the text, and both were used for sensitivity studies, discussed in the Performance Trends Section of the text.

A block diagram representative of the boiler/dryer system and the accompanying streams is shown in Figure E.1. Brief descriptions of the process streams and variable names and descriptions are listed in Table E.1. Note that the variable names listed are identical to the FORTRAN variables used in the simulation programs, and represent the same quantities. Other variables not listed appear throughout the course of the program development. These, too, are FORTRAN. (The use of a single name for both the variables used in the development of the material and energy balances, and the corresponding
Figure E.1 Process flow diagram of general boiler/dryer system
Table E.1  Descriptions of the Process Streams and Variables of the General Boiler/Dryer System Shown in Figure 1

<table>
<thead>
<tr>
<th>Stream</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>wet (wood waste) fuel that is fed directly to the dryer</td>
</tr>
<tr>
<td>2</td>
<td>wet fuel that bypasses the dryer and is fed to the boiler</td>
</tr>
<tr>
<td>3</td>
<td>dry fuel that exits the dryer and is fed to the boiler</td>
</tr>
<tr>
<td>4</td>
<td>combustion air</td>
</tr>
<tr>
<td>5</td>
<td>boiler exhaust</td>
</tr>
<tr>
<td>6</td>
<td>air leakage into the dryer</td>
</tr>
<tr>
<td>7</td>
<td>dryer exhaust</td>
</tr>
<tr>
<td>Qsteam</td>
<td>steam demand of the boiler</td>
</tr>
<tr>
<td>Qheat</td>
<td>radiative, conductive and convective losses from the boiler</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALF</td>
<td>Air leakage factor, expressed as decimal percent of the dry gas that enters the dryer in the boiler exhaust</td>
</tr>
<tr>
<td>EA</td>
<td>Combustion excess air (decimal percent)</td>
</tr>
<tr>
<td>FFRD1</td>
<td>Fuel flow rate, bone-dry, stream 1</td>
</tr>
<tr>
<td>FFRD2</td>
<td>Fuel flow rate, bone-dry, stream 2</td>
</tr>
<tr>
<td>FFRD3</td>
<td>Fuel flow rate, bone-dry, stream 3</td>
</tr>
<tr>
<td>FHR</td>
<td>Ambient humidity ratio (lbs water/lb dry air)</td>
</tr>
<tr>
<td>FR</td>
<td>Feed ratio, defined as the ratio of the dryer feed flow rate to the dryer bypass flow rate</td>
</tr>
<tr>
<td>FMCD1</td>
<td>Fuel moisture content (dry basis), stream 1 (dryer inlet) (decimal percentage)</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>FMCD2</td>
<td>Fuel moisture content (dry basis), stream 2 (dryer bypass) (decimal percent)</td>
</tr>
<tr>
<td>FMCD3</td>
<td>Fuel moisture content (dry basis), stream 3 (dryer exit) (decimal percent)</td>
</tr>
<tr>
<td>HHV</td>
<td>Fuel higher heating value (BTU/lb dry wood)</td>
</tr>
<tr>
<td>HTLF</td>
<td>Boiler heat loss factor, expressed as a percentage of the fuel higher heating value</td>
</tr>
<tr>
<td>HTLOSSB</td>
<td>Boiler heat loss (BTU/hour)</td>
</tr>
<tr>
<td>PCTCL</td>
<td>Percent carbon loss, expressed as a percentage of the fuel ultimate analysis carbon</td>
</tr>
<tr>
<td>PCT1</td>
<td>Percent of the total available energy in the boiler exhaust that is used for drying</td>
</tr>
<tr>
<td>PCT2</td>
<td>Percent of the total available energy in the boiler exhaust that is used to heat the (wood waste) fuel, and the water contained in the fuel at the dryer exit, from the entrance to the exit temperature of the dryer</td>
</tr>
<tr>
<td>TAM</td>
<td>Ambient temperature (°F)</td>
</tr>
<tr>
<td>TBE</td>
<td>Boiler exhaust temperature (°F)</td>
</tr>
<tr>
<td>TDE</td>
<td>Dryer exhaust temperature (°F)</td>
</tr>
<tr>
<td>TDI</td>
<td>Dryer inlet temperature (usually assumed to be the boiler exhaust temperature) (°F)</td>
</tr>
<tr>
<td>TF1</td>
<td>Dryer inlet fuel temperature (°F)</td>
</tr>
<tr>
<td>TF2</td>
<td>Bypass stream fuel temperature (°F)</td>
</tr>
<tr>
<td>TF3</td>
<td>Dryer exit fuel temperature (°F)</td>
</tr>
<tr>
<td>QSTEAM</td>
<td>Boiler steam demand (BTU/hour)</td>
</tr>
<tr>
<td>ULTC</td>
<td>Ultimate analysis carbon (lbs carbon/lb dry wood)</td>
</tr>
<tr>
<td>ULTH</td>
<td>Ultimate analysis hydrogen (lbs hydrogen/lb dry wood)</td>
</tr>
<tr>
<td>ULTO</td>
<td>Ultimate analysis oxygen (lbs oxygen/lb dry wood)</td>
</tr>
</tbody>
</table>
variables in the simulation programs simplifies the development of each and eliminates confusion.)

Both models were developed to provide an accurate as possible representation of the boiler/dryer system, one that would be useful in particular to the forest products industry. The principle objective in the creation of both models was to develop a computer program that would take user-specified values of operational parameters and constraints as input, and provide useful process information, in particular the reduction of fuel moisture content resulting from the use of a rotary dryer, and the fuel consumption and efficiency of the boiler. Consequently, the solution variables chosen were (1) the fuel moisture content, dry basis, at the dryer exit (FMCD3) and, (2) the (oven-dry) fuel flow rate passing through the dryer (FFRD3). (Casual inspection of the block diagram in Figure E.1 immediately proposes the use of two equations to model the boiler/dryer system, those being the overall energy balances of each, the boiler and the dryer. Two equations require two unknowns for solution; the solution variables mentioned above appeared to be adequate choices for the two unknowns.)

The operational parameters were chosen under the assumption that the user would have knowledge of the operating characteristics peculiar to the boiler under study. These operational parameters are the following:

* Boiler steam demand, in energy terms (QSTEAM)
* Boiler exhaust temperature, after final heating surface (TBE)

* Combustion excess air (EA)

* Boiler heat losses, expressed as a percentage of the higher heating value of the fuel (available from the boiler manufacturer) (HTLF)

* Carbon losses (carryover), expressed as a percentage of the ultimate analysis carbon (PCTCL)

The fixed constraints of operation were considered in this study to be the following:

* Ambient temperature (TAM)

* Ambient humidity ratio (FHR)

* Stockpile fuel moisture content, dry basis (FMCD1)

* Stockpile fuel temperature (usually assumed to be the ambient temperature) (TF1)

* Fuel ultimate analysis (ULTC, ULTH, ULTO)

* Fuel higher heating value (HHV)

(Literature values for the fuel ultimate analysis (carbon, hydrogen, and oxygen) and the fuel higher heating value for various species of wood may be found in Appendix B.)

Other parameters required by the simulation program that must be estimated or set by the user concern primarily the dryer. These are the following:

* Dryer inlet temperature (usually assumed to be equal to the boiler exhaust temperature) (TDI)
* Dryer exhaust temperature - user-specified - SIM 1 (TDE)
* Fuel temperature, dryer exit - user-specified - SIM 1 (TF3)
* Dryer thermodynamic efficiency - user-specified - SIM 2 (PCT1)
* Dryer air leakage, expressed as percent of the dry gas flow rate to the dryer from the boiler (ALF)
* Feed ratio (the ratio of the fuel flow rate entering the dryer to the fuel flow rate bypassing the dryer) (FR)

In addition to the solution variables, both programs output the following:

* Boiler efficiency
* Total fuel flow rate to the boiler
* Bypass fuel flow rate
* Fuel savings resulting from the installation of a dryer
* All gas stream flow rates and humidities
* Dryer exhaust temperature - calculated - SIM 2
* Fuel temperature, dryer exit - calculated - SIM 2

The various flow rates and their respective properties are calculated for both "without dryer" and "with dryer" cases, were applicable. In addition, the percent change, relative to the "without dryer" case, in flows and properties are calculated and appear in the output of each program.

The assumptions used in each program are the following:
* Quantities are input and output using the English system of units
* Moisture contents are used as dry basis
* The process is essentially steady-state
* The fuel is composed entirely of wood waste (wood and bark)
* Carbon exiting the boiler appears in two forms: Charcoal and CO₂

As previously implied, both simulation programs use typical material and energy balances to develop two overall energy equations, one each for the boiler and the dryer. The equations developed are nonlinear in nature, and require an iterative-type solution technique. The development of these equations and the techniques of solution are discussed in detail later in this section. Brief flow charts for each of the programs are presented at the end of this section with program listings and sample output.

**Preliminary Concepts**

Before proceeding with the rigorous development of the material and energy balances of the boiler/dryer system it is appropriate to develop some of the concepts used in the ensuing analysis. Once these preliminary concepts have been established, the remaining development should proceed smoothly, allowing the reader to refer back to one location should questions arise.
(a) **Basis of Calculation**

The time basis of calculation of the material and energy flows in this analysis is one hour, in accordance with the convention of expressing boiler capacity in terms of pounds of steam per hour.

The respective flows, both molar and mass, are expressed in terms of dry wood flow rate. For example, the combustion air flow rate is expressed in terms of total fuel flow rate (bone-dry) to the boiler (and of course the stated excess air), which is ultimately written in terms of the dry wood flow rate through the dryer. (See the ensuing discussion concerning the "Feed Ratio".)

(b) **Feed Ratio (FR)**

Referring to Figure E.1 one notes that the fuel stream entering the boiler is composed of two essentially separate flows: (1) the dry wood flow exiting the dryer, and (2) the (wet) bypass or blend stream. The addition of the bypass stream to the boiler/dryer system does lend to the versatility of the model, yet requires a third variable to be calculated or specified, unless that variable can be specified in terms of another variable that would exist regardless of the existance of the blend stream.

The latter option is decidedly the simplest method to use, hence the development of the "feed ratio" which implicitly specifies the flow rate (bone-dry) of the bypass stream in terms of the flow rate passing through the dryer. The feed ratio is given as:

\[
\text{Feed Ratio (FR)} = \frac{\text{Fuel flow rate through the dryer (FFRD3)}}{\text{Bypass fuel flow rate (FFRD2)}}
\]

The flow rate of the bypass stream may then be represented in terms
of the flow rate through the dryer as:  \( \text{FFRD2} = \frac{\text{FFRD3}}{\text{FR}} \)

The total fuel flow to the boiler (\( \text{FFRDT} \)) may be described as follows:

\[
\text{FFRDT} = \text{FFRD2} + \text{FFRD3} = \frac{\text{FFRD3}}{\text{FR}} + \text{FFRD3}
\]

Thus:

\[
\text{FFRDT} = \frac{(\text{FR} + 1)}{\text{FR}} \cdot \text{FFRD3}
\]

Note that in each case, the flows are written in terms of the solution variable \( \text{FFRD3} \). This is quite useful in both the development and actual programming of the models. Note also that the boiler/dryer system can be modeled assuming only one input fuel stream simply by setting the feed ratio equal to a large number, such as 10,000.

(c) "Quasi"-Ultimate Analysis

One of the more common methods of expressing the composition of a fuel, in this case wood waste, is through the use of the ultimate analysis. The ultimate analysis yields the respective contribution of each of the components of the fuel in terms of mass percent. For example, the ultimate analysis of Douglas-fir yields a carbon composition of 52.3 percent, or 0.523 pounds of carbon per pound bone-dry wood.

For the purposes of this study, however, it is handier to express the wood composition as a molar composition. The heat capacities of the combustion gases are most commonly presented as molar heat capacities. Even though they can be easily converted to the mass basis, it was thought to be more efficient, if only in terms of
programming, to convert the mass flows of the wood components to molar flows, and use the heat capacities of the combustion and related gases as found in the literature. Use of the "quasi"-ultimate analysis also lends itself to the development of the heat of formation of dry wood (to be covered later), maintaining the standard conventions of calorimetric data.

The "quasi"-ultimate analysis is quite easily derived by dividing the ultimate analysis by the molecular weight of the species in question. For example, the "quasi"-ultimate analysis of the components of interest to this study (carbon, hydrogen, and oxygen) may be determined as:

- \[ X \text{ (lb-atoms Carbon/lbm)} = \frac{\text{ULTC}}{12.01115 \text{ lbm}} \]
- \[ Y \text{ (lb-atoms Hydrogen/lbm dry wood)} = \frac{\text{ULTH}}{1.00797 \text{ lbm}} \]
- \[ Z \text{ (lb-atoms Oxygen/lbm dry wood)} = \frac{\text{ULTO}}{15.9994 \text{ lbm}} \]

(Note that ULTC, ULTH, and ULTO are the ultimate analysis values for carbon, hydrogen, and oxygen, expressed as decimal percent. They are also Fortran variables representing the same quantities, as X, Y, and Z are the Fortran equivalents of the "quasi"-ultimate analyses.)

(d) The First Law of Thermodynamics and the Control Volume

This section is presented as a brief refresher to those readers with some background in engineering thermodynamics. It is also fundamental to the "black box" analysis used in the development of the
material and energy balances of the boiler/dryer system (and also to the experimental material and energy balances found in Appendices C and D.)

Simply put, the first law of thermodynamics states that both mass and energy are conserved quantities. That is to say, that in any process (with the possible exception of a nuclear reaction) neither mass nor energy are created or destroyed. As applied to a boiler, for example, all the fuel that enters the boiler also exits the boiler, either as stack gas or ash. Although the fuel exits the boiler in a different form than it entered, it does not matter—the mass remains the same. Similarly, energy is conserved within the confines of the boiler. Although it would appear that energy is "created" in the boiler, it actually is "contained" within the chemical bonds of the molecules that make up the fuel, and is "released" during the combustion process. This energy then exits the boiler in the process steam, the stack gas, or in the radiative, convective, and conductive losses. Again, although the form has changed, the energy remains the same.

Carrying this example a bit farther, consider the boiler section of Figure E.1. This "box" is nothing more than an abstract representation of the boiler, the confines of which may be termed the "control volume" representing the actual boiler. If one assumes that the boiler is operated such that the steam demand is constant with time (not a bad assumption), and that the fuel flow rate and condition are relatively constant, in addition to the combustion air flow
rate, one may categorize the boiler as a "steady-state, steady-flow" process. Again, all the fuel (mass) and energy that enters the boiler control volume exits the boiler control volume, in one form or another. Furthermore, fundamental to the steady-state, steady-flow process is the assumption that the "internal energy" within the control volume remains constant with time. In other words, the boiler remains at a relatively constant temperature over time, and there is no net accumulation or depletion of "fuel" within the boiler.

The concepts of the control volume and the steady-state, steady-flow assumption are very useful tools in the analysis of any continuous process. One need not "get into the boiler" to analyze the combustion of fuel (in terms of material and energy flows), as the processes occurring within the boiler, as stated previously, are constant with time. One simply need examine the material and energy flows of the streams crossing the boundaries of the control volume to "analyze" what is happening inside.

The first law of thermodynamics for a general flow process is shown below:

\[
\delta Q_{cv} - \dot{W}_{cv} + (\Sigma h_i m_i)_{in} - (\Sigma h_j m_j)_{out} = \frac{d(mU)}{dt}_{cv}
\]

where: \(\delta Q_{cv}\) is the rate of "heat" flow to or from the control volume (by convention, the "heat" leaving the control volume is negative in sign; "heat" entering is positive)
\( \delta W_{cv} \) is the rate of work done by or on the control volume (by convention, work done by the control volume is positive in sign; work done on the control volume is negative)

\( m_{i,j} \) is the mass (or molar) flow rates of species \( i \) or \( j \) that cross the boundaries of the control volume

\( h_{i,j} \) is the "enthalpy", or energy, relative to an established reference state, that is "contained" by species \( i \) or \( j \)

\( (mU)_{cv} \) is the "internal energy" contained within the control volume

Under the assumption of a steady-state, steady-flow process, and also assuming that no work is done on or by the control volume (as in the case of both the boiler and the dryer) the first law equation may be reduced to the following equation:

\[
\delta Q_{cv} + (\Sigma h_i m_i)_{in} - (\Sigma h_j m_j)_{out} = 0
\]

The material and energy balances for both the boiler and the dryer ultimately lead to the two equations of the form shown above. The material balances are required for the total energy balances; consequently, they appear implicitly in the overall energy balances used to model the boiler/dryer system.

(e) Reference Temperature and the Heat of Formation of Dry Wood

The concept of enthalpy was briefly touched upon in the previous section. Enthalpy can be expressed in several forms, although in
this study it appears in principally two forms: (1) sensible heat, and latent heats (i.e. vaporization), representing the heat effects of changes in the state of a system or species, such as the heat effects of change in temperature, and, (2) the "chemical" energy which represents the heat effects of changes in the chemical composition of a system or species (for example, the "higher heating value" of a fuel is essentially the heat effect resulting from the combustion of said fuel; it is in essence the (negative of the) "enthalpy of combustion" measured at a standard, or reference temperature (more on this later).

Sensible heat may be most easily defined by the following expression:

$$h_{p,i} = \int C_{p,i} \, dT$$

$C_{p,i}$ represents the heat capacity of species $i$, and is usually dependent on temperature, hence its placement inside the integral sign. (Conversely, the heat capacity of species $i$ at a particular temperature may be represented in general as:

$$C_{p,i} \ T = (\frac{dh}{dT})_p \ T$$

the $p$ subscript on the derivative indicating "at constant pressure"; the $T$ subscript indicating that the derivative, ergo the heat capacity, is evaluated at that temperature.)

Note that enthalpy is a somewhat intangible quantity, and cannot be assigned a definite, or absolute value (one can't collect a pound of enthalpy in a bucket, for example.) The quantification of enthalpy requires that one establish a point of reference (i.e., a
reference temperature) as a point of zero enthalpy, thus measuring the enthalpy relative to that zero point (thus, if one has two buckets, each containing enthalpy, and places them both on a beam balance, one can only measure the difference in the enthalpy contained by the respective buckets.)

The form of enthalpy that is characterized by changes in the chemical makeup of a species or system may be illustrated by the combustion of carbon:

\[
C(s) + O_2(g) \rightarrow CO_2(g) \quad \Delta h_f^{25°C} = -169315 \text{ BTU/lb-mole CO}_2
\]

Shown above is the stoichiometric equation for the combustion of carbon, or the formation of carbon dioxide. The value listed to the right of the equation is the "heat of formation of carbon dioxide (and also the heat of combustion of carbon) at one atmosphere pressure and 25°C (77°F)". The heat of formation represents, by convention, the heat released or absorbed in the formation of a molecular species, in this case carbon dioxide, from its constituent elements at the standard states (calorimetric convention) mentioned above. Heat is released in the formation of carbon dioxide, consequently the heat of formation is presented as a negative quantity. This is in accordance with thermodynamic convention that heat released by the formation of a chemical species (which may be assumed to be the system in question) is considered a negative quantity. Likewise, heat absorbed by formation is considered to be positive. The heat of formation, as well as the heat of reaction, of any chemical species may be calculated, and need not be measured, by knowledge of the
heats of formation (or reaction) of the component species in the stoichiometric equation. This calculation requires the use of "Hess' Law of Summation" (see any good thermodynamics text.) Perhaps the easiest way to illustrate the above concept is through the following example, the "heat of formation of dry wood."

Although wood is composed of a multitude of chemical species, it may be modeled as one "chemical" through the use of the "quasi"-ultimate analysis (presented previously, the use of which is further substantiated here) of the major component elements. In addition, one has at easy access the values of the higher heating value (HHV) of the fuel in question. Higher heating value is commonly reported as a positive quantity when in actuality it is the "heat of combustion" of the said fuel and is, by thermodynamic convention, a negative quantity. Of further note, the "higher" in the higher heating value results from the assumption that the water formed in the combustion process is present in the liquid state (the latent heat of vaporization is "released" from the system with the condensation of water, yielding a "higher" value than if the water remained as vapor.)

With the above ideas in mind, one may write the combustion of wood as a chemical species as:

\[
C_xH_yO_z(s) + (x + \frac{Y}{4} - \frac{Z}{2}) O_2 \rightarrow xCO_2(g) + \frac{Y}{2} H_2O(l) \Delta h_c \text{\textdegree } C \text{ DW } (-HHV)
\]

The determination of the heat of formation of dry wood proceeds by writing the equations for the formation of the combustion products of water and carbon dioxide (by convention, the heat of formation of
the elements as they exist in nature is assumed to be zero):

\[ C_xH_yO_z(s) + (x + \frac{y}{4} - \frac{z}{2}) O_2(g) \rightarrow xCO_2(g) + \frac{y}{2} H_2O(l) \quad -HHV \]

\[ \frac{y}{2} H_2O(l) \rightarrow \frac{y}{2} H_2(g) + \frac{y}{4} O_2(g) \quad \frac{y}{2} (-\Delta h_f H_2O(1)) \]

\[ xCO_2(g) + xC(s) + xO_2(g) \quad x (-\Delta h_f CO_2(g)) \]

These equations may be "summed" in the same manner that one would total three algebraic equations, yielding the following stoichiometric equation:

\[ C_xH_yO_z(s) \rightarrow xC(s) + \frac{y}{4} H_2(g) + \frac{z}{2} O_2(g); \]

\[ \Delta h_f dry\ wood = HHV + \frac{y}{2} (-\Delta h_f H_2O(1)) + x(-\Delta h_f CO_2(g)) \]

Ultimately, the heat of formation of dry wood is obtained by writing the above equation and the accompanying heat effect in reverse. (Note that this is the same procedure used in the development of this equation; the formation equations were written as "de-formation" equations, also switching the signs on the respective heats of formation.) The final equation is as follows:

\[ xC(s) + \frac{y}{4} H_2(g) + \frac{z}{2} O_2(s) \rightarrow C_xH_yO_z(s) \quad \Delta h_f Dry\ Wood \]

where:

\[ \Delta h_f Dry\ Wood = HHV + \frac{y}{2} (-\Delta h_f H_2O(1)) + x(-\Delta h_f CO_2(g)) \]

Note that the heat of formation is calculated on a per mass dry wood basis, in accord with the "quasi"-ultimate analysis values in terms of pound-moles (component) per pound dry wood.

The concept of heat of formation may be carried one step further in the case of wood when one considers the heat of sorption of wood. The heat of sorption is the heat effect resulting from the absorption
of water, sometimes referred to as "bound" water, below the fiber saturation point of wood. Water in this state is held by the fibrous component of the wood through formation of hydrogen bonds between the bound water and the hydroxyl groups of the cellulosic material, and requires additional energy above the latent heat of vaporization for its removal from the wood. To account for this albeit minor heat effect, the concept of the "heat of formation of wet wood" is presented.

In the same manner used above, the heat of formation of wet wood may be determined by examining the following equations:

\[ xC(s) + \frac{y}{4} H_2(g) + \frac{z}{2} O_2(g) \rightarrow C_xH_yO_z(s) + \Delta h_f \text{ Dry Wood} \]

\[ C_xH_yO_z(s) + n H_2O(1) \rightarrow C_xH_yO_z:nH_2O \]

\[ (\Delta h_{\text{sorption}}) \]

thus:

\[ xC(s) + \frac{y}{4} H_2(g) + \frac{z}{2} O_2(g) + n H_2O(1) \rightarrow C_xH_yO_z:nH_2O \]

\[ \Delta h_f \text{ Wet Wood} \]

The magnitude of the heat of sorption is dependent on the moisture content of the wood, increasing nonlinearly as the moisture content decreases. Two average values are used for the heat of sorption in this study: (1) -354 BTU per pound of water sorbed, for the wet basis moisture content range of 0 to 10 percent, and, (2) -284 BTU per pound of water sorbed for the moisture content range of 10 to 20 percent (Smith, 1974). No heat effects from sorption are observed above the fiber saturation point moisture content of approximately twenty percent, wet basis.
No doubt the reader is by now wondering "So how does this heat of formation business fit into this study?" The explanation is forthcoming.

The concept of the first law of thermodynamics for a flow process was developed in the preceding pages, subsequently followed by the concept of enthalpy, which was shown to exist in at least two forms, sensible heat and heat of formation. Concurrent with the development of the concept of enthalpy was the establishment of the use of a reference temperature as a "yardstick" by which the changes in state and composition of a system are measured.

The culmination of these ideas is the use of the "black box" concept in the modeling and measurement of flow processes. One need not trace the path of the process throughout its course. One may describe the process solely in terms of the input and output flows and respective enthalpies, noting that enthalpy is a "state function" and independent of path. The same holds true in the case of a reacting process, providing that both the input and output (reactant and product) enthalpies are referenced to the same state. In this case, the reference state is "the elements at 25 °C", hence the development of the heats of formation (from the component elements) of dry and wet wood. In the reacting process, the respective input and output total enthalpies are the combination of both the heat of formation and the sensible heat, relative to the same temperature.

The utility and validity of the first law approach to the evaluation of a flow process cannot be over-emphasized. As space (and
time) is limited in this report, it is suggested that the reader obtain a good thermodynamics text and examine the use of the first law in detail. Two highly recommended texts are Smith and Van Ness (1975) and Van Wylen and Sonntag (1978).

Material and Energy Balances

As previously stated, the analysis of the boiler/dryer system involves the development of material and energy balance for both the boiler and dryer, ultimately leading to a first law-type equation for each of the respective components. These equations are developed within this section, including a detailed account of the differences between the two models/programs used in this study. As a reminder, the bases of calculation are the following:

* per hour of operation
* thermodynamic quantities relative to the elements at 25 °C (77 °F)
* gas stream component flows in terms of bone-dry wood flow rates

(a) Boiler Material and Energy Balances

The boiler material and energy balances developed in the following pages consider the contributions of four independent streams. They are:

* Fuel feed stream from dryer (Input)
* Blend or bypass fuel stream (Input)
* Combustion air stream (Input)
* Boiler exhaust stream (Output)

In addition to the material and energy contributions listed above, two energy flows are considered (although they do not appear in the energy "balance sheets", they are nonetheless considered in the final overall energy equation for the boiler). They are:

* Boiler steam load or demand
* Boiler heat losses (convective, conductive, and radiative losses)

Before proceeding with the development of the boiler material and energy balances, it is appropriate to develop the quantities of EA, O2REQ, O2FED, N2FED, AIRFED, and H2OFED, which appear in both the boiler and dryer material and energy balances.

Combustion excess air (EA) effectively establishes the flow rate of combustion air to the boiler in terms of the oven-dry fuel flow rate to the boiler. Excess air is conventionally defined as (in terms of decimal percentage):

$$EA = \frac{O_2 \text{ fed to boiler (O2FED)} - O_2 \text{ theoretically required (O2REQ)}}{O_2 \text{ theoretically required}}$$

(Excess air may also be referred to as excess oxygen; both quantities are equal and represent the same thing.)

Theoretical oxygen (O2REQ) is determined through examination of the stoichiometric equation describing combustion, and is defined as the "moles of oxygen theoretically required for complete combustion of the fuel to the combustion products of water and carbon dioxide".
Consider again the stoichiometric equation for (complete) combustion:

\[ C_xH_yO_z(s) + (x + \frac{y}{4} - \frac{z}{2}) O_2(g) + xCO_2(g) + \frac{y}{2} H_2O(g) \]

The theoretical oxygen required is shown above as the stoichiometric coefficient of oxygen, and, in this case, is in units of "pound-moles of oxygen (theoretically required) per pound of oven-dry wood". Once the theoretical oxygen is established, it becomes an easy matter to calculate the oxygen fed to the boiler, in terms of the dry wood flow rate to the boiler, after assuming a value (decimal percentage) for the excess air, by simple rearrangement of the defining equation of excess air. Thus:

\[ O_2\text{FED} = (1 + EA) O_2\text{REQ} \quad \text{(lb-moles } O_2/\text{lb}_m \text{ Dry Wood)} \]

The nitrogen flow rate to the boiler is then readily established by noting that the ratio of nitrogen to oxygen in the atmosphere is a set, known value; thus,

\[ N_2\text{FED} = 3.7619 \times O_2\text{FED} \quad \text{(lb-moles } N_2/\text{lb}_m \text{ Dry Wood)} \]

Subsequently, the ambient water fed to the boiler with the combustion air is calculated by noting the ratio of moles of air to moles of oxygen in the atmosphere, and the ambient humidity ratio (FHR) (lb\text{m} H_2O/\text{lb}_m \text{ dry air}). Thus:

\[ \text{AIRFED} = 4.7619 \times O_2\text{FED} \quad \text{(lb-moles air/\text{lb}_m \text{ Dry Wood)} } \]

\[ \text{H2OFED} = \text{AIRFED} \left( \frac{29.0 \text{ lb}_m \text{ air/\text{lb-mole air}}}{18.016 \text{ lb}_m H_2O/\text{lb-mole H}_2O} \right) (\text{lb-moles } H_2O/\text{lb}_m \text{ dry wood}) \]

With the above information firmly in mind, one may proceed with the ensuing material and energy balances.
(1) **Boiler material balances**

The material and energy balances are most easily established through the use of a "balance sheet" approach not dissimilar to the balance sheets used by accountants. This approach summarizes the flows of each of the species or components (and the enthalpic contributions of each, in the case of energy balances), totalling the individual contributions as one proceeds down each column and to the right. The utility of this approach is basically one of record-keeping; each component, and its contribution to the whole, is accounted for, decreasing the prospect of its becoming lost in the jumble of a "standard" equation or balance.

All the material and energy balances presented in this manner are presented as both inputs and outputs; a total of eight such "balance sheets" are found in this and the ensuing sections.

In an effort to eliminate confusion concerning several of the flows listed in the boiler material balances, as well as the following material and energy balances, recall for a moment the concept of the feed ratio and the basis by which the combustion oxygen/nitrogen flow rates are established. The combustion oxygen flow rate, for example, is given in terms of "pound-moles of oxygen fed to the boiler per pound of dry fuel (fed to the boiler)". Consequently, the determination of the total flow of oxygen to the boiler requires a value for the total fuel flow rate to the boiler. Recall that the total fuel flow rate to the boiler is written in terms of the flow rate of dry wood passing through the dryer. Albeit redundant, these
relationships are shown below for the simple purpose of clarification.

The total fuel flow to the boiler, composed of two streams, may be written as:

\[ FFRDT = FFRD2 + FFRD3 = \left(\frac{FR+1}{FR}\right)FFRD3 \text{ (lb\,m dry wood/hr)} \]

Thus the total flow rate of oxygen to the boiler is written as:

\[ \text{Total Oxygen Flow to Boiler} = \frac{FR+1}{FR} \text{ FFRD3 lb DW \hr} \left(0.2\text{FED lb-moles} \text{ DW} \text{ O}_2 \right) \]

The boiler material balances are shown in Figures E-2 (Input to boiler) and E-3 (Output streams).

(2) Boiler Energy Balances

The boiler energy balances are written in much the same fashion as the material balances, and are presented in Figures E-4 (Input) and E-5 (Output). (Note: The heat capacity equations and heats of formation for each component may be found in Appendix D.)

The total energy balance about the boiler forms the first of the two equations describing the boiler/dryer system. This equation is essentially the first law equation with respect to the boiler, and is of the following form:

\[ \delta Q_{\text{Steam}} + \delta Q_{\text{Heat Loss}} + \dot{H}_{\text{Input}} - \dot{H}_{\text{Output}} = 0 \]

where:

\[ \delta Q_{\text{Steam}} \text{ is the specified steam demand of the boiler, in terms of energy} \]

\[ \delta Q_{\text{heat loss}} \text{ is the sum total of the convective, radiative, and conductive losses from the boiler} \]
**Basis:** per hour of operation

<table>
<thead>
<tr>
<th>Species</th>
<th>Wood (lbₘ)</th>
<th>O₂ (lb-moles)</th>
<th>N₂ (lb-moles)</th>
<th>H₂O (lb-moles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood - Stream 2</td>
<td>(\text{FFRD}_3) (\frac{\text{FR}}{\text{FR}})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water - Stream 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>((\text{FFRD}_3) (\frac{\text{FMCD}_2}{18.016}))</td>
</tr>
<tr>
<td>Wood - Stream 3</td>
<td>(\text{FFRD}_3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water - Stream 3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>((\text{FFRD}_3) (\frac{\text{FMCD}_3}{18.016}))</td>
</tr>
<tr>
<td>Combustion Air</td>
<td>-</td>
<td>(\text{FFRD}_3) (\frac{\text{FR}+1}{\text{FR}})(02FED)</td>
<td>(\text{FFRD}_3) (\frac{\text{FR}+1}{\text{FR}})(N2FED)</td>
<td>(\text{FFRD}_3) (\frac{\text{FR}+1}{\text{FR}})(H2OFED)</td>
</tr>
</tbody>
</table>

**Total Input Flow Rates:**

- **Wood:** \(\text{FFRD}_3 + \frac{\text{FFRD}_3}{\text{FR}} = \text{FFRD}_3\) \(\frac{\text{FR}+1}{\text{FR}}\) (lbₘ dry wood/hr)  
- **O₂:** \(\text{FFRD}_3\) \(\frac{\text{FR}+1}{\text{FR}}\)(02FED) (lb-moles O₂/hr)  
- **N₂:** \(\text{FFRDE}\) \(\frac{\text{FR}+1}{\text{FR}}\)(N2FED) (lb-moles N₂/hr)  
- **H₂O:** \(\text{FFRD}_3\) \(\frac{\text{FR}+1}{\text{FR}}\)(H2OFED) + \(\frac{\text{FFRD}_3}{\text{FR}}\) \(\frac{\text{FMCD}_2}{18.016}\) + \(\frac{\text{FMCD}_3}{18.016}\) (lb-moles H₂O/hr)

---

*Figure E.2 Boiler material balance - input*
**Basis:** per hour of operation

<table>
<thead>
<tr>
<th>Species</th>
<th>( \text{CO}_2 ) (lb-moles)</th>
<th>( \text{O}_2 ) (lb-moles)</th>
<th>( \text{N}_2 ) (lb-moles)</th>
<th>( \text{H}_2\text{O} ) (lb-moles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) ) ( X )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>-</td>
<td>( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) ) ( (\text{O}_2\text{FED}-\text{O}_2\text{REQ}) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>-</td>
<td>-</td>
<td>( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) ) ( \text{N}_2\text{FED} )</td>
<td></td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>( \text{FFRD3} \left[ \left( \frac{1}{\text{FR}} \right) \left( \frac{\text{FMCD}_2}{18.016} \right) + \left( \frac{\text{FMCD}_3}{18.016} \right) + \left( \frac{\text{FR}+1}{\text{FR}} \right) \left( \frac{\text{Y}}{2} + \text{H}_2\text{O}\text{FED} \right) \right] )</td>
</tr>
</tbody>
</table>

**Total Output Flow Rates:**

| \( \text{CO}_2 \) | \( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) \) \( X \) |
| \( \text{O}_2 \) | \( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) \) \( (\text{O}_2\text{FED}-\text{O}_2\text{REQ}) \) |
| \( \text{N}_2 \) | \( \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) \) \( \text{N}_2\text{FED} \) |
| \( \text{H}_2\text{O} \) | \( \text{FFRD3} \left[ \left( \frac{1}{\text{FR}} \right) \left( \frac{\text{FMCD}_2}{18.016} \right) + \left( \frac{\text{FMCD}_3}{18.016} \right) + \left( \frac{\text{FR}+1}{\text{FR}} \right) \left( \frac{\text{Y}}{2} + \text{H}_2\text{O}\text{FED} \right) \right] \) (lb-moles \( \text{H}_2\text{O}/\text{hr} \))

*Figure E.3 Boiler Material Balance - Output*
Basis: per hour of operation

Reference state: the elements at 77°F (TREF)

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow Rate</th>
<th>x</th>
<th>(Sensible heat + Formation Energy) = Total Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (Stream 2)</td>
<td>FFRD3 FR</td>
<td></td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{wood}}dT + \Delta h_{f_{wetwood}}^{FMCD2}]</td>
</tr>
<tr>
<td>Water (Stream 2)</td>
<td>FFRD3 FR</td>
<td></td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{H_2O}}dT + \Delta h_{f_{H_2O(1)}}]</td>
</tr>
<tr>
<td>Wood (Stream 3)</td>
<td>FFRD3 FR</td>
<td></td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{wood}}dT + \Delta h_{f_{wetwood}}^{FMCD3}]</td>
</tr>
<tr>
<td>Water (Stream 3)</td>
<td>FFRD3 FR</td>
<td></td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{H_2O}}dT + \Delta h_{f_{H_2O(1)}}]</td>
</tr>
<tr>
<td>O₂</td>
<td>FFRD3 FR+1</td>
<td>(\frac{FR+1}{FR})</td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{O_2}}dT + 0]</td>
</tr>
<tr>
<td>N₂</td>
<td>FFRD3 FR+1</td>
<td>(\frac{FR+1}{FR})</td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{N_2}}dT + 0]</td>
</tr>
<tr>
<td>H₂O (vapor)</td>
<td>FFRD3 FR+1</td>
<td>(\frac{FR+1}{FR})</td>
<td>[\frac{TF}{TREF} \int_{TREF}^{TF} C_{p_{H_2O(g)}}dT + \Delta h_{f_{H_2O(g)}}]</td>
</tr>
</tbody>
</table>

Figure E.4 Boiler energy balance - input
Figure E.4 Footnotes - (Continued)

1 TF2 - "Temperature, fuel, stream 2"
2 TF3 - "Temperature, fuel, stream 3"
3 TAM - "Temperature, ambient"
Basis: per hour of operation

Reference state: the elements at 77°F (TREF)

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow Rate</th>
<th>( x ) (Sensible heat + Formation energy) = Total enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>FFRD3 ( \left( \frac{FR+1}{FR} \right) (X) )</td>
<td>[ \text{TBE} \left( \frac{\text{TBE}}{\text{TREF}} \right) \int_{\text{TREF}}^{\text{TBE}} C_{p_{CO_2}} \text{dT} + \Delta h_{fCO_2} ]</td>
</tr>
<tr>
<td>O(_2)</td>
<td>FFRD3 ( \left( \frac{FR+1}{FR} \right) (02FED-02REQ) )</td>
<td>[ \text{TBE} \left( \frac{\text{TBE}}{\text{TREF}} \right) \int_{\text{TREF}}^{\text{TBE}} C_{p_{O_2}} \text{dT} + 0 ]</td>
</tr>
<tr>
<td>N(_2)</td>
<td>FFRD3 ( \left( \frac{FR+1}{FR} \right) (N2FED) )</td>
<td>[ \text{TBE} \left( \frac{\text{TBE}}{\text{TREF}} \right) \int_{\text{TREF}}^{\text{TBE}} C_{p_{N_2}} \text{dT} + 0 ]</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>FFRD3 ( \left( \frac{1}{FR} \frac{\text{FMCD2}}{18.016} + \frac{\text{FMCD3}}{18.016} \right) + \left( \frac{FR+1}{FR} \right) \left( \frac{Y}{2} + \text{H2OFED} \right) )</td>
<td>[ \text{TBE} \left( \frac{\text{TBE}}{\text{TREF}} \right) \int_{\text{TREF}}^{\text{TBE}} C_{p_{H_2O}} (g) \text{dT} + \Delta h_{fH_2O(g)} ]</td>
</tr>
</tbody>
</table>

\(^{1}\text{TBE} - "Temperature, boiler exhaust"

Figure E.5 Boiler energy balance - output
\( \dot{H} \) is the total energy (enthalpy) contained within the input (EINB) and output (EOUTB) streams, relative to the elements at 77 °F.

The boiler heat loss term is expressed as a percentage (expressed here as decimal percentage, appearing here as HTLFB - "Heat Loss Factor; Boiler") of the higher heating value (HHV) of the fuel. The (hourly) heat loss term for the boiler is thusly written as:

\[
\text{HTLOSSB} = (\text{FFRD3}) \times (\text{HHV}) \times (\text{HTLFB}) \times \left(\frac{\text{FR} + 1}{\text{FR}}\right)
\]

The boiler overall energy balance is ultimately written (again in Fortran) as:

\[
\text{EINB} - \text{EOUTB} - \text{QSTEAM} - \text{HTLOSSB} = 0
\]

Note that both QSTEAM and HTLOSSB represent energy flows exiting the boiler. Consequently, in keeping with thermodynamic convention, they appear as negative terms in the above equation.

(b) Dryer Material and Energy Balances

The dryer material and energy balances for both simulation models/programs are developed in this section. The "black box" approach used in the analysis of the dryer considers the contributions of five streams, or flows. They are

* Fuel feed stream (Input)
* Boiler exhaust stream (Input)
* Air leakage (into) dryer (Input)
* Dry fuel stream (Output)
* Dryer exhaust (Output)
The dryer heat loss is considered to be essentially negligible (assuming a well-insulated dryer combined with a low driving force for heat transfer to the environment) and is not directly considered in this study. One may indirectly compensate, however, for heat loss to the ambient by assuming a slightly lower dryer exhaust temperature (SIM1), or by a slightly lower dryer thermodynamic efficiency (SIM2). One may also compensate for dryer heat loss in the overall system by using a slightly larger value than is conventionally used for the boiler heat loss. It is not that confusing when one considers that the two "control volumes" used in this study may be combined as one overall control volume, thus the individual losses may be lumped together as a total heat loss "stream" for the entire system.

(1) **Dryer material balances**

The dryer material balances are presented in balance sheet form in Figures E-6 (Input) and E-7 (Output). Note that the air leakage into the dryer (AIR) is specified in terms of the dry gas flow rate (molar) of the boiler exhaust stream; air leakage is expressed as a (decimal) percentage of the dry gas flow rate (ALF - "Air Leakage Factor"). Thus the total air leakage to the dryer may be determined as:

\[
\text{AIR} = \text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) \text{ALF} \left( \frac{\text{X} + \text{O2FED}-\text{O2REQ}+\text{N2FED}}{\text{FR}} \right)
\]

(Recall that "X" is the stoichiometric coefficient of carbon dioxide as shown previously, and represents the lb-moles of carbon dioxide formed in combustion, per pound dry wood.) The ambient water carried
Basis: per hour of operation

### Flow rates

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow rate expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>( \text{FFRD}3 \left( \frac{\text{FR}+1}{\text{FR}} \right) (X) )</td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>( \text{FFRD}3 \left( \frac{\text{FR}+1}{\text{FR}} \right) (02\text{FED}-02\text{REQ}) )</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>( \text{FFRD}3 \left( \frac{\text{FR}+1}{\text{FR}} \right) (\text{N2FED}) )</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} ) (in boiler exhaust)</td>
<td>( \text{FFRD}3 \left[ \left( \frac{1}{\text{FR}} \right) \left( \frac{\text{FMCD}2}{18.016} \right) + \left( \frac{\text{FMCD}3}{18.016} \right) + \left( \frac{\text{FR}+1}{\text{FR}} \right) \left( \frac{\text{Y}}{2} + \text{H2OFED} \right) \right] )</td>
</tr>
<tr>
<td>Air (air leakage)</td>
<td>( \text{AIR} = \text{FFRD}3 \left( \frac{\text{FR}+1}{\text{FR}} \right) (\text{ALF}) (X + 02\text{FED} - 02\text{REQ} + \text{N2FED}) )</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} ) (water vapor in air)</td>
<td>( \text{AIR} (\text{FHR}) \left( \frac{29.0}{18.016} \right) )</td>
</tr>
<tr>
<td>Wood - Stream 1</td>
<td>( \text{FFRD}3 )</td>
</tr>
<tr>
<td>Water - Stream 1</td>
<td>( \text{FFRD}3 \left( \frac{\text{FMCD}1}{18.016} \right) )</td>
</tr>
</tbody>
</table>

Figure E.6 Dryer material balance - input
### Basis: per hour of operation

#### Flow rates

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow Rate Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>$\text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) (\text{X})$ (lb-mole CO$_2$/hr)</td>
</tr>
<tr>
<td>O$_2$</td>
<td>$\text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) (\text{O2FED}-\text{O2REQ}) + 0.21 \text{ AIR}$ (lb-mole O$_2$/hr)</td>
</tr>
<tr>
<td>N$_2$</td>
<td>$\text{FFRD3} \left( \frac{\text{FR}+1}{\text{FR}} \right) (\text{N2FED}) + 0.79 \text{ AIR}$ (lb-mole N$_2$/hr)</td>
</tr>
<tr>
<td>H$_2$O (dryer exhaust)</td>
<td>$\text{FFRD3} \left[ \left( \frac{1}{\text{FR}} \right) \left( \frac{\text{FMCD2}}{18.016} \right) + \left( \frac{\text{FMCD3}}{18.016} \right) + \left( \frac{\text{FR}+1}{\text{FR}} \right) \left( \frac{\text{Y} + \text{H2OFED}}{2} \right) + \left( \frac{\text{FMCD1}-\text{FMCD3}}{18.016} \right) \right]$ + Air (FHR) $\left( \frac{29.0}{18.016} \right)$ (lb-mole H$_2$O/hr)</td>
</tr>
<tr>
<td>Wood - Stream 3</td>
<td>$\text{FFRD3}$ 1b$_m$ dry wood/hr</td>
</tr>
<tr>
<td>Water - Stream 3</td>
<td>$\text{FFRD3} \left( \frac{\text{FMCD3}}{18.016} \right)$ 1b-mole H$_2$O/hr</td>
</tr>
</tbody>
</table>

**Figure E.7** Dryer material balance - output
into the dryer with the air leakage may then be calculated as:

\[
\text{Ambient } H_2O = (\text{AIR})(FHR) \left( \frac{29.0 \text{ lb-m Air/lb-mole air}}{18.016 \text{ lb-m } H_2O \text{ lb-mole } H_2O} \right)
\]

(2) **Dryer energy balances (SIM 1)**

The dryer energy balances used were developed in the same manner as the boiler energy balances, and are shown in Figures E-8 (Input) and E-9 (Output).

The overall energy balance for the dryer is much the same as the overall energy balance equation for the boiler. Note however, that since the heat loss from the dryer is neglected, no heat flow term is required in the following equation:

\[
H_{\text{input}} - H_{\text{output}} = 0
\]

where \( H \) represents the total energy (enthalpy), relative to the reference state, of both the input (EIND) and the output (EOUTD) streams. Accordingly the dryer overall equation is written as (in terms of the Fortran variables shown above):

\[
EIND - EOUTD = 0
\]

By referring to Figures E-8 and E-9, one notes the use of the concept of the heat of formation for a non-reactive system. This was done primarily to account for the latent heat of vaporization of water. Note that in the case of the water held by the fuel, the heat of formation is for liquid water. In the case of water present in the dryer exhaust stream, the heat of formation is for water vapor. The heats of formation of the fuel and carbon dioxide are presented
### Basis: per hour of operation

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow Rate</th>
<th>Sensible heat + Formation Energy</th>
<th>Total Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>FFRD3 ( \frac{(FR+1)}{FR} ) ((X)) \ x \ \int_{TREF}^{TDI} C_p CO₂ dT \ + \ Δ h_f CO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>FFRD3 ( \frac{(FR+1)}{FR} ) ((O₂FED-0₂REQ)) \ x \ \int_{TREF}^{TDI} C_p O₂ dT \ + \ 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>FFRD3 ( \frac{(FR+1)}{FR} ) ((N₂FED)) \ x \ \int_{TREF}^{TDI} C_p N₂ dT \ + \ 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O (in boiler exhaust)</td>
<td>FFRD3 ( \frac{(1)}{FR(18.016)} + \frac{(FMCD₂)}{18.016} + \frac{(FR+1)}{FR} \frac{(Y + H₂O)FED)}{18.016} \ x \ \int_{TREF}^{TAM} C_p H₂O(g) + Δ h_f H₂O(g) \</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air (air leakage)</td>
<td>AIR</td>
<td>\ \int_{TREF}^{TAM} C_p Air dT \ + \ 0</td>
<td></td>
</tr>
<tr>
<td>H₂O (water vapor in air)</td>
<td>AIR ( \frac{(29.0)}{18.016} ) \ x \ \int_{TREF}^{TAM} C_p H₂O(g) + Δ h_f H₂O(g)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure E.8 Dryer energy balance -input
Figure E.8 (Continued)

<table>
<thead>
<tr>
<th></th>
<th>FFRD3</th>
<th>[ TFL^2 \left( \frac{C_{pwood}dT}{T_{REF}} \right) + \Delta h_{f_{wood}}^{FMCD1} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood - Stream 1</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Water - Stream 1</td>
<td>FFRD3(18.016)</td>
<td>[ TF^1 \left( \frac{C_{pH_2O}dT}{T_{REF}^{(1)}} \right) + \Delta h_{f_{H_2O}}^{(1)} ]</td>
</tr>
</tbody>
</table>

1. TDI - "Temperature, dryer inlet"
2. TF1 - "Temperature, fuel, stream 1"
Basis: per hour of operation

Reference: the elements at 77°F (TREF)

<table>
<thead>
<tr>
<th>Species</th>
<th>Flow Rate</th>
<th>x</th>
<th>(Sensible heat + Formation Energy) Total Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>FFRD3 \left(\frac{FR+1}{FR}\right)(x)</td>
<td>\int_{TREF}^{TDE} \frac{Cp_{CO₂} dT}{TREF} + Δh_fCO₂</td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>FFRD3 \left(\frac{FR+1}{FR}\right)(O₂FED-O₂REQ) + 0.21 AIR</td>
<td>\int_{TREF}^{TDE} \frac{Cp_{O₂} dT}{TREF} + 0</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>FFRD3 \left(\frac{FR+1}{FR}\right)(N₂FED) + 0.79 AIR</td>
<td>\int_{TREF}^{TDE} \frac{Cp_{N₂} dT}{TREF} + 0</td>
<td></td>
</tr>
<tr>
<td>H₂O (in dryer)</td>
<td>FFRD3 \left(1+\frac{FMCD2}{18.016}\right) + \frac{FR+1}{FR} \left(\frac{Y}{2} + H₂OFEF\right) + \frac{FMCD1-FMCD3}{18.016} + \text{AIR (FHR) } \left(\frac{29.0}{18.016}\right)</td>
<td>\int_{TREF}^{TDE} \frac{Cp_{H₂O} dT}{TREF} + Δh_fH₂O</td>
<td></td>
</tr>
<tr>
<td>Wood - Stream 3</td>
<td>FFRD3</td>
<td>\int_{TREF}^{TF₃²} \frac{Cp_{wood} dT}{TREF} + Δh_{fwood}</td>
<td></td>
</tr>
<tr>
<td>Water - Stream 3</td>
<td>FFRD3 \frac{FMCD3}{18.016}</td>
<td>\int_{TREF}^{TF₃} \frac{Cp_{H₂O}}{TREF} + Δh_{fH₂O}</td>
<td></td>
</tr>
</tbody>
</table>

Figure E.9 Dryer energy balance - output
primarily for purposes of accounting, and have no effect (inputs and outputs cancel) in the overall dryer energy equation.

The use of the heats of formation in this manner further illustrates the use of the control volume approach in the analysis of a process or system. In the case of the drying process, one need not trace the path of the process from: (1) heating the fuel and water to the temperature of evaporation (difficult to assess to begin with, as vaporization occurs at or near the wet bulb temperature, and not at the normal boiling point of water, a common misconception), (2) Vaporization of the water at that temperature (again difficult to assess, as the latent heat of vaporization is somewhat dependent on temperature), and (3) Heating or cooling the water vapor to the exit temperature of the dryer. The control volume approach takes all of these three steps into account by simply referencing the input and output conditions to the same reference state, thereby eliminating the confusion (and potential for serious error) of the "pathway" method just described.

(3) Dryer energy balances (SIM 2)

The development of SIM 2 used the concept of dryer thermodynamic, or heating efficiency, to predict the amount of drying occurring within the confines of the dryer. The use of thermodynamic efficiency was prompted by the analysis of experimental data (see Appendix D), which quantized the energy flows within the dryer into the following categories:

* Energy purged to the ambient in the dryer exhaust
* Sensible heat required to heat the dryer air leakage from the ambient to the dryer exhaust temperature

* Sensible heat required to heat the fuel, and the water contained within the fuel that is not evaporated, from the inlet temperature to the dryer exit temperature

* Energy actually used in the evaporation of water

The development of the dryer equation for the second generation program is somewhat different than the "black box" approach presented in previous sections. It does however make use of the dryer material balances presented in Figures E-6 and E-7.

The first step in the development involves the determination of the available energy, relative to the ambient temperature, that enters the dryer in the boiler exhaust. In essence, the available energy is the total sensible heat of the boiler exhaust components (carbon dioxide, water, oxygen, and nitrogen); Figure E-8 may be used as a representative available energy equation, disregarding the non-boiler exhaust inputs as well as the heats of formation of the exhaust constituent species. Thus the total available energy entering the dryer (AVAILEN), may be written as:

\[ \text{AVAILEN} = \sum_{i} (m_{i} \cdot C_{pi} \cdot dT) \]

where \( m_{i} \) and \( C_{pi} \) are the respective flow rates and heat capacities of boiler exhaust species \( i \). Recall that TDI is "Temperature; Dryer Inlet"; TAM is "Temperature; Ambient".
The second stage of the development makes use of the "energy partitioning" concept summarized above. Defining PCT1 as the (decimal) percentage of the total available energy that is actually used for drying (AVDRY), and PCT2 as the percentage of the total available energy that is used to heat the fuel and the water contained in that fuel that is not evaporated from the dryer inlet temperature (TF1) to the exit temperature (TF2), (QSENS), the energy that remains is the sum of the energy required to heat the air leakage from the ambient temperature (TAM) to the dryer exhaust temperature (TDE) and that energy purged to the ambient in the dryer exhaust. This remaining energy may be referred to as "lost energy" (QHTL). Thus:

\[ QHTL = (1 - PCT1 - PCT2) (AVAILEN) \]

Once this "lost energy" has been determined, the dryer exhaust temperature may be calculated. It is necessary that the dryer exhaust temperature be known in order to calculate the amount of water evaporated, as the energy "partitioned" into drying includes not only the latent heat of vaporization of water, but also the energy required to heat the vapor from the wet bulb temperature (the fuel particle surface is at or near the wet bulb temperature throughout the course of drying, until the fiber saturation point of the wood is reached) to the dryer exhaust temperature. Due to the complexity of the heat capacity equations used in this study, the determination of the dryer exhaust temperature requires an iterative-type solution of the following equation:
QHTL = \sum_{i}^{TAM} \left( m_{i} T_{i} \right) + M_{air} \int_{TAM}^{TDE} C_{p,air} dT

Out of general interest, the exit temperature of the fuel stream may be determined using an iterative solution of the following equation:

QSENS = (PCT2)(AVAILEN) = FFRD3 \int_{TF1}^{TF3} C_{p, fuel} dT
+ FFRD3 (FMCD1 - FMCD3)C_{p,H_{2}O}(TF3 - TF1)

The final equation is a function of both solution variables (as both the above equations are), as well as the dryer exhaust temperature which in itself is a function of both variables. This final equation is perhaps the most representative as the second equation describing the boiler/dryer system. (Actually, all of the above equations describe the processes occurring within the dryer, and the equation written below as the "final" equation cannot stand without them.)

Treating the water that is actually evaporated as the system in question, and defining AVORY as the energy used for drying, a first law-like equation may be written as shown below:

AVORY = (PCT1)(AVAILEN)

Thus:

AVORY + FFRD3 \left( \frac{FMCD1 - FMCD3}{18.016} \right) \left( C_{p,H_{2}O}(1)(TF1 - TREF) + \Delta h_{f,H_{2}O}(1) \right) - \left( \int_{TREF}^{TDE} C_{p,H_{2}O}(g) dT + \Delta h_{f,H_{2}O}(g) \right) = 0

Note that TREF is the reference temperature used in this study (77 °F). Note also that, as mentioned previously, the use of the re-
spective heats of formation of liquid water (input) and the water vapor (output) automatically accounts for the latent heat of vaporization of the water.

Methods of Solution

In the previous sections two overall energy equations describing the boiler/dryer system were developed for each of the respective models. Again, the solution variables are: (1) the flow rate of bone-dry wood through the dryer (FFRD3), and, (2) the fuel moisture content, dry basis, of the fuel exiting the dryer (FMCD3). Examination of these equations reveal that they are nonlinear in nature. Consequently, they require an iterative-type solution technique.

Various techniques are available for the solution of nonlinear equations such as these, yet all follow the same basic steps to determine of the solution. These steps are summarized as:

* Initial estimates of the values of the solution variables are made
* These initial estimates are used throughout the subsequent calculations, ultimately...
* Determining new values of the solution variables
* These new values are compared to the initial values
* If they are in relative agreement with the initial estimates, calculation ceases. If not, the calculated values (or modifications of the calculated values) are used as
new estimates, and the process is repeated until conditions of satisfactory convergence are met.

The method of solution used by both SIM1 and SIM2 was a modified Newton-Raphson technique (this technique will be explained in due course), available as a subroutine (ZSYSIM) in the International Mathematical and Statistical Library (IMSL) software package available at Oregon State University. IMSL software is available throughout the world, although in most cases requires the use of a mainframe computer, as it is quite extensive.

Due to the likelihood that IMSL (or a mainframe) will not be readily available to the reader, the standard Newton-Raphson technique, in general form, is developed below. This development should allow the reader to develop his own software subroutine for the solution of the equations developed above.

Consider in general two nonlinear equations of the form shown below:

\[ f_1(x_1, x_2) = 0 \]
\[ f_2(x_1, x_2) = 0 \]

These nonlinear equations may be linearized by Taylor Series expansion (only the first two terms of the expansion are used) to yield the following linear equations:

\[ f_1(x_1, x_2) = 0 \approx f_1(x_1', x_2') + \frac{\partial f_1}{\partial x_1} (x_1 - x_1') + \frac{\partial f_1}{\partial x_2} (x_2 - x_2') \]
\[ f_2(x_1, x_2) = 0 \approx f_2(x_1', x_2') + \frac{\partial f_2}{\partial x_1} (x_1 - x_1') + \frac{\partial f_2}{\partial x_2} (x_2 - x_2') \]

These equations may be rearranged and written in the general matrix form of \( AX = B \), as shown below:
The "prime" superscripts on the independent variables denote the point about which the Taylor Series is expanded. Note also that the partial derivatives in the A-matrix and the respective functions appearing in the B-matrix are evaluated at these same points of expansion.

The above matrix equation may be recast in the form of interest to the Newton-Raphson technique as:

\[
\begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & x_1, x_2 \\
\frac{\partial f_2}{\partial x_1} & x_1, x_2 \\
\frac{\partial f_1}{\partial x_2} & x_1, x_2 \\
\frac{\partial f_2}{\partial x_2} & x_1, x_2 \\
\end{bmatrix}
\begin{bmatrix}
(x_1 - x_1^i) \\
(x_2 - x_2^i) \\
\end{bmatrix}
= 
\begin{bmatrix}
f_1(x_1^i, x_2^i) \\
f_2(x_1^i, x_2^i) \\
\end{bmatrix}
\]

The method of solution is summarized below:

* estimate \( x_1^i, x_2^i \)
* expand by Taylor Series about the points \( x, x \)
* solve the linearized equations using standard methods of linear equation solution
* calculate \( x_{1}^{i+1}, x_{2}^{i+1} \) using the following relationships:

\[
x_{1}^{i+1} = x_1 + x_{1}^i, x_{2}^{i+1} = x_2 + x_{2}^i
\]
* compare $x_{i+1}^i$ with $x_{1}^i$, $x_{i+1}^i$ with $x_{2}^i$ (calculation ceases when estimated and calculated values are in relative agreement)

* repeat the above steps until conditions of satisfactory convergence are met.

Convergence tolerance may be established through the use of relative error; execution ceasing when the calculated relative error is of magnitude less than or equal to some previously (user) specified value of tolerance. Relative error is defined as:

$$\text{Relative Error} = \left| \frac{x_{i+1}^i - x_i^i}{x_i^i} \right|$$

In the event that it is difficult (or indeed impossible) to evaluate analytically the partial derivatives of the functions in question, one may evaluate them numerically, as illustrated below:

$$\left. \frac{\partial f_1}{\partial x_1} \right|_{x_1, x_2} = \frac{f_1(x_1, x_2) - f_1(x_1 + \delta, x_2)}{\delta}$$

where the value of $\delta$ is much smaller in magnitude than $x_1$.

The Newton-Raphson method may be used to solve any number of nonlinear equations simply by expanding the above treatment for two equations into a system of $n$ equations. The only limitations to the number of equations are those of speed of computation and capacity of the available computer. For a more thorough development of the Newton-Raphson technique, as well as other useful concepts of numeri-
cal mathematics, it is suggested that the reader consult a numerical methods reference, such as compiled by Carnahan, et al. (1969).

Contrasts and Similarities Between SIM1 and SIM2

Both programs/models developed in conjunction with this study yield solution values that are in relatively good agreement, as shown in the Case Studies Section of the text, although both use different sets of constraints (both sets of constraints are integrally related to each other, consequently one would expect quite similar performance). As indicated previously, SIM1 fixes, in addition to the other parameters of interest, the dryer exit temperatures for both the gas and fuel streams. SIM2 takes a somewhat different approach by fixing both the percentage of the total available energy entering the dryer that is used in the drying process (dryer thermodynamic efficiency), and the percentage of the total available energy that is taken up in the sensible heat of the wood stream, and thus calculates both of the dryer exit temperatures, as opposed by fixing them as input parameters as does SIM1.

Both programs/models have their respective advantages and disadvantages. SIM1 is useful in the analysis of a boiler/dryer system that fixes, by means of a feedback control loop, the dryer exhaust temperature; the first system analyzed, Dryer A, used this type of control approach. SIM2, alternatively, is more of a general model than is SIM1, and allows the use of thermodynamic efficiency estimates to predict the performance of a rotary dryer. It is important
to note that in both cases the sensible heat requirements of the fuel stream are of minor importance, and can be estimated, either in terms of fuel exit temperature or as percent of available energy, with little loss in the overall reliability of the model.

The limitations of each program deal primarily with the operating characteristics of each dryer. For example, the utility of SIM1 diminishes in the event that the system in question does not make use of a dryer exhaust control system, essentially allowing the dryer exhaust temperature to fluctuate in response to fluctuations in boiler exhaust and fuel stream flow rates and conditions. The program could be easily modified to a real time basis in which the various fluctuations could be taken into account. Also, each model/program assumes that the dryer is properly loaded; both models depart from reality at low dryer fuel feed rates.

In any process simulation there always exists areas open to improvement. The models developed in this study are no exception. There are several areas in which further development would be an asset to the modeling of rotary dryers. One such area of development is the extensive analysis of rotary dryers currently in operation, under a greater variety of operating conditions than the scope of this study would allow. Greater depth of analysis would afford the possible development of empirical equations of dryer performance. Such equations would model dryer performance as a function of boiler exhaust gas flow rate and temperature, air leakage, fuel conditions, etc.
A second area of improvement also deals with the development of dryer performance equations. This second approach, currently in development at Oregon State University, involves the development of rigorous mathematical equations of heat, mass and momentum transfer. The equations would then be solved simultaneously, utilizing a variety of numerical techniques, thus evaluating the behavior of the rotary dryer.

Copies of each of the simulation programs developed in this study, as well as sample outputs, are presented in the following pages. The sample outputs follow the respective programs and illustrate predicted boiler/dryer performance and associated process stream flows and conditions under moderate operating conditions of: 100% stockpile fuel moisture content (dry basis), 100% combustion excess air, a boiler exhaust temperature of 400 °F. The sample output of Program SIM1 assumes a dryer exhaust temperature of 200 °F. The sample output of Program SIM2 assumes a dryer thermodynamic, or heating efficiency of 50% (50% of the total available energy in the boiler exhaust stream is used for drying). Brief flowcharts for each program are shown in Figures E.10 and E.11.
Calculate fuel flow rate, etc., for boiler alone (used as initial "guesstimate" for FFRD3; stockpile fuel moisture content (FMCD1) used for initial "guesstimate" of FMCD3

CALL ZSYSTEM

CALL ENBAL

Summary Calculations

Printout

STOP

Figure E.10 Program SIM1 flowchart
SIM1 Program Listing

LIST,F=KIRK11
PROGRAM KIRK11 (OUTPUT, TAPE6=OUTPUT)

EXTERNAL ENBAL, ENT
DIMENSION VAR(2), WA(8), FMU(6)
COMMON/TEMP/TREF, TAM, TF1, TF2, TF3, TDI, TDE, TBE
COMMON/HEAT/CW, CICE, DELHF, HFH20L, HFH20G, HFCO2, HTLFB, QSTEAM, HHV
COMMON/QUANT/XT, X, Y, Z, O2FED, O2REQ, N2FED, H2OFED, FRI, DRYEFF, ALF
COMMON/MOIST/FMCD1, FMCD2, FMCD3T, FHR, GSF
COMMON/RARE/HFDW, N
COMMON/BICK/FUEL3, SORBWA3, FUEL2, SORBWA2, COMAIR, EINB
COMMON/BOCK/EXGASB, EXWAB, EDOUTB, HTLOSSB
COMMON/DICK/FUEL1, SORBWA1, GASIN, WAIN, AIRIN, AIR, EIND
COMMON/DOCK/FUEL3XD, SORBWAX, EXGASD, EXWAD, VAPWA, AROUT, EDOUTD
COMMON/DICK/FUEL1, SORBWA1, GASIN, WAIN, AIRIN, AIR, EIND
COMMON/DOCK/FUEL3XD, SORBWAX, EXGASD, EXWAD, VAPWA, AROUT, EDOUTD
COMMON/DICK/FUEL3XD, SORBWAX, EXGASD, EXWAD, VAPWA, AROUT, EDOUTD
REAL N2FED

DATA CW, CICE, DELHF /18.021, 9.0440, 2585.768/
DATA HFH20L, HFH20G, HFCO2 /-122991.23, -104054.61, -169315.18/
DATA ULTC, ULTH, ULTO, HHV /0.523, 0.063, 0.405, 9050.0 /
DATA TREF, TAM, TF1, TF2, TF3 /77.0, 70.0, 60.0, 60.0, 100.0 /
DATA TDI, TDE, TBE, FHR, ALF, GSF /478.0, 200.0, 478.0, 0.0054, 0.10, 1.0 /
DATA FMCD1, FMCD2 /1.0628, 1.0628 /
DATA QSTEAM, FRI, HTLFB, DRYEFF, EA /62322000.0, 1.0E+050.050.0 . 1.380 /
DATA QMSTEAM, PCTCL /60000.0, 0.086 /
DATA NSIG, EPS, ITMAX, N /3, 1.0E-04, 50, 2 /
DATA (FMU(I), I=1, 6) /28.01, 44.01, 18.016, 28.02, 32.00, 29.00 /

PRELIMINARY CALCULATIONS

N=0
X=ULTC/12.01115
XT=(1.0-PCTCL)*X
Y=ULTH/1.00797
Z=ULTO/15.9994
O2REQ=X+Y/4.0-Z/2.0
O2FED=O2REQ*(1.0+EA)
N2FED = 3.7619 \times 02FED
AIRFED = 4.7619 \times 02FED
H2OFED = AIRFED \times \frac{29.0}{18.016} \times FHR
HFDW = Y/2.0 \times HFH2OL + X \times HFCO2 + HHV
O2REQ = (XT/X) \times O2REQ

CALCULATE FUEL REQUIREMENT FOR BOILER SANS DRYER,
ASSUMING THE FUEL TEMPERATURE AND FUEL MOISTURE CONTENT
(DRY BASIS) TO BE THE RESPECTIVE TEMPERATURE AND MOISTURE
CONTENT OF THE STOCKPILE.

IN ADDITION TO USE AS A COMPARISON WITH FUEL FLOWRATE WITH
DRYER ON LINE, THESE VALUES ARE USED AS INITIAL ESTIMATES
FOR THE SUBROUTINE ZSYSTM.

DM = 1.0
COMGAS = 02FED \times ENT(1,5,DM,TREF,TAM) + N2FED \times ENT(1,4,DM,TREF,TAM)
1 + H2OFED \times ENT(1,3,DM,TREF,TAM) + HFH20G
COMFUEL = ENT(2,DM,DM,TREF,TF1) + ENT(3,DM,FMCD1,DM,DM)
SORBH20 = ENT(4,DM,DM,TREF,TF1) + HFH20L
EI = COMGAS + COMFUEL + (FMCD1/18.016) \times SORBH20
EXGAS = XT \times (ENT(1,2,DM,TREF,TBE) + HFCO2) + N2FED \times ENT(1,4,DM,TREF,TBE)
1 + (O2FED - O2REQ) \times ENT(1,5,DM,TREF,TBE)
2 + (Y/2.0 + FMCD1/18.016 + H2OFED) \times ENT(1,3,DM,TREF,TBE) + HFH20G
FUEL = QSTEAM/((EI - EXGAS) - HTLFB \times HHV)
EFFBWO = QSTEAM/((FUEL + HHV)

VAR(1) = FUEL
VAR(2) = FMCD1

CALL ZSYSTM(ENBAL,EPS,NSIG,M,VAR,ITMAX,WA,ENT,IER)

SUMMARY CALCULATIONS AND PRINTOUT STATEMENTS

FUEL FLOW RATES; DRY BASIS

FFRD3 = VAR(1)
FFRD2 = FFRD3/FR
FFRD1 = FFRD2 + FFRD3
FFRCOMP = FFRD1 \times (1.0 + FMCD1)
FSAVD = FUEL - FFRD1

MOISTURE CONTENTS
FMCD3=VAR(2)
FMCD=(FMCD2*FFRD2+FMCD3*FFRD3)/FFRDT
FMCW1=FMCD1/(1.0+FMCD1)
FMCW2=FMCD2/(1.0+FMCD2)
FMCW3=FMCD3/(1.0+FMCD3)
FMCWT=FMCDT/(1.0+FMCDT)

FUEL FLOW RATES; WET BASIS

FFRD1=FFRD3
FFR1=FFRD1*(1.0+FMCD1)
FFR2=FFRD2*(1.0+FMCD2)
FFR3=FFRD3*(1.0+FMCD3)
FFRWT=FFRDT*(1.0+FMCDT)
FUELW=FUEL*(1.0+FMCD1)
FSAVW=FUELW-FFRCOMP

EFFBW=QSTEAM/(FFRDT*HHV)
QSTEAM2=QSTEAM/1.0E+06

MOISTURE CONTENTS;
CONVERSION FROM DECIMAL FRACTION TO PERCENT

PCFMCD1=100.0*FMCD1
PCFMCD2=100.0*FMCD2
PCFMCD3=100.0*FMCD3
PCFMCDT=100.0*FMCDT
PCFMCM1=100.0*FMCW1
PCFMCM2=100.0*FMCW2
PCFMCM3=100.0*FMCW3
PCFMCMWT=100.0*FMCWT

VARIABLE PARAMETERS;
CONVERSION FROM DECIMAL FRACTION TO PERCENT

PCULTC=ULTC*100.0
PCULTH=ULTH*100.0
PCULTO=ULTO*100.0
PCEFBWO=EFFBWO*100.0
PCEFBW=EFFBW*100.0
PCALF=ALF*100.0
PCPCTCL=PCTCL*100.0
PCEA=EA*100.0
PCHLBF=HTLBF*100.0

CALCULATION OF GAS FLOW RATES

SCFMCA=(AIRFED+H2OFED)*(359.0/60.0)*FFRDT
ACFMCA=SCFMCA*{(459.6+TAM)/491.6}
SCFM1A=(AIRFED+H2OFED)*(359.0/60.0)*FUEL
ACFM1A=SCFM1A*{(459.6+TAM)/491.6}
\[
\begin{align*}
SCFMBE &= (XT+\text{AIRFED}-02REQ+H2OFED+(\text{FMCDT}/18.016) + 172.0)*(359.0/60.0)*FUEL \\
ACFMIE &= SCFMIE*((459.6+\text{TBE})/491.6) \\
SCFMIE &= (XT+\text{AIRFED}-02REQ+H2OFED+(\text{FMCDT}/18.016) + 172.0)*(359.0/60.0)*FUEL \\
ACFMIE &= SCFMIE*((459.6+\text{TBE})/491.6) \\
SCFNII &= GSF*SCFMBE \\
ACFMDI &= SCFMD1W459.6+TDE)/491.6) \\
SCFMDE &= SCFMD1+(GSF*\text{AIR}*1.0+FHR*(29.0/18.016)) + ((\text{FMCM}-\text{FMCD3})/18.016))*(359.0/60.0)*FFRD3 \\
ACFMDE &= SCFMD1*(((459.6+\text{TDE})/491.6) \\
SCFMDAL &= GSF*\text{AIR}*(1.0+FHR*(29.0/18.016))*(359.0/60.0)*FFRD3 \\
ACFMDAL &= SCFMD1*(((459.6+\text{TDE})/491.6) \\
CATERMD &= \text{AIRFED}*\text{FMW}(6) \\
CATERMW &= \text{H2OFED}*\text{FMW}(3) \\
BETERMD &= \text{AIRFED}*\text{FMW}(6)-02REQ*\text{FMW}(5)+XT*\text{FMW}(2) \\
BETERM2 &= (Y+2.0*\text{H2OFED})*\text{FMW}(3) \\
FMCAD &= \text{CATERMD}+\text{FFRD3} \\
FMCAW &= \text{CATERMW}+\text{FFRD3} \\
FMCAT &= \text{FMCAD}+\text{FMCAW} \\
HRCA &= \text{FMCAW}/\text{FMCAD} \\
FMIAD &= \text{CATERMD}+\text{FUEL} \\
FMIAW &= \text{CATERMW}+\text{FUEL} \\
FMIAT &= \text{FMIAD}+\text{FMIAW} \\
HR1A &= \text{FMIAW}/\text{FMIAD} \\
FMBED &= \text{BETERMD}+\text{FFRD3} \\
FMBEW &= (\text{BETERM2}+\text{FMCDT})+\text{FFRD3} \\
FMBET &= \text{FMBED}+\text{FMBEW} \\
HRBE &= \text{FMBEW}/\text{FMBED} \\
FMIED &= \text{BETERMD}+\text{FUEL} \\
FMIEW &= (\text{BETERM2}+\text{FMCD1})+\text{FUEL} \\
HR1E &= \text{FMIEW}/\text{FMIED} \\
FMDID &= \text{GSF}+\text{FMBED} \\
FMDIW &= \text{GSF}+\text{FMBEW} \\
FMDIT &= \text{GSF}+\text{FMBET} \\
HRDI &= \text{HRBE} \\
FMDALD &= \text{GSF}*\text{AIR}*(\text{FMW}(6)+\text{FFRD3} \\
FMDALW &= \text{FMDALD}+\text{FHR} \\
FMDALT &= \text{FMDALD}+\text{FMDALW} \\
FMDED &= \text{FMDILD}+\text{FMDALD} \\
FMDEW &= \text{FMDIWL}+\text{FMDALW}*(\text{FMCD1}-\text{FMCD3})*\text{FFRD3} \\
FMDET &= \text{FMDILD}+\text{FMDEW}
\end{align*}
\]
HRDE = FMDEW/FMDED

CALCULATION OF PERCENT CHANGE OF PARAMETERS RESULTING FROM INCORPORATION OF DRYER

PCBE = PC (EFFBW0, EFFBW)
PCMCDD = PC (FMCD1, FMCD3)
PCMCWD = PC (FMCW1, FMCW3)
PCTF3 = PC (TF1, TF3)

PCMCDT = PC (FMCD1, FMCDT)
PCMCWT = PC (FMCW1, FMCW3)
PCFRDT = PC (FUEL, FFRDT)
PCFRWT = PC (FUELW, FFRCOMP)

PCCAS = PC (SCFM1A, SCFMCA)
PCCAA = PC (ACFM1A, ACFMCA)

PCBES = PC (SCFM1E, SCFMBE)
PCBEA = PC (ACFM1E, ACFMBE)

PCFMBE = PC (FM1ED, FMBEED)
PCFMET = PC (FM1ET, FMETE)
PCHRBE = PC (HR1E, HRBE)

WRITE STATEMENTS

WRITE(6,100)
WRITE(6,101)
WRITE(6,104) HHV
WRITE(6,102) PCULTC, PCULTH, PCULTO
WRITE(6,105) PCFMCD1, PCFMCW1
WRITE(6,106) TF1
WRITE(6,107)
WRITE(6,108) TAM, FHR
WRITE(6,110) PCEA
WRITE(6,109) TBE
WRITE(6,111) PCHTCL
WRITE(6,112) PCPCTCL
WRITE(6,113) QMSTEAM, QSTEAM2
WRITE(6,114) FR
WRITE(6,115) TDI, PCALF
WRITE(6,141) TDE
WRITE(6,142) TF3
WRITE(6,117)
WRITE(6,118)
WRITE(6,139) PCEFBD, PCEFBU, PCBE
WRITE(6,127)
WRITE(6,120) PCFMCD1, PCFMCDT, PCFMCD1, PCFMCDT, PCFMCD1, PCFMCDT, PCFMCD1, PCFMCDT
WRITE(6, 121) FUEL,FFRDT,PCFRDT,FUELW,FFRW,PCFRW
WRITE(6, 143) FSAV,W,FSAV
WRITE(6, 119)
WRITE(6, 120) PCFMC1,PCFMC3,PCMC3,PCFMCW,PCMCW3,PCMCW
WRITE(6, 140) FFRD3,FFRD3,FFRU1,FFRU3
WRITE(6, 122) TF1,TF3,PCF3
WRITE(6, 123)
WRITE(6, 124) PCFMC2,PCFMCW2
WRITE(6, 125) FFRD2,FFRW2
WRITE(6, 126) TF2
WRITE(6, 128)
WRITE(6, 129) TAM, TAM
WRITE(6, 130) SCFM1A,SCFMCA,PCCAS,ACFM1A,ACFMCA,PCCAS
WRITE(6, 147) FMAD,FMCAD,FMAT,FMAT,HR1A,HRCA
WRITE(6, 131)
WRITE(6, 132) TBE, TBE
WRITE(6, 133) SCFM1E,SCFMBE,PCBES,ACFM1E,ACFMBE,PCBES
WRITE(6, 145) FM1ED,FMBED,PCFMED,FME1,FMBET,PCFMET,
1 HR1E,HRBE,PCHRBE
WRITE(6, 133)
WRITE(6, 134) TDI
WRITE(6, 135) SCFM1D,ACFM1D
WRITE(6, 146) FMDID,FMDIT,HRD1
WRITE(6, 144)
WRITE(6, 148) TAM
WRITE(6, 139) PCALF
WRITE(6, 135) SCFM1E,SCFMAL,PCBMAL,ACFM1E,ACFMAL,PCBMAL
WRITE(6, 146) FMDID,FMDIT,HRD1
WRITE(6, 136)
WRITE(6, 137) TDE
WRITE(6, 135) SCFMDE,ACFMDE
WRITE(6, 146) FMDID,FMDIT,HRD1

FORMAT STATEMENTS

100 FORMAT(///20X,*BOILER/DRYER TANDEM SIMULATION DATA AND OUTPUT*/
1 20X,*RAYMOND W. KIRK*/20X,*DEPARTMENT OF CHEMICAL ENGINEERING*/
2 20X,*DEPARTMENT OF FOREST PRODUCTS*/20X,*OREGON STATE*,
3 * UNIVERSITY*/20X,*CORVALLIS, OREGON*/20X,*SIMULATION INPUT*,
4 * DATA*/)
101 FORMAT(15X,*FUEL CHARACTERISTICS*/)
102 FORMAT(7X,*CARBON FRACTION IN DRY FUEL (ULTIMATE ANALYSIS)*,18X,
1 20X,F15.4,5X,*(PERCENT MASS)*/7X,*HYDROGEN FRACTION IN DRY FU*,
2 *EL (ULTIMATE ANALYSIS)*,16X,20X,F15.4,5X,*(PERCENT MASS)*/
3 7X,*OXYGEN FRACTION IN DRY FUEL (ULTIMATE ANALYSIS)*,18X,
4 20X,F15.4,5X,*(PERCENT MASS)*
104 FORMAT(5X,*HIGHER HEATING VALUE OF DRY FUEL (HHV)*,29X,20X,
1 F15.4,5X,*(BTU/LB)*)
105 FORMAT(5X,*WET FUEL MOISTURE CONTENT; DRY BASIS*,31X,20X,F15.4,5X,
1 *(PERCENT MASS)*/5X,*WET FUEL MOISTURE CONTENT; WET BASIS*,31X.
2 20X,F15.4,5X,*(PERCENT MASS)*)

106 FORMAT(5X,*WET FUEL TEMPERATURE (USUALLY ASSUMED TO BE AMBIENT*,
 1  * TEMPERATURE)*,3X,20X,F15.4,5X,*(DEG.F)*)
107 FORMAT(15X,*OPERATIONAL PARAMETERS AND CONSTRAINTS*/)
108 FORMAT(5X,*AMBIENT TEMPERATURE*,48X,20X,F15.4,5X,*(DEG.F)*)
  1 5X,*AMBIENT HUMIDITY RATIO*,45X,20X,F15.4,5X,*(LB H2O/LB DRY*,
  2  * AIR*)
109 FORMAT(5X,*BOILER EXHAUST TEMPERATURE*,41X,20X,F15.4,5X,*(DEG.F)*)
110 FORMAT(5X,*COMBUSTION EXCESS AIR*,46X,20X,F15.4,5X,*(PERCENT)*)
111 FORMAT(5X,*RADIATIVE, CONVECTIVE, AND UNACCOUNTED LOSSES IN*,
  1  * BOILER,*/7X,*EXPRESSED AS PERCENT HIGHER HEATING VALUE*,
  2 24X,20X,F15.4,5X,*(PERCENT)*)
112 FORMAT(5X,*CARBON/CHARCOAL LOSSES (CARRYOVER), EXPRESSED AS*/
  1 7X,*PERCENT OF ULTIMATE ANALYSIS OF CARBON IN FUEL*,19X,20X,
  2 F15.4,5X,*(PERCENT)*)
113 FORMAT(5X,*BOILER STEAM LOAD (MASS)*,43X,20X,F15.4,5X,*(LB/HR)*)
  1 5X,*BOILER STEAM LOAD (ENERGY)*,41X,20X,F15.4,5X,*(MBTU/HR)*)
114 FORMAT(5X,*FUEL FEED RATIO, EXPRESSED AS THE RATIO OF*/
  1 7X,*(DRY) FUEL PASSING THROUGH DRYER TO (DRY) FUEL*,
  2 * BYPASSING DRYER*,3X,20X,F15.4)
115 FORMAT(5X,*DRYER INLET TEMPERATURE*,44X,20X,F15.4,5X,*(DEG.F)*)
  1 5X,*DRYER AIR LEAKAGE, EXPRESSED AS PERCENT OF*/
  2 7X,*INCOMING DRY GAS FROM BOILER EXHAUST*,29X,20X,F15.4,
  3 5X,*(PERCENT)*)
116 FORMAT(5X,*THERMODYNAMIC (DRYING) EFFICIENCY, EXPRESSED AS*,
  1  * PERCENT OF AVAILABLE ENERGY (RELATIVE TO THE AMBIENT*,
  2  * TEMPERATURE),*/7X,*(IE, THAT PERCENT OF AVAILABLE ENERGY*,
  3  * THAT IS USED TO*/*7X,*EVAPORATE WATER FROM THE FUEL STREAM*,
  4  * PASSING THROUGH THE DRYER)*,2X,20X,F15.4,5X,*(PERCENT)*/
  5 5X,*PERCENT OF AVAILABLE ENERGY TAKEN UP IN THE SENSIBLE HEAT*,
  6  * OF*/7X,*THE FUEL AND THE SORBED WATER THAT IS NOT EVAPORATED*,
  7 13X,20X,F15.4,5X,*(PERCENT)*)
117 FORMAT(/20X,*SIMULATION OUTPUT DATA*/)
118 FORMAT(10X,*PARAMETERS*,56X,*WITHOUT DRYER*,9X,*WITH DRYER*,
  1 8X,*PERCENT CHANGE/*)
119 FORMAT(5X,*FUEL - DRYER STREAMS (PARAMETERS UNDER "WITHOUT",
  1  * DRYER" DENOTE*/28X,*CONDITIONS, ETC, OF INPUT STREAM TO*,
  2 28X,*PARAMETERS UNDER "WITH DRYER" DENOTE*/
  3 28X,*CONDITIONS OF OUTPUT STREAM FROM DRYER")*)
120 FORMAT(7X,*MOISTURE CONTENT; DRY BASIS (PERCENT)*)
  1 28X,3(F15.4,5X)/
  1 7X,*MOISTURE CONTENT; WET BASIS (PERCENT)*)
  1 28X,3(F15.4,5X))
121 FORMAT(7X,*FLOW RATE; DRY (LB/HR)*,43X,3(F15.4,5X)/7X,
  1 *FLOW RATE; WET (LB/HR)*)
122 FORMAT(7X,*TEMPERATURE (DEG.F)*,46X,3(F15.4,5X))
123 FORMAT(/5X,*FUEL - BYPASS (OR BLEND) STREAM*/
124 FORMAT(7X,*MOISTURE CONTENT; DRY BASIS (PERCENT)*)
  1 28X,20X,F15.4/
  1 7X,*MOISTURE CONTENT; WET BASIS (PERCENT)*)
125 FORMAT(7X,*FLOW RATE; DRY (LB/HR)*,43X,20X,F15.4/
  1 7X,*FLOW RATE; WET (LB/HR)*)
126 FORMAT(7X,*TEMPERATURE (DEG.F)*)
127 FORMAT(/5X,*FUEL - GROSS TOTAL TO BOILER*/

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without Dryer</th>
<th>With Dryer</th>
<th>Percentage Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOISTURE CONTENT (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOISTURE CONTENT (wet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW RATE (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW RATE (wet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE (deg F)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FUNCTION ENBAL(VAR,K,ENT)

FUNCTION ENBAL IS THE FUNCTION ACCESSED BY SUBROUTINE ZSYSTEM TO FURNISH THE VALUES OF THE FUNCTIONS WHICH DEFINE THE SYSTEM OF (NONLINEAR) EQUATIONS BEING SOLVED

AS A REMINDER,

VAR(1)=FFRD3, THE MASS FLOW RATE OF DRY FUEL EXITING THE DRYER (LBR)
VAR(2)=FMCD3, THE MOISTURE CONTENT, DRY BASIS, OF SAID FUEL

DIMENSION VAR(2)
COMMON/TEMP/TREF,TAM,TF1,TF2,TF3,TDI,TDE,TBE
COMMON/HEAT/CW,CICE,DELHF,HFH2OL,HFH20G,HFCO2,HTLFB,QSTEAM,HHV
COMMON/MOIST/FMCD1,FMCD2,FMCD3,T,FHR,GSF
COMMON/QUANT/XT,X,Y,Z,O2FED,O2REQ,N2FED,H2OFED,FR,DRYEFF,ALF
COMMON/BICK/FUEL3,SORBWA3,FUEL2,SORBWA2,COMAIR,EINB
COMMON/DOCK/EXGASB,EXWAB,EOUTB,HTLOSB
COMMON/DICK/FUEL1,SORBWA1,GASIN,WAIN,AIRIN,AIR,EIND
COMMON/DOCK/FUEL3XD,SORBWAX,EXGASD,EXWAD,VAPWA,AIROUT,EOUTD

REAL N2FED

DM=1.0
FFRD3=VAR(1)
FMCD3=VAR(2)
GO TO (5,10),K

SECTION 1
MATERIAL (IMPLICIT) AND ENERGY BALANCE ABOUT BOILER
RELATIVE TO 77 DEGREES FAHRENHEIT

INPUT

5 FUEL3=ENT(2,DM,DM,TREF,TF3)+ENT(3,DM,FMCD3,DM,DM)
FUEL2=(1.0/FR)*(ENT(2,DM,DM,TREF,TF2)+ENT(3,DM,FMCD2,DM,DM))
SORBWA2=(1.0/FR)*(FMCD2/18.016)*(ENT(4,DM,DM,TREF,TF2)+H2H2OL)
COMAIR=((1.0+FR)/FR)*(02FED*ENT(1,5,DM,TREF,TAM)
=+N2FED*ENT(1,4,DM,TREF,TAM)+H2OFED*ENT(1,3,DM,TREF,TAM)
+H2OFED)
EINB=FFRD3*(FUEL3+SORBWA3+FUEL2+SORBWA2+COMAIR)

OUTPUT

EXGASB=((1.0+FR)/FR)*(XT*(ENT(1,2,DM,TREF,TBE)+HFCO2)
+H2OFED*ENT(1,4,DM,TREF,TBE)+(02FED-02REO)*ENT(1,5,DM,TREF,TBE))
EXWAB=((FMCD3/18.016)+(1.0/FR)*(FMCD2/18.016)+((1.0+FR)/FR)*(1.0/FR)
+H2OFED**)(ENT(1,3,DM,TREF,TBE)+H2H2OL)
EOUTB=FFRD3*(EXGASB+EXWAB)

STEAM LOAD + HEAT LOSS + ENTHALPY(IN) - ENTHALPY(OUT) = 0

HTLOSB=ABS(HTLFB*FFRD3*((1.0+FR)/FR)*HHV)
ENBAL=EINB-EOUTB-HTLOSB-QSTEAM
RETURN

SECTION 2
MATERIAL (IMPLICIT) AND ENERGY BALANCE ABOUT DRYER

INPUT

10 FUEL1=ENT(2,DM,DM,TREF,TF2)+ENT(3,DM,FMCD1,DM,DM)
SORBWA1=(FMCD1/18.016)*(ENT(4,DM,DM,TREF,TF2)+H2H2OL)
GASIN = ((1.0 + FR)/FR) * (XT * (ENT(1, 2, DM, TREF, TD1) + HFCO2)
+ (02FED - 02REQ) * ENT(1, 5, DM, TREF, TD1) + H2OFED * ENT(1, 4, DM, TREF, TD1))
WAIN = ((FMCD3/18.016) + (1.0/FR) * (FMCD2/18.016) + ((1.0 + FR)/FR) * (Y/2.0) + H2OFED) * (ENT(1, 3, DM, TREF, TDE) + HFH20G)
AIR = ALF * ((1.0 + FR)/FR) * (XT * (ENT(1, 2, DM, TREF, TD1) + HFCO2)
+ (02FED - 02REQ) * ENT(1, 5, DM, TREF, TD1) + H2OFED)
AIRIN = AIR * (0.79 * ENT(1, 4, DM, TREF, TAM) + 0.21 * ENT(1, 5, DM, TREF, TAM) + FHR * (29.0/18.016) * (ENT(1, 3, DM, TREF, TDE) + HFH20G))
EIND = FFRD3 * (FUEL1 + SORBWA1 + GSF * (GASIN + WAIN + AIRIN))

OUTPUT

FMCD3T = (1.0/DRIEFF) * (FMCD3 - FMCD1) + FMCD1
FUEL3XD = ENT(2, DM, DM, TREF, TF3) + ENT(3, DM, FMCD3T, DM, DM)
SORBWAX = (FMCD3T/18.016) * (ENT(4, DM, DM, TREF, TF3) + HFH20L)
EXGASD = ((1.0 + FR)/FR) * (XT * (ENT(1, 2, DM, TREF, TDE) + HFCO2)
+ (02FED - 02REQ) * ENT(1, 5, DM, TREF, TDE) + H2OFED) * ENT(1, 4, DM, TREF, TDE)
EXWAD = ((FMCD3/18.016) + (1.0/FR) * (FMCD2/18.016) + ((1.0 + FR)/FR) * (Y/2.0)
+ H2OFED) * (ENT(1, 3, DM, TREF, TDE) + HFH20G)
VAPWA = ((FMCD1 - FMCD3T)/18.016) * (ENT(1, 3, DM, TREF, TDE) + HFH20G)
AIROUT = AIR * (0.79 * ENT(1, 4, DM, TREF, TDE) + 0.21 * ENT(1, 5, DM, TREF, TDE) + FHR * (29.0/18.016) * (ENT(1, 3, DM, TREF, TDE) + HFH20G))
EOUTD = FFRD3 * (FUEL3XD + SORBWA1 + GSF * (EXGASD + EXWAD + AIROUT) + VAPWA)

HEAT LOSS + ENTHALPY(IN) - ENTHALPY(OUT) = 0

HTLOSSD = 0.0
ENBAL = EIND - EOUTD - HTLOSSD
RETURN

FUNCTION PC(UO, W)
PC = ((W - WO)/WO) * 100.0
RETURN

FUNCTION ENT(K, J, FMCD, T1, T2)
FUNCTION ENT IS THE FUNCTION ACCESSED BY BOTH THE MAIN,
OR MASTER, PROGRAM AND THE SUBROUTINE ZSYSTM TO CALCULATE
VARIOUS THERMODYNAMIC QUANTITIES, IE., ENTHALPYS RELATIVE TO
THE REFERENCE TEMPERATURE
K REFERS TO THE "MINIFUNCTION" WITHIN ENT
THAT IS ACCESSED BY ENBAL
J IS THE CHARACTERISTIC SPECIES NUMBER;

CO=SPECIES 1
CO2=SPECIES 2
H2O=SPECIES 3
N2=SPECIES 4
O2=SPECIES 5

FMCD FUEL MOISTURE CONTENT, DRY BASIS
T1 INITIAL (USUALLY REFERENCE) TEMPERATURE
T2 FINAL (SPECIES OR STREAM) TEMPERATURE

COMMON/RARE/HFDW,N
COMMON/HEAT/CW,CICE,DELHF,HFH2O,L,HFH2O,G,HTLOSS,QSTEAM,HHV

DIMENSION A(5),B(5),C(5),D(5)
DATA (A(I),I=1,5)/6.9192,8.6305,7.997,6.93117,6.95507/
DATA (B(I),I=1,5)/0.04912E-02,0.50586E-02,0.08222E-02,
1 0.02628E-02,0.13838E-02/
DATA (C(I),I=1,5)/0.02827E-05,-0.230E-05,0.06058E-05,
1 0.04559E-05,-0.04841E-05/
DATA (D(I),I=1,5)/-0.13265E-09,0.44598E-09,-0.21469E-09,
1 -0.17155E-09,0.07833E-09/

N=N+1
GO TO (5,10,15,20),K

5 TC2=(T2-32.0)/1.8
TC1=(T1-32.0)/1.8
ENT=A(J)*(TC2-TC1)+B(J)*(TC2*TC2-TC1*TC1)+C(J)*(TC2**3-TC1**3)
1  +D(J)*(TC2**4-TC1**4)
RETURN

10 TC2=(T2-32.0)/1.8
TC1=(T1-32.0)/1.8
ENT=0.266*(TC2-TC1)+0.000580*(TC2*TC2-TC1*TC1)
RETURN

15 FN=FMCD
QBOUND=284.0
IF(FMCD.LT.0.1111) QBOUND=354.0
IF(FMCD.GT.0.25) FN=0.25
ENT=HFDW-FN*QBOUND
RETURN

20 AA=0.0
BB=1.0
IF(T2.LT.32.0) AA=1.0
IF(T2.LT.32.0) BB=0.0
ENT=AA*(CICE*(T2-32.0)-DELHF+CW*(32.0-T1))+BB*CW*(T2-T1)
RETURN
END
## SIM1 Sample Output

### Boiler/Dryer Tandem Simulation Data and Output

**Raymond W. Kirk**  
Department of Chemical Engineering  
Department of Forest Products  
Oregon State University  
Corvallis, Oregon

#### Simulation Input Data

**Fuel Characteristics**
- Higher Heating Value of Dry Fuel (HHV)
- Carbon Fraction in Dry Fuel (Ultimate Analysis)
- Hydrogen Fraction in Dry Fuel (Ultimate Analysis)
- Oxygen Fraction in Dry Fuel (Ultimate Analysis)
- Wet Fuel Moisture Content; Dry Basis
- Wet Fuel Moisture Content; Wet Basis
- Wet Fuel Temperature (Usually Assumed to Be Ambient Temperature)

**Operational Parameters and Constraints**
- Ambient Temperature
- Ambient Humidity Ratio
- Combustion Excess Air
- Boiler Exhaust Temperature
- Radiative, Convective, and Unaccounted Losses in Boiler, Expressed as Percent Higher Heating Value
- Carbon/Charcoal Losses (Carryover), Expressed as Percent of Ultimate Analysis of Carbon in Fuel
- Boiler Steam Load (Mass)
- Boiler Steam Load (Energy)
- Fuel Feed Ratio, Expressed as the Ratio of (Dry) Fuel Passing Through Dryer to (Dry) Fuel Bypassing Dryer
- Dryer Inlet Temperature
- Dryer Air Leakage, Expressed as Percent of Incoming Dry Gas from Boiler Exhaust
- Dryer Exhaust Temperature
- Fuel Temperature; Dryer Exit

<table>
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<tr>
<th>Characteristic</th>
<th>Value 1</th>
<th>Unit 1</th>
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<tbody>
<tr>
<td>Higher Heating Value of Dry Fuel</td>
<td>9050.0000</td>
<td>(BTU/LB)</td>
</tr>
<tr>
<td>Carbon Fraction in Dry Fuel</td>
<td>52.3000</td>
<td>(PERCENT MASS)</td>
</tr>
<tr>
<td>Hydrogen Fraction in Dry Fuel</td>
<td>6.3000</td>
<td>(PERCENT MASS)</td>
</tr>
<tr>
<td>Oxygen Fraction in Dry Fuel</td>
<td>40.5000</td>
<td>(PERCENT MASS)</td>
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<tr>
<td>Wet Fuel Moisture Content; Dry Basis</td>
<td>100.0000</td>
<td>(PERCENT MASS)</td>
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<tr>
<td>Wet Fuel Moisture Content; Wet Basis</td>
<td>50.0000</td>
<td>(PERCENT MASS)</td>
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<tr>
<td>Wet Fuel Temperature</td>
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<td>(DEG.F)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>60.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Ambient Humidity Ratio</td>
<td>0.076</td>
<td>(LB H2O/LB DRY AIR)</td>
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<tr>
<td>Combustion Excess Air</td>
<td>100.0000</td>
<td>(PERCENT)</td>
</tr>
<tr>
<td>Boiler Exhaust Temperature</td>
<td>400.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Radiative, Convective, and Unaccounted Losses</td>
<td>5.0000</td>
<td>(PERCENT)</td>
</tr>
<tr>
<td>Carbon/Charcoal Losses (Carryover)</td>
<td>8.6000</td>
<td>(PERCENT)</td>
</tr>
<tr>
<td>Boiler Steam Load (Mass)</td>
<td>100000.0000</td>
<td>(LB/HR)</td>
</tr>
<tr>
<td>Boiler Steam Load (Energy)</td>
<td>106.0000</td>
<td>(MBTU/HR)</td>
</tr>
<tr>
<td>Fuel Feed Ratio</td>
<td>100000.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Dryer Inlet Temperature</td>
<td>400.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Dryer Air Leakage</td>
<td>10.0000</td>
<td>(PERCENT)</td>
</tr>
<tr>
<td>Dryer Exhaust Temperature</td>
<td>200.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Fuel Temperature; Dryer Exit</td>
<td>110.0000</td>
<td>(DEG.F)</td>
</tr>
<tr>
<td>Parameters</td>
<td>Without Dryer</td>
<td>With Dryer</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>Boiler Efficiency (Percent)</td>
<td>60.6557</td>
<td>65.2911</td>
</tr>
<tr>
<td>Fuel - Gross Total to Boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content; Dry Basis (Percent)</td>
<td>100.0000</td>
<td>67.1651</td>
</tr>
<tr>
<td>Moisture Content; Wet Basis (Percent)</td>
<td>50.0000</td>
<td>40.1789</td>
</tr>
<tr>
<td>Flow Rate; Dry (LB/HR)</td>
<td>19310.1451</td>
<td>17935.2227</td>
</tr>
<tr>
<td>Flow Rate; Wet (LB/HR)</td>
<td>30620.2902</td>
<td>29986.1276</td>
</tr>
<tr>
<td>Fuel Savings; Dry (LB/HR)</td>
<td>1370.9224</td>
<td>2741.8448</td>
</tr>
<tr>
<td>Fuel Savings; Wet (LB/HR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel - Dryer Streams (Parameters under &quot;Without Dryer&quot; denote conditions, etc, of input stream to dryer; parameters under &quot;With Dryer&quot; denote conditions of output stream from dryer)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content; Dry Basis (Percent)</td>
<td>100.0000</td>
<td>67.1640</td>
</tr>
<tr>
<td>Moisture Content; Wet Basis (Percent)</td>
<td>50.0000</td>
<td>40.1788</td>
</tr>
<tr>
<td>Flow Rate; Dry (LB/HR)</td>
<td>17939.0433</td>
<td>17939.0433</td>
</tr>
<tr>
<td>Flow Rate; Wet (LB/HR)</td>
<td>35878.0866</td>
<td>29987.7088</td>
</tr>
<tr>
<td>Temperature (Deg.F)</td>
<td>60.0000</td>
<td>110.0000</td>
</tr>
<tr>
<td>Fuel - Bypass (or Blend) Stream</td>
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<td></td>
</tr>
<tr>
<td>Moisture Content; Dry Basis (Percent)</td>
<td>100.0000</td>
<td>100.0000</td>
</tr>
<tr>
<td>Moisture Content; Wet Basis (Percent)</td>
<td>50.0000</td>
<td>50.0000</td>
</tr>
<tr>
<td>Flow Rate; Dry (LB/HR)</td>
<td>.1794</td>
<td>.3589</td>
</tr>
<tr>
<td>Flow Rate; Wet (LB/HR)</td>
<td>.1794</td>
<td>.3589</td>
</tr>
<tr>
<td>Temperature (Deg.F)</td>
<td>60.0000</td>
<td>60.0000</td>
</tr>
<tr>
<td>Combustion Air Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Temperature (Deg.F)</td>
<td>60.0000</td>
<td>60.0000</td>
</tr>
<tr>
<td>Flow Rate (SCFM)</td>
<td>51803.6595</td>
<td>48125.8623</td>
</tr>
<tr>
<td>Flow Rate (ACFM)</td>
<td>54754.2341</td>
<td>50866.9611</td>
</tr>
<tr>
<td>Flow Rate; Dry (LB/HR)</td>
<td>248059.1339</td>
<td>230448.1930</td>
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<tr>
<td>Flow Rate; Wet (LB/HR)</td>
<td>249936.9416</td>
<td>232192.6058</td>
</tr>
<tr>
<td>Humidity Ratio (LB H2O/LB Dry Gas)</td>
<td>.0076</td>
<td>.0076</td>
</tr>
</tbody>
</table>
### Boiler Exhaust Characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Exhaust Temperature (Deg.F)</td>
<td>400.000</td>
<td>400.000</td>
<td>10.2797</td>
</tr>
<tr>
<td>Flow Rate (Scfm)</td>
<td>61513.9996</td>
<td>55190.5618</td>
<td>-10.2797</td>
</tr>
<tr>
<td>Flow Rate (Acfm)</td>
<td>107561.8907</td>
<td>96504.8961</td>
<td>-10.2797</td>
</tr>
<tr>
<td>Flow Rate; Dry (Lb/hr)</td>
<td>255612.2299</td>
<td>237465.0574</td>
<td>-7.0995</td>
</tr>
<tr>
<td>Flow Rate; Wet (Lb/hr)</td>
<td>287672.1179</td>
<td>261358.3380</td>
<td>-9.1471</td>
</tr>
<tr>
<td>Humidity Ratio (Lb H20/Lb Dry Gas)</td>
<td>.1254</td>
<td>.1006</td>
<td></td>
</tr>
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</table>

### Dryer Inlet Gas Characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer Inlet Temperature (Deg.F)</td>
<td>400.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate (Scfm)</td>
<td>55190.5618</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate (Acfm)</td>
<td>96504.8961</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate; Dry (Lb/hr)</td>
<td>237465.0574</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate; Wet (Lb/hr)</td>
<td>261358.3380</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity Ratio (Lb H20/Lb Dry Gas)</td>
<td>.1006</td>
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</table>

### Dryer Air Leakage Characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature (Deg.F)</td>
<td>60.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dryer Air Leakage (Percent - See Above)</td>
<td>10.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate (Scfm)</td>
<td>47923.1064</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate (Acfm)</td>
<td>50555.5372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate; Dry (Lb/hr)</td>
<td>22903.8856</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate; Wet (Lb/hr)</td>
<td>23077.2680</td>
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<td></td>
</tr>
<tr>
<td>Humidity Ratio (Lb H20/Lb Dry Gas)</td>
<td>.0076</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Dryer Exhaust Characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer Exhaust Temperature (Deg.F)</td>
<td>200.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate (Scfm)</td>
<td>59973.4682</td>
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</tr>
<tr>
<td>Flow Rate (Acfm)</td>
<td>80469.1447</td>
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<td></td>
</tr>
<tr>
<td>Flow Rate; Dry (Lb/hr)</td>
<td>260368.9430</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Rate; Wet (Lb/hr)</td>
<td>290326.1239</td>
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<td></td>
</tr>
<tr>
<td>Humidity Ratio (Lb H20/Lb Dry Gas)</td>
<td>.1151</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

0.260 CP SECONDS EXECUTION TIME.
Calculate fuel flow rate, etc., for boiler alone (used as initial "guesstimate" for FFRD3; stockpile fuel moisture content (FMCD1) used for initial "guesstimate" of FMCD)

CALL ZSYSTM

CALL ENBAL

Summary Calculations

Printout

STOP

(FFRD3_i, FMCD3_i)

(FFRD3_{i+1}, FMCD3_{i+1})

yes

decision

no

i = i + 1

do: FFRD3_{i+1} = FFRD3_i
FMCD3_{i+1} = FMCD3_i

Figure E.11 Program SIM2 flowchart
SIM2 Program Listing

LIST,F=KIRK12
PROGRAM KIRK12 (OUTPUT,TAPE6=OUTPUT)

EXTERNAL ENBAL,ENT
DIMENSION VAR(2),WA(8),FMW(6)
COMMON/TEMP/TREF,TAM,TF1,TF2,TF3,TDI,TDE,TBE
COMMON/HEAT/CW,CICE,DELHF,HFH20L,HFH20G,HFCO2,HTLFB,OSTEAM,HHV
COMMON/QUANT/XT,X,Y,Z,O2FED,O2REG,N2FED,H2OFED,FR,DYREFF,ALF
COMMON/MOIST/FMCD1,FMCD2,FMCDO,FHR,GSF
COMMON/RARE/HFDW,N
COMMON/PART/PCT1,PCT2,EPSDE,EPSFT,JMAX,LMAX,DELTAT
COMMON/BICK/FUEL3,SORBWA3,FUEL2,SORBWA2,COAIR,EINB
COMMON/BOCK/EXGASB,EXWAB,EOUTB,HTLOSSB
COMMON/DICK/AVD,AWD,AVAILEN,DHL,DSENS
COMMON/DOCK/AVDRY,EWIN,EWAIN,EWAOUT
COMMON/LAW/BXG,BXW,AIR,DAL

REAL N2FED

DATA CW,CICE,DELHF/18.021,9.0440,2585.768/
DATA HFH20L,HFH20G,HFCO2/-122991.23,-104054.61,-169315.18/
DATA ULTC,ULTH,ULTO,HHV/0.523,0.063,0.405,9050.0/
DATA TREF,TAM,TF1,TF2,TF3/77.0,60.0,60.0,100.0/
DATA TDI,TDE,TBE,FHR,ALF,GSF/400.0,200.0,400.0,0.0076,0.10,1.0/
DATA FMCD1,FMCD2,PCTCL/1.00,1.00,0.0860/
DATA OSTEAM,FR,HTLFB,DYREFF,EA/106000000.0,0.001,0.05,1.0,1.00/
DATA GMSTEAM/100000.0/
DATA NSIG,EPS,ITMAX,M/3,1.0E-04,50,2/
DATA (FMW(I),I=1,6)/28.01,44.01,18.016,28.02,32.00,29.00/
DATA PCT1,PCT2,EPSDE,EPSFT,JMAX,LMAX,DELTAT/0.50,0.025,1.0E-03,1.0E-03,25,25,0.01/

PRELIMINARY CALCULATIONS

N=0
X=ULTC/12.01115
XT=(1.0-PCTCL)*X
Calculate fuel requirement for boiler sans dryer, assuming the fuel temperature and fuel moisture content (dry basis) to be the respective temperature and moisture content of the stockpile.

In addition to use as a comparison with fuel flowrate with dryer on line, these values are used as initial estimates for the subroutine ZSYSTM.

```
Y = ULTH / 1.00797
Z = UTLQ / 15.9994
02REQ = X * Y / 4.0 - Z / 2.0
02FED = 02REQ * (1.0 + EA)
N2FED = 3.7619 * 02FED
AIRFED = 4.7619 * 02FED
H2OFED = AIRFED * (29.0 / 18.016) * FHR
HFDW = Y / 2.0 * HFH20L + X * HFCO2 + HHV
02REQ = (XT / X) * 02REQ
```

```
DM = 1.0
COMGAS = 02FED * ENT(1, 5, DM, TREF, TAM) + N2FED * ENT(1, 4, DM, TREF, TAM)
1 + H2OFED * ENT(1, 3, DM, TREF, TAM) + HFH20G
COMFUEL = ENT(2, DM, DM, TREF, TF1) + ENT(3, DM, FMCD1, DM, DM)
SORBH20 = ENT(4401, DM, TREF, TF1) + HFH2O1
EI = COMGAS + COMFUEL + (FMCD1 / 18.016) * SORBH20
EXGAS = XT * (ENT(1, 2, DM, TREF, TBE) + HFCO2) + N2FED * ENT(1, 4, DM, TREF, TBE)
1 + (02FED - 02REQ) * ENT(1, 5, DM, TREF, TBE)
2 + Y / 2.0 * FMCD1 / 18.016 + H2OFED) * (ENT(1, 3, DM, TREF, TBE) + HFH20G)
FUEL = OSTEAM / ((EI - EXGAS) - HTLFB * HHV)
EFDW = OSTEAM / (FUEL * HHV)
```

```
VAR(1) = FUEL
VAR(2) = FMCD1
```

```
CALL ZSYSTM(ENBAL, EPS, NSIG, H, VAR, ITMAX, WA, ENT, IER)
```

Summary calculations and printout statements

Fuel flow rates; dry basis

```
FFRD3 = VAR(1)
FFRD2 = FFRD3 / FR
FFRDT = FFRD2 + FFRD3
FFRDCOMP = FFRDT * (1.0 + FMCD1)
```
FSAVD=FUEL-FFRDT

MOISTURE CONTENTS

FMCD3=VAR(2)
FMCDT=(FMCD2*FFRD2+FMCD3*FFRD3)/FFRDT
FMCD1=FMCD1/(1.0+FMCD1)
FMCD2=FMCD2/(1.0+FMCD2)
FMCD3=FMCD3/(1.0+FMCD3)
FMCDT=FMCDT/(1.0+FMCDT)

FUEL FLOW RATES; WET BASIS

FFRD1=FFRD3
FFRW1=FFRD1*(1.0+FMCD1)
FFRW2=FFRD2*(1.0+FMCD2)
FFRW3=FFRD3*(1.0+FMCD3)
FFRWT=FFRDT*(1.0+FMCD7)
FUELW=FUEL*(1.0+FMCD1)
FSAVW=FUELW-FFRCOMP

EFFBW=GSTEAM/(FFRDT*HHU)
OSTEAM2=GSTEAM/1.0E+06

MOISTURE CONTENTS;
CONVERSION FROM DECIMAL FRACTION TO PERCENT

PCFMCD1=100.0*FMCD1
PCFMCD2=100.0*FMCD2
PCFMCD3=100.0*FMCD3
PCFMCDT=100.0*FMCDT
PCFMCW1=100.0*FMCW1
PCFMCW2=100.0*FMCW2
PCFMCW3=100.0*FMCW3
PCFMCGT=100.0*FMCWT

VARIOUS PARAMETERS;
CONVERSION FROM DECIMAL FRACTION TO PERCENT

PCULTC=ULTC*100.0
PCULTH=ULTH*100.0
PCULTO=ULTO*100.0
PCEFBW0=EFFBW0*100.0
PCEFBW=EFFBW*100.0
PCALF=ALF*100.0
PCPCT1=PCT1*100.0
PCPCT2=PCT2*100.0
PCPCTCL=PCTCL*100.0
PCEA=EA*100.0
PCHTLB=HTLFB*100.0
CALCULATION OF GAS FLOW RATES

\[
\begin{align*}
\text{SCFMCA} &= (\text{AIRFED} + \text{H2OFED}) \times (359.0/60.0) \times \text{FFRDT} \\
\text{ACFMCA} &= \text{SCFMCA} \times ((459.6 + \text{TAM}) / 491.6) \\
\text{SCFMIA} &= (\text{AIRFED} + \text{H2OFED}) \times (359.0/60.0) \times \text{FUEL} \\
\text{ACFMIA} &= \text{SCFMIA} \times ((459.6 + \text{TAM}) / 491.6) \\
\text{SCFMBE} &= (\text{AIRFED} - \text{O2RE0} + \text{H2OFED} + \text{XT} + (\text{FMCDT}/18.016) \\
&\quad \times (359.0/60.0) \times \text{FFRT} \\
\text{ACFMBE} &= \text{SCFMBE} \times ((459.6 + \text{TBE}) / 491.6) \\
\text{SCFMIE} &= (\text{AIRFED} - \text{O2RE0} + \text{H2OFED} + \text{XT} + (\text{FMCD1}/18.016) \\
&\quad \times (359.0/60.0) \times \text{FUEL} \\
\text{ACFMIE} &= \text{SCFMIE} \times ((459.6 + \text{TBE}) / 491.6) \\
\text{SCFMDE} &= \text{SCFMDE} \times ((459.6 + \text{TDI}) / 491.6) \\
\text{SCFMDE} &= \text{SCFMDE} \times (\text{GSF} \times \text{AIR} \times (1.0 + \text{FHR} \times (29.0/18.016)) \\
&\quad \times (359.0/60.0) \times \text{FRD3} \\
\text{ACFMDE} &= \text{SCFMIE} \times ((459.6 + \text{TBE}) / 491.6) \\
\text{SCFMAL} &= \text{GSF} \times \text{AIR} \times (1.0 + \text{FHR} \times (29.0/18.016)) \times (359.0/60.0) \times \text{FRD3} \\
\text{ACFMAL} &= \text{SCFMAL} \times ((459.6 + \text{TAM}) / 491.6)
\end{align*}
\]

\[
\begin{align*}
\text{CATERMD} &= \text{AIRFED} \times \text{FMU}(6) \\
\text{CATERMW} &= \text{H2OFED} \times \text{FMU}(3) \\
\text{BETERMD} &= \text{AIRFED} \times \text{FMU}(6) - \text{O2RE0} \times \text{FMU}(5) + \text{XT} \times \text{FMU}(2) \\
\text{BETERM} &= (\text{Y} / 2.0 + \text{H2OFED}) \times \text{FMU}(3)
\end{align*}
\]

\[
\begin{align*}
\text{FMCAW} &= \text{CATERMD} \times \text{FFRDT} \\
\text{FMCAW} &= \text{CATERMW} \times \text{FFRDT} \\
\text{FMCAT} &= \text{FMCAW} \times \text{FFRDT} \\
\text{HRCAC} &= \text{FMCAW} / \text{FMCAW}
\end{align*}
\]

\[
\begin{align*}
\text{FM1AD} &= \text{CATERMD} \times \text{FUEL} \\
\text{FM1AW} &= \text{CATERMW} \times \text{FUEL} \\
\text{FM1AT} &= \text{FM1AD} \times \text{FM1AW} \\
\text{HR1A} &= \text{FM1AT} / \text{FM1AT}
\end{align*}
\]

\[
\begin{align*}
\text{FM1ED} &= \text{BETERMD} \times \text{FFRRT} \\
\text{FM1EW} &= (\text{BETERM2} + \text{FMCDT}) \times \text{FFRRT} \\
\text{FMBE} &= \text{FM1ED} \times \text{FM1EW} \\
\text{HRBE} &= \text{FMBE} / \text{FM1ED}
\end{align*}
\]

\[
\begin{align*}
\text{FMDID} &= \text{GSF} \times \text{FM1ED} \\
\text{FMDIW} &= \text{GSF} \times \text{FM1EW} \\
\text{FMDIT} &= \text{GSF} \times \text{FMBE} \\
\text{HRDI} &= \text{HRBE}
\end{align*}
\]

\[
\begin{align*}
\text{FMDAL} &= \text{GSF} \times \text{AIR} \times \text{FMU}(6) \times \text{FFRRT}
\end{align*}
\]
C

FMDALW=FMDALD\times FHR
FMDALT=FMDALD+FMDALW

C

FMDE=FMDD+FMDDL
FMDEW=FMDDW+FMDDL+(FMCD1-FMCD3)\times FFRD3
FMDEW=FMDEN+FMDEW
HRDE=FMDEW/FMDEW

C

CALCULATION OF PERCENT CHANGE OF PARAMETERS
RESULTING FROM INCORPORATION OF DRYER

PCBE=PC(EFFW0, EFFB)
PCMCDD=PC(FMCD1, FMCD3)
PCMCWD=PC(FMCW1, FMCW3)
PCTF3=PC(TF1, TF3)

C

PCMC=PC(FMCD1, FMCDT)
PCMCWD=PC(FMCW1, FMCW1)
PCFRTD=PC(FUEL, FFRB)
PCFRWT=PC(FUELW, FFRRC)

C

PCAS=PC(SCFM1A, SCFMCA)
PCUA=PC(ACFM1A, ACFMCA)

C

PCBE=PC(SCFM1E, SCFMBE)
PCBEA=PC(ACFM1E, ACFMBE)

C

PCFMBED=PC(FM1ED, FM1ED)
PCFMBET=PC(FM1ET, FM1ET)
PCHRBE=PC(HR1E, HRBE)

C

WRITE STATEMENTS

WRITE(6,100)
WRITE(6,101)
WRITE(6,104) HHV
WRITE(6,102) PCULTC, PCULTH, PCULTO
WRITE(6,105) PCFMC1, PCFMCW1
WRITE(6,106) TF1
WRITE(6,107)
WRITE(6,108) TAM, FHR
WRITE(6,110) PCEA
WRITE(6,109) TBE
WRITE(6,111) PCHTLB
WRITE(6,112) PCPCPLC
WRITE(6,113) QMSTEAM, QSTEAM2
WRITE(6,114) FR
WRITE(6,115) TDI, PCALF
WRITE(6,116) PCPC1, PCPC2

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103 FORMAT(* *)
104 FORMAT(5X,*HIGHER HEATING VALUE OF DRY FUEL (HHV)*,29X,20X,
1  F15.4,5X,* (BTU/LB)*)
105 FORMAT(5X,*WET FUEL MOISTURE CONTENT; DRY BASIS*,31X,20X,F15.4,5X,
1  *(PERCENT MASS)*/5X,*WET FUEL MOISTURE CONTENT; WET BASIS*,31X,
2  20X,F15.4,5X,* (PERCENT MASS)*)
106 FORMAT(5X,*WET FUEL TEMPERATURE (USUALLY ASSUMED TO BE AMBIENT*,
1  1  * TEMPERATURE)*,3X,20X,F15.4,5X,* (DEG.F)*)
107 FORMAT(/15X,*OPERATIONAL PARAMETERS AND CONSTRAINTS*/)
108 FORMAT(5X,*AMBIENT TEMPERATURE*,46X,20X,F15.4,5X,* (DEG.F)*/
1  5X,*AMBIENT HUMIDITY RATIO*,45X,20X,F15.4,5X,* (LB H2O/LB DR/4,
2  * AIR*)
109 FORMAT(5X,*BOILER EXHAUST TEMPERATURE*,41X,20X,F15.4,5X,* (DEG.F)*)
110 FORMAT(5X,*COMBUSTION EXCESS AIR*,46X,20X,F15.4,5X,* (PERCENT)*)
111 FORMAT(5X,*RADIATIVE, CONVECTIVE, AND UNACCOUNTED LOSSES IN*,
1  1  1  * BOILER*,/7X,*EXRESSED AS PERCENT HIGHER HEATING VALUE*,
2  24X,20X,F15.4,5X,* (PERCENT)*)
112 FORMAT(5X,*CARBON/CHARCOAL LOSSES (CARRYOVER), EXPRESSED AS*/
1  1  1  7X,*PERCENT OF ULTIMATE ANALYSIS OF CARBON IN FUEL*,19X,20X,
2  F15.4,5X,* (PERCENT)*)
113 FORMAT(5X,*BOILER STEAM LOAD (MASS)*,43X,20X,F15.4,5X,* (LB/HR)*
1  5X,*BOILER STEAM LOAD (ENERGY)*,41X,20X,F15.4,5X,* (MBTU/HR)*)
114 FORMAT(5X,*FUEL FEED RATIO, EXPRESSED AS THE RATIO OF*/
1  1  1  7X,* (DRY) FUEL PASSING THROUGH DRYER TO (DRY) FUEL*,
2  2  BYPASSING DRYER*/3X,20X,F15.4)
115 FORMAT(5X,*DRYER INLET TEMPERATURE*,44X,20X,F15.4,5X,* (DEG.F)*/
1  5X,*DRYER AIR LEAKAGE, EXPRESSED AS PERCENT OF*/
2  7X,*INCOMING DRY GAS FROM BOILER EXHAUST*,29X,20X,F15.4,
3  5X,* (PERCENT)*)
116 FORMAT(5X,*THERMODYNAMIC (DRYING) EFFICIENCY, EXPRESSED AS*/
1  1  1  1  * PERCENT OF AVAILABLE*/7X,*ENERGY (RELATIVE TO THE AMBIENT*,
2  2  * TEMPERATURE)*,7X,* (IE, THAT PERCENT OF AVAILABLE ENERGY)*,
3  3  THAT IS USED TO*/7X,*EVAPORATE WATER FROM THE FUEL STREAM*,
4  4  * PASSING THROUGH THE DRYER)*,2X,20X,F15.4,5X,* (PERCENT)*
5  5  5X,*PERCENT OF AVAILABLE ENERGY TAKEN UP IN THE SENSIBLE HEAT*,
6  6  * OF*/7X,*THE FUEL AND THE SORBED WATER THAT IS NOT EVAPORATED*,
7  13X,20X,F15.4,5X,* (PERCENT)*)
117 FORMAT(/20X,*SIMULATION OUTPUT DATA*/)
118 FORMAT(10X,*PARAMETERS*,56X,*WITHOUT DRYER*,9X,*WITH DRYER*,
1  1  1  1  8X,*PERCENT CHANGE*/)
119 FORMAT(5X,*FUEL - DRYER STREAMS (PARAMETERS UNDER WITHOUT*,
1  1  1  1  * DRYER" DENOTE*/28X,*CONDITIONS, ETC, OF INPUT STREAM TO*,
2  2  DRYER);/28X,*PARAMETERS UNDER "WITH DRYER" DENOTE*/
3  3  28X,*CONDITIONS OF OUTPUT STREAM FROM DRYER")
120 FORMAT(7X,*MOISTURE CONTENT; DRY BASIS (PERCENT)*,28X,3(F15.4,5X)/
1  7X,*MOISTURE CONTENT; WET BASIS (PERCENT)*,28X,3(F15.4,5X))
121 FORMAT(7X,*FLOW RATE; DRY (LB/HR)*,43X,3(F15.4,5X)/7X,
1  1  FLOW RATE; WET (LB/HR)*,43X,3(F15.4,5X))
122 FORMAT(7X,*TEMPERATURE (DEG.F)*,46X,3(F15.4,5X))
123 FORMAT(/5X,*FUEL - BYPASS (OR BLEND) STREAM*)
FUNCTION ENBAL(VAR,K,ENT)

FUNCTION ENBAL IS THE FUNCTION ACCESSED BY SUBROUTINE ZSYSYM TO FURNISH THE VALUES OF THE FUNCTIONS WHICH DEFINE THE SYSTEM OF (NONLINEAR) EQUATIONS BEING SOLVED

AS A REMINDER,
VAR(1)=FFRD3, THE MASS FLOW RATE OF DRY FUEL EXITING THE DRYER

STOP
END

FUNCTION ENBAL(VAR,K,ENT)
VAR(2) = FMCD3, THE MOISTURE CONTENT, DRY BASIS, OF SAID FUEL

DIMENSION VAR(2)
COMMON/TEMP/TREF, TAM, TF1, TF2, TF3, TD1, TDE, TBE
COMMON/HEAT/CW, CICE, DELHF, HFH2OL, HFH2OG, HFCO2, HTLFB, QSTEAM, HHV
COMMON/MOIST/FMCD1, FMCD2, FMCD3, FHR, GSF
COMMON/QUANT/XT, X, Y, Z, O2FED, O2RED, N2FED, H2OFED, FR, DRYEFF, ALF
COMMON/PART/PCT1, PCT2, EPSDE, EPSFT, JMAX, LMAX, DELTAT
COMMON/BICK/FUEL3, SORBWA3, FUEL2, SORBWA2, COMAIR, EINB
COMMON/BOCK/EXGASB, EXWAB, EOUTB, HTLOSSB
COMMON/DICK/AVD, AWD, AVAILEN, QHTL, QSENS
COMMON/DOCK/AVDRY, EWAIN, EWAOIT

REAL N2FED

DM = 1.0
FFRD3 = VAR(1)
FMCD3 = VAR(2)
GO TO (5, 10), K

SECTION 1
MATERIAL (IMPLICIT) AND ENERGY BALANCE ABOUT BOILER
RELATIVE TO 77 DEGREES FAHRENHEIT

INPUT

FUEL3 = ENT(2, DM, DM, TREF, TF3) + ENT(3, DM, FMCD3, DM, DM)
SORBWA3 = (FMCD3/18.016) * (ENT(4, DM, DM, TREF, TF3) + HFH2OL)
FUEL2 = (1.0/FR) * (ENT(2, DM, DM, TREF, TF2) + ENT(3, DM, FMCD2, DM, DM))
SORBWA2 = (1.0/FR) * (FMCD2/18.016) * (ENT(4, DM, DM, TREF, TF2) + HFH2OL)
COMAIR = ((1.0 + FR)/FR) * (O2FED * ENT(1, 5, DM, TREF, TAM)
1 + N2FED * ENT(1, 4, DM, TREF, TAM) + H2OFED * (ENT(1, 3, DM, TREF, TAM))
2 + HFH20G))
EINB = FFRD3 * (FUEL3 + SORBWA3 + FUEL2 + SORBWA2 + COMAIR)

OUTPUT

EXGASB = ((1.0 + FR)/FR) * (XT * (ENT(1, 2, DM, TREF, TBE) + HFCO2)
EOUTB = FFRD3 * (EXGASB + EXWAB)

STEAM LOAD + HEAT LOSS + ENTHALPY(IN) - ENTHALPY(OUT) = 0

HTLOSSB = ABS(HTLFB * FFRD3 * (1.0 + FR)/FR * HHV)
ENBAL = EINB - EOUTB - HTLOSSB - QSTEAM
RETURN
SECTION 2
MATERIAL (IMPLICIT) AND ENERGY BALANCE ABOUT DRYER

DETERMINATION OF TOTAL ENERGY AVAILABLE IN EXHAUST FROM
BOILER (AVAILEN), RELATIVE TO THE AMBIENT TEMPERATURE
(QUASI-AVAILABILITY)

\[
10 \quad \text{AVAILEN} = \text{FFRD3} \times \text{GSF} \times (\text{AVD} + \text{AWD})
\]

\[
\text{AVD} = \frac{(1.0 + \text{FR})}{\text{FR}} \times (\text{XT} \times \text{ENT}(1, 2, \text{DM}, \text{TAM}, \text{TDI}) + \text{N2FED} \times \text{ENT}(1, 4, \text{DM}, \text{TAM}, \text{TDI}) + (\text{O2FED} - \text{O2REG}) \times \text{ENT}(1, 5, \text{DM}, \text{TAM}, \text{TDI}))
\]

\[
\text{AWD} = \left(\frac{\text{FMCD3}}{18.016}\right) + \left(\frac{1.0}{\text{FR}}\right) \times \left(\frac{\text{FMCD2}}{18.016}\right) + \left(\frac{1.0 + \text{FR}}{\text{FR}}\right) \times (\text{H2OFED} + \text{Y}/2.0) \times \text{ENT}(1, 3, \text{DM}, \text{TAM}, \text{TDI})
\]

DETERMINATION OF ENERGY "PARTITIONING", WHERE:

PCT1 = PERCENT OF AVAILABLE ENERGY USED IN THE EVAPORATION/
DRYING PROCESS (ESSENTIALLY THE THERMODYNAMIC
EFFICIENCY OF THE PROCESS)

PCT2 = PERCENT OF AVAILABLE ENERGY THAT IS "LOST" TO THE
SENSIBLE HEAT OF THE FUEL STREAM AND THE SORBED WATER THAT REMAINS WITH THE FUEL
THE REMAINING "AVAILABLE" ENERGY IS "LOST" TO CONVECTIVE
AND RADIATIVE THERMAL LOSSES, AIR LEAKAGE, AND TO THE ENVIRONMENT DIRECTLY (PURGED TO THE AMBIENT AT THE EXHAUST TEMPERATURE OF THE DRYER)

\[
\text{QHTL} = (1.0 - \text{PCT1} - \text{PCT2}) \times \text{AVAILEN}
\]

ITERATIVE DETERMINATION OF DRYER EXHAUST TEMPERATURE USING NEWTON’S METHOD

\[
\text{DO } 15 \text{ J}=1, \text{JMAX}
\]

\[
\text{F} = \text{DXT}(\text{TDE}, \text{TAM}, \text{QHTL}, \text{FFRD3})
\]

\[
\text{TDEP} = \text{TDE} + \text{DELTAT}
\]

\[
\text{FD} = \text{DXT}(\text{TDEP}, \text{TAM}, \text{QHTL}, \text{FFRD3})
\]

\[
\text{DFDT} = (\text{FD} - \text{F}) / \text{DELTAT}
\]

\[
\text{TDE2} = \text{TDE} - \text{F} / \text{DFDT}
\]

\[
\text{CHK} = \text{ABS}((\text{TDE2} - \text{TDE}) / \text{TDE})
\]

IF(\text{CHK}.LE.\text{EPSDE}) GO TO 20

15 \text{TDE} = \text{TDE2}

WRITE(6,16) \text{JMAX}, \text{TDE}

16 FORMAT(/10X,*NEWTON’S METHOD FOR DRYER EXHAUST TEMPERATURE*/
1 10X,*DOES NOT CONVERGE IN *,I4,* ITERATIONS*/
2 10X,*LATEST VALUE OF DRYER EXHAUST TEMPERATURE IS: *,F7.2,
3 *(DEG.FAHR.)*//10X,*EXECUTION CEASES AT THIS POINT*)

STOP

20 \text{TDE} = \text{TDE2}
ITERATIVE DETERMINATION OF FUEL STREAM EXIT TEMPERATURE
USING NEWTON'S METHOD

QSENS=PCT2*AVAILEN
DO 25 L=1,LMAX
F2=FXT(TF3,TF1,QSENS,FFRD3)
TF3P=TF3+DELTAT
FD2=FXT(TF3P,TF1,QSENS,FFRD3)
DF2DT=(FD2-F2)/DELTAT
TF32=TF3-F2/DF2DT
CHK=ABS((TF32-TF3)/TF3)
IF(CHK.LE.EPSFT) GO TO 70 30
25 TF3=TF32
WRITE(6,26) LMAX,TF3
26 FORMAT(/10X,*NEWTON'S METHOD FOR FUEL EXIT TEMPERATURE*/
  1 10X,*DOES NOT CONVERGE IN *,I4f,* ITERATIONS*/
  2 10X,*LATEST VALUE OF FUEL EXIT TEMPERATURE IS: *,F7.2,
  3 10X,*(DEG.FAHR.)*//10X,*EXECUTION CEASES AT THIS POINT*)
STOP

30 TF3=TF32

ENERGY BALANCE ON THAT WATER THAT IS ACTUALLY EVAPORATED
(REFERENCE STATE: THE ELEMENTS AT 77 DEG. FAHR. (TREF))

AVDRY=PCT1*AVAILEN

INPUT
EWAIN=ENT(4,DM,DM,TREF,TF1)+HFH2OL

OUTPUT
EWAOUT=ENT(1,3,DM,TREF,TDE)+HFH2OG

"AVAILABLE" ENERGY USED FOR DRYING + ENTHALPY(IN) - ENTHALPY(OUT) = 0

ENBAL=FFRD3*((FMCD1-FMCD3)/18.016)*(EWAIN-EWAOUT)+AVDRY
RETURN
END

FUNCTION DXT(TDE,TAM,GHTL,FFRD3)
EXTERNAL ENT
COMMON/QUANT/XT,X,Y,Z,O2FED,O2REQ,H2FED,H2OFED,FR,DYEFF,ALF
COMMON/HOIST/FMCD1,FMCD2,FMCD3,FHR,GSF
COMMON/LAW/BXG,BXW,AIR,DAL
REAL N2FED

DM=1.0
BXG=1.0*(1.0+FR/FR)*(XT*ENT(1,2,DM,TAM,TDE) + N2FED*ENT(1,4,DM,TAM,TDE) + (02FED-02REQ)*ENT(1,5,DM,TAM,TDE))
BXW=((FMCD3/18.016)+(1.0/FR)*(FMCD2/18.016) + (1.0+FR)/FR)*(H2OFED+Y/2.0)*ENT(1,3,DM,TAM,TDE)
AIR=ALF*((1.0+FR)/FR)*(XT+(O2FED-O2REQ)+N2FED)
DAL=AIR*(ENT(1,6,DM,TAM,TDE)
DXT=FFRD3*GSF*(BXG+BXW+DAL)-OHTL
RETURN
END

FUNCTION FXT(TF3,TF1,0SENS,FFRD3)
EXTERNAL ENT
COMMON/MOIST/FMCD1,FMCDF2,FMCD3,FHR,GSF

DM=1.0
DHFUEL=ENT(2,DM,FMCD1,TF1,TF3)+ENT(3,DM,FMCD1,DM,DM)
-DH2OF=(FMCD3/18.016)*DHWATER
DXT=FFRD3*(DHFUEL+(FMCD3/18.016)*DHWATER)-OSENS
RETURN
END

FUNCTION PC(W0,W)
PC=((W-W0)/W0)*100.0
RETURN
END

FUNCTION ENT(K,J,FMCD,T1,T2)

FUNCTION ENT IS THE FUNCTION ACCESSED BY BOTH THE MAIN, OR MASTER, PROGRAM AND THE SUBROUTINE ZSYSTM TO CALCULATE VARIOUS THERMODYNAMIC QUANTITIES, IE., ENTHALPYS RELATIVE TO THE REFERENCE TEMPERATURE

K REFERS TO THE "MINIFUNCTION" WITHIN ENT THAT IS ACCESSED BY ENBAL
J IS THE CHARACTERISTIC SPECIES NUMBER;
C0=SPECIES 1
C02=SPECIES 2
H2O=SPECIES 3
N2=SPECIES 4
O2=SPECIES 5
AIR=SPECIES 6

FMCD FUEL MOISTURE CONTENT, DRY BASIS
T1 INITIAL (USUALLY REFERENCE) TEMPERATURE
T2 FINAL (SPECIES OR STREAM) TEMPERATURE

COMMON/RARE/HFDW,N
COMMON/HEAT/CW,CICE,DELHF,HFH2DL,HFH20G,HFCO2,HTLFB,GSTEAM,HHV

DIMENSION A(6),B(6),C(6),D(6)
DATA (A(I),I=1,6)/6.9192,8.6305,7.997,6.9317,6.955,6.9168/
DATA (B(I),I=1,6)/0.04912E-02,0.50586E-02,0.08222E-02,0.02628E-02,0.13838E-02,0.04956E-02/
DATA (C(I),I=1,6)/0.02822E-05,-0.230E-05,0.06058E-05,1.04559E-05,-0.04841E-05,0.02542E-05/
DATA (D(I),I=1,6)/-0.13265E-09,0.44598E-09,-0.21469E-09,1.07833E-09,-0.11741E-09,0.00000E+00/

N=N+1
GO TO (5,10,15,20),K

5 TC2=(T2-32.0)/1.8
TC1=(T1-32.0)/1.8
ENT=A(J)*(TC2-TC1)+B(J)*(TC2**2-TC1**2)+C(J)*(TC2**3-7*TC1**3)
+D(J)*(TC2**4-TC1**4)
RETURN

10 TC2=(T2-32.0)/1.8
TC1=(T1-32.0)/1.8
ENT=0.266*(TC2-TC1)+0.000580*(TC2**2-TC1**2)
RETURN

15 FN=FMCD
QBOUND=284.0
IF(FMCD.LT.0.1111) QBOUND=354.0
IF(FMCD.GT.0.25) FN=0.25
ENT=HFDW-FN*QBOUND
RETURN

20 AA=0.0
BB=1.0
IF(T2.LT.32.0) AA=1.0
IF(T2.LT.32.0) BB=0.0
ENT=AA*(CICE*(T2-32.0)-DELHF+CW*(32.0-T1))+BB*CW*(T2-T1)
RETURN
END

EOI ENCOUNTERED.
### SIM2 Sample Output

**BOILER/DRYER TANDEM SIMULATION DATA AND OUTPUT**

**RAYMOND U. KIRK**
**DEPARTMENT OF CHEMICAL ENGINEERING**
**DEPARTMENT OF FOREST PRODUCTS**
**OREGON STATE UNIVERSITY**
**CORVALLIS, OREGON**

**SIMULATION INPUT DATA**

#### FUEL CHARACTERISTICS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher Heating Value of Dry Fuel (HHV)</td>
<td>9050.0000 (BTU/LB)</td>
</tr>
<tr>
<td>Carbon Fraction in Dry Fuel (Ultimate Analysis)</td>
<td>52.3000 (PERCENT MASS)</td>
</tr>
<tr>
<td>Hydrogen Fraction in Dry Fuel (Ultimate Analysis)</td>
<td>6.3000 (PERCENT MASS)</td>
</tr>
<tr>
<td>Oxygen Fraction in Dry Fuel (Ultimate Analysis)</td>
<td>40.5000 (PERCENT MASS)</td>
</tr>
<tr>
<td>Wet Fuel Moisture Content; Dry Basis</td>
<td>100.0000 (PERCENT MASS)</td>
</tr>
<tr>
<td>Wet Fuel Moisture Content; Wet Basis</td>
<td>50.0000 (PERCENT MASS)</td>
</tr>
<tr>
<td>Wet Fuel Temperature (usually assumed to be ambient temperature)</td>
<td>60.0000 (DEG.F)</td>
</tr>
</tbody>
</table>

#### OPERATIONAL PARAMETERS AND CONSTRAINTS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature</td>
<td>60.0000 (DEG.F)</td>
</tr>
<tr>
<td>Ambient Humidity Ratio</td>
<td>.0076 (LB H2O/LB DRY AIR)</td>
</tr>
<tr>
<td>Combustion Excess Air</td>
<td>100.0000 (PERCENT)</td>
</tr>
<tr>
<td>Boiler Exhaust Temperature</td>
<td>400.0000 (DEG.F)</td>
</tr>
<tr>
<td>Radiative, Convective, and Unaccounted Losses in Boiler, expressed as percent higher heating value</td>
<td>5.0000 (PERCENT)</td>
</tr>
<tr>
<td>Carbon/Charcoal Losses (Carryover), expressed as percent of ultimate analysis of carbon in fuel</td>
<td>8.6000 (PERCENT)</td>
</tr>
<tr>
<td>Boiler Steam Load (mass)</td>
<td>100000.0000 (LB/HR)</td>
</tr>
<tr>
<td>Boiler Steam Load (Energy)</td>
<td>104.0000 (MBTU/HR)</td>
</tr>
<tr>
<td>Fuel Feed Ratio, expressed as the ratio of (Dry) Fuel passing through Dryer to (Dry) Fuel bypassing Dryer</td>
<td>100000.0000 (MBTU/HR)</td>
</tr>
<tr>
<td>Dryer Inlet Temperature</td>
<td>400.0000 (DEG.F)</td>
</tr>
<tr>
<td>Dryer Air Leakage, expressed as percent of incoming dry gas from boiler exhaust</td>
<td>10.0000 (PERCENT)</td>
</tr>
<tr>
<td>Thermodynamic (drying) efficiency, expressed as percent of available energy (relative to the ambient temperature), (i.e., that percent of available energy that is used to evaporate water from the fuel stream passing through the dryer)</td>
<td>50.0000 (PERCENT)</td>
</tr>
<tr>
<td>Percent of available energy taken up in the sensible heat of the fuel and the sorbed water that is not evaporated</td>
<td>2.5000 (PERCENT)</td>
</tr>
</tbody>
</table>
## SIMULATION OUTPUT DATA

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>WITHOUT DRYER</th>
<th>WITH DRYER</th>
<th>PERCENT CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOILER EFFICIENCY (PERCENT)</strong></td>
<td>60.6557</td>
<td>65.0018</td>
<td>7.1561</td>
</tr>
<tr>
<td><strong>FUEL - GROSS TOTAL TO BOILER</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOISTURE CONTENT; DRY BASIS (PERCENT)</td>
<td>100.0000</td>
<td>67.3433</td>
<td>-32.6567</td>
</tr>
<tr>
<td>MOISTURE CONTENT; WET BASIS (PERCENT)</td>
<td>50.0000</td>
<td>40.2426</td>
<td>-19.5148</td>
</tr>
<tr>
<td>FLOW RATE; DRY (LB/HR)</td>
<td>19310.1451</td>
<td>18019.0587</td>
<td>-6.6861</td>
</tr>
<tr>
<td>FLOW RATE; WET (LB/HR)</td>
<td>38620.2902</td>
<td>30153.6819</td>
<td>-6.6861</td>
</tr>
<tr>
<td>FUEL SAVINGS; DRY (LB/HR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUEL SAVINGS; WET (LB/HR)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FUEL - DRYER STREAMS** (PARAMETERS UNDER WITHOUT DRYER" DENOTE CONDITIONS, ETC, OF INPUT STREAM TO DRYER; PARAMETERS UNDER "WITH DRYER" DENOTE CONDITIONS OF OUTPUT STREAM FROM DRYER)

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>WITHOUT DRYER</th>
<th>WITH DRYER</th>
<th>PERCENT CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOISTURE CONTENT; DRY BASIS (PERCENT)</td>
<td>100.0000</td>
<td>67.3429</td>
<td>-32.6571</td>
</tr>
<tr>
<td>MOISTURE CONTENT; WET BASIS (PERCENT)</td>
<td>50.0000</td>
<td>40.2425</td>
<td>-19.5150</td>
</tr>
<tr>
<td>FLOW RATE; DRY (LB/HR)</td>
<td>18018.8785</td>
<td>18018.8785</td>
<td>0.0000</td>
</tr>
<tr>
<td>FLOW RATE; WET (LB/HR)</td>
<td>36037.7570</td>
<td>30153.3215</td>
<td>-19.5150</td>
</tr>
<tr>
<td>TEMPERATURE (DEG.F)</td>
<td>60.0000</td>
<td>81.5350</td>
<td>35.9177</td>
</tr>
</tbody>
</table>

**FUEL - BYPASS (OR BLEND) STREAM**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>WITHOUT DRYER</th>
<th>WITH DRYER</th>
<th>PERCENT CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOISTURE CONTENT; DRY BASIS (PERCENT)</td>
<td>100.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOISTURE CONTENT; WET BASIS (PERCENT)</td>
<td>50.0000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW RATE; DRY (LB/HR)</td>
<td></td>
<td>.1902</td>
<td></td>
</tr>
<tr>
<td>FLOW RATE; WET (LB/HR)</td>
<td></td>
<td>.3604</td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE (DEG.F)</td>
<td></td>
<td>60.0000</td>
<td></td>
</tr>
</tbody>
</table>

**COMBUSTION AIR CHARACTERISTICS**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>WITHOUT DRYER</th>
<th>WITH DRYER</th>
<th>PERCENT CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBIENT TEMPERATURE (DEG.F)</td>
<td>60.0000</td>
<td>60.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>FLOW RATE (SCFM)</td>
<td>51803.6595</td>
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0.299 CP SECONDS EXECUTION TIME.