Simulation modeling of a biofueled energy system

Munir Ahmad

Iowa State University
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Simulation modeling of a biofueled energy system

Ahmad, Munir, Ph.D.

Iowa State University, 1990

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Simulation modeling of a biofueled energy system

by

Munir Ahmad

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PART III. APPENDIX C. INPUT PARAMETERS FOR LIFE CYCLE COST ANALYSIS OF MCNAY BIOMASS ENERGY SYSTEM
DEDICATION

The author dedicates this work to his father Mehr Allah Yar Sargana Sial who passed away while author was abroad (in the United States of America) for study. May Allah (God) bless his soul.
A technological society depends upon the production and use of large amounts of energy. Energy is not only a commodity, it is also an idea—an intellectual concept which stands out in the history of modern scientific and engineering thought (Dorf, 1981). Unfortunately, at the present time in the United States, roughly 94% of this precious commodity comes from fossil fuels. These are finite, depletable, nonrenewable. The fossil fuels (combinations of carbon and hydrogen atoms) were formed some 10 to 500 million years ago. Once they have been oxidized back into carbon dioxide and water, they are gone forever as far as humanity is concerned.

According to a well publicized estimate, the time period for consuming 80% of the world oil resources \((200*10^9 \text{ bbl})\) is about 65 years (Hubbert, 1969). Hubbert also predicted that 80% of the total U.S. natural gas resource would be used between the years 1950 and 2015, based on the total recoverable proven reserves of \(36.5*10^{12} \text{ m}^3\) \((1290*10^{12} \text{ ft}^3)\). Coal is the most abundant fossil fuel in the United States. The total estimated proven recoverable reserves are \(1.5*10^{12} \text{ tons}\) \((20\% \text{ of the world coal resources})\). Kraushaar and Ristinen (1984) estimated that the \(1.50*10^{12} \text{ tons resource would last only 97 years (assuming an initial consumption rate of 600*10^6 tons and growth rate of 5\%). This means the fossil fuels are rapidly approaching}\)
Nuclear power is expected to play an important role in the energy picture by the year 2000; but it is limited by environmental constraints (Cheremisinoff et al., 1980). Therefore, various forms of solar energy, such as direct (space heating and electricity generation) and indirect (biofuels) are the hope of the future.

Advantages of using biomass as a fuel are that, to the extent it can be grown and used without damage to the environment, it contains negligible sulfur and does not create air pollution problems that are associated with coal, it generates little ash, and is continually renewable on a year-to-year basis. Pimentel et al. (1983) estimated that there will be 700 million tons of dry biomass potentially available for fuel in the year 2000. If the available biomass is used solely as a fuel for direct combustion, a total net heat energy of about 5 quadrillion kJ/year will be produced. This means the biomass can provide the nation with as much as 5% of its total projected energy needs of 100 quadrillion kJ in the year 2000. The use of wood for residential heating is increasing. In the residential sector, wood supplied 0.9 quadrillion kJ and over 6 million households relied on wood as the main heating fuel (Annual Energy Review, 1988).

Iowa State University has undertaken a project to demonstrate the use of wood-biomass as an alternative energy source for farms,
and to provide information to establish optimum sizes, seasonal performance, and configuration of equipment for heating buildings at its McNAY Research Center. This study was undertaken to perform simulation modelling of the McNAY biofueled hydronic heating system, because a computer simulation: (1) leads to a better understanding of the proposed system design; (2) facilitates the evaluation of effects of complex component interactions upon a system design; (3) provides useful information on effects of design changes on the long term performance of the system.

Figure 1 presents a typical configuration of a biofueled hydronic heating system. At present no software package is available to assist the users of biofuels in predicting seasonal energy requirements, and seasonal thermal performance of their boiler systems. The determination of seasonal performance of wood fired boilers is based solely on experiments, and these are often difficult and expensive to conduct.

Objectives

The principal objective of this study is to develop a simulation model of a biofueled energy system to achieve the following:

a. To predict design and seasonal energy requirements of the system;

b. To predict the seasonal thermal performance of biofueled boilers, and to provide an inexpensive tool to evaluate the
Figure 1. A typical configuration of a biofueled hydronic heating system
effects of design changes on the long term performance of the system;
c. To select the appropriate size or capacity of biofueled boilers to meet the system load requirement.
d. To determine the seasonal fuel requirement of the heating system;
e. To perform the economic analysis of biofueled heating system (based on life cycle savings or present worth analysis);
f. To perform a parametric analysis of the most critical and uncertain variables of the biofueled energy system.
PART I. COMPUTER MODEL FOR THERMAL LOAD ANALYSIS OF BUILDING ENVELOPE
INTRODUCTION

To perform simulation modeling of a biofueled energy system, it is imperative to predict the load imposed on the boiler system by the building envelope. In addition, determination of design and seasonal energy requirements of the building envelope play an important role in predicting the appropriate size or capacity of a biofueled boiler and seasonal fuel requirement of the system, respectively.

Numerous comprehensive building energy analysis computer programs, performing hour-by-hour type calculations, have been developed. The application of these detailed programs requires large scale computer systems, and entails input preparation time and computer usage costs (Sud and Kusuda, 1982). These programs are not readily accessible to practicing engineers because of their complexity and difficulties in usage (Knebel, 1983). Additionally, these programs were not developed to simulate biomass fueled energy systems.

A microcomputer program for thermal load analysis of a building envelope (THERM) was developed. THERM is based on the modified bin method developed by ASHRAE TC 4.7. THERM, like the modified bin method, performs quasi-steady state calculations at different outdoor temperatures. These calculations account for a large number of factors affecting the building load and energy usage. THERM also predicts the basement heating load using simplified dimensionless
relations for heat loss from basements developed by the Solar Energy Laboratory, Madison Wisconsin (Yard et al., 1984).

The main objectives of the Computer Program for Thermal Load Analysis of Building Envelope (THERM) were:

1. To predict the hourly heating load at various bin temperatures;

2. To predict the design and the seasonal energy requirement of the building envelope.

The predicted hourly heating loads at various bin temperatures would be used for simulating a biofueled boiler (in the second part of this dissertation). Likewise, the seasonal energy requirement of the building envelope provides a base for estimating the seasonal fuel requirement of the system.
REVIEW OF LITERATURE

Energy Analysis Procedures

The available energy analysis models can be divided into three categories according to the number of ambient conditions and time increments involved in the calculation (ASHRAE Handbook, 1989):

Single measure models
Multiple measure models
Detailed simulations models

Single measure models

Single measure models involve correlation of energy use with a single environmental parameter. These are based on steady-state heat transfer, and the environmental parameter used is the temperature difference between the indoor space and the outdoor air temperature. Examples of single measure models include the degree day method, and variable base degree hours method.

The traditional Degree Day (DD) procedure for estimating heating energy requirements is based on the assumption that, on a long-term average, solar and internal gains will offset heat loss when the mean daily outdoor temperature is 18.3 °C, and that fuel consumption will be proportional to the difference between the mean daily temperature and 18.3 °C (McQuiston and Parker, 1988). The traditional degree day procedure has very limited applicability; it overpredicts the heating
and cooling loads even for single story residences (Kusuda et al., 1981), while its use for commercial buildings usually gives unreliable results.

The Variable Base Degree Day (VBDD) method counts degree days based on the balance point temperature, defined as the average outdoor temperature whereby internal heat sources plus solar heat gain exactly offset the envelope heat loss due to conduction and air-leakage. The balance point temperature may differ from the traditionally assumed value of 18.3 °C, particularly for modern residences where the air leakage has been reduced and the internal heat generated by appliances and lighting has been increased, and where the indoor temperature was set lower than the customary 23.9 °C. Kusuda et al. (1981) reported that for a single story residence, all the predicted heating loads by VBDD fall within 10% of those computed by DOE-2, while the cooling loads fall within a 15% range. Claridge et al. (1985) compared the traditional degree day and variable base degree day predictions with measured heat consumption of 20 houses in the Denver area. Their study revealed that the average consumption predicted by the traditional degree day method was 1.82 times the metered use, and the average prediction by the VBDD was 1.44 times the metered use.

The Variable Base Degree Hour (VBDH) is method the same in principle as the variable base degree day method. The difference in
the two calculated methods is mainly in the calculation of the
weather parameters. The heating degree days are calculated based on
daily average temperatures, while degree-hours are calculated from
hourly temperatures. Alereza (1985) used the VBDH for calculating
heating and cooling energy use in commercial buildings with single
zone package Heating Ventilation and Air-Conditioning (HVAC) systems.
He compared his results with values generated by the DOE-2 building
energy analysis computer model. His results revealed that the VBDH
results were mostly within plus or minus 15% of DOE-2 for most cases
examined.

Multiple measure models

The multiple measure models include the effects of more than one
environmental parameter upon energy use. Example of the multiple
measure models are the standard bin method and the modified bin
method.

The standard bin method involves making instantaneous energy
calculations at several different outdoor dry bulb temperatures and
weighting each result by the number of hours of temperature
occurrence within each bin (ASHRAE Handbook, 1989). The bins are
usually 2.8 °C in size, and were pre-tabulated in U.S. Air Force
Manual 88-29 (1978). This method, however, is also based on steady
state heat transfer and does not account for many of the transient
processes that occur in a real situation.
The principal drawback of this procedure is the interpolation between end points corresponding to the summer and winter design envelope loads. The summer cooling loads are based on the design hour load and do not account for the variation in the transmission and solar loads which on the average are much lower than design hour values. These loads could be further reduced by cloud cover and other effects. Conversely the winter heating design envelope loads ignore solar effects, and on any given day, the solar effects could significantly reduce the total losses through the envelope. Additionally, the standard bin procedure does not have provision for simulating various heating, ventilating, and air conditioning systems. Kusuda et al. (1981) compared the annual heating and cooling loads obtained by the standard bin method for single story residences in 10 cities with those obtained from the DOE-2 program. He did not get satisfactory agreement between the results obtained by the two methods.

The modified bin method developed by the ASHRAE TC 4.7 subcommittee on simplified energy calculations has the advantage of allowing off-design calculations by use of diversified rather than peak load values to establish the load as a function of outdoor dry bulb temperature. The modified bin method also has provision for simulating various HVAC systems (Knebel, 1983). One of the strongest points of the modified bin procedure is the use of the cooling load
temperature difference concept, which takes into account the building thermal mass that has been completely ignored in the standard bin method (Rudy, 1980).

Kusuda (1981) compared the results obtained by the modified bin method with seven large computerized dynamic simulation energy analysis procedures, AXCESS, BLAST, BLDSIM, ESAS, DOE-2, ECUBE, and TRACE, for medium sized office buildings in Washington, D.C., for four different heating/cooling systems (terminal reheat system, the double duct system, the variable air volume system, and the 4-pipe fan coil system with and without heat reclaim). He found good agreement between the modified bin method and all of the computerized dynamic simulation methods. Additionally, comparisons for single story masonry construction buildings were also undertaken for Atlanta, Chicago, Forth Worth, and Phoenix. The results obtained by TC4.7 fall well within 15% of the DOE-2 results (Kusuda et al., 1981).

**Detailed simulations models**

Because of the wide ranging and constantly changing internal and external factors that determine thermal loads on commercial and industrial buildings, frequent evaluation is needed to obtain reasonably accurate estimates of annual energy consumption (ASHRAE Handbook, 1989). To achieve this, numerous comprehensive building energy analysis computer programs that perform hourly calculations
have been developed. These programs model the hourly envelope heat transfer process as well as detailed HVAC system and equipment simulations to estimate the building energy usage.

Kusuda (1981) lists the following factors that can be considered by detailed computer simulation programs that are otherwise ignored by single and multiple measure models:

1. Calculation of instantaneous space sensible load, using building construction characteristics and hourly climatic data such as outdoor temperature, humidity, solar insolation, and wind speed direction.

2. Thermal storage effect of the building, in terms of the evening cooling down and morning pickup.

3. Transient effects on controls (time dependent thermostat and fan switch setting).

4. Simulation of energy storage systems.

Cuba (1975) prepared a bibliography of available computer programs in the general area of heating, refrigerating, air conditioning, and ventilating systems. Programs for simulating solar systems are also included in this reference. In general, some of the recognized public domain building simulation programs are:

1. Alternate Choice Comparison For Energy Systems Selection (AXCESS) developed by Seyle, Stevenson, Value, and Krecht under contract to the Edison Electric Institute.
2. The Building Loads and Systems Thermodynamics Program (BLAST) developed by the U.S. Army Construction Laboratory (CERL).

3. Honeywell Total Building Simulation (BULDSIM) developed by Honeywell Inc.

4. DOE-2. developed by Lawrence Berkely Laboratory (LBL).


8. Thermal Analysis Research Program (TARP) developed by the National Bureau of Standards.

9. Trane Air Conditioning Economics (TRACE) developed by the TRANE Company, Lacrosse, Wisconsin.

These computer simulation programs are potentially powerful tools for predicting the hourly energy use of residential and commercial buildings that incorporate various conservation alternatives. With the exception of TARP, all the above programs simulate envelope loads as well as system thermodynamics. TARP is a thermal loads calculation program and does not do any system simulation. EMPS is restricted to residential energy simulation and
was designed specifically to evaluate solar and other alternative energy technologies (Sorrell et al., 1985).

Sorrell et al. (1985) verified the accuracy of three computer programs, DOE-2-1B, EMPS 2.1, and TARP 84 in predicting the hourly energy use of residential structures by comparing simulation results with experimental values for several unoccupied, residential test buildings. They found that agreement between predicted and measured results was within 10% to 20% for all three programs on an hourly basis and within 5% to 20% for periods of one to three days.

Robertson and Christian (1985) conducted an experimental study, called the Southwest Thermal Mass Study (STMS), at Tesuque, Pueblo, New Mexico. In addition, to evaluate the effect of envelope thermal mass on the heating energy consumption of conventional (nonsolar) residential buildings, they also simulated the performance of the test buildings using four computer codes, namely DOE-2.1A, DOE-2.1C, BLAST, and DEROB. Despite problematical thermal behavior within these test buildings and input differences between models, cumulative measured loads versus model predictions loads agreed within plus or minus 10% for one-to two-week periods.

The energy analysis programs are based upon detailed dynamic simulation of hourly building performance, inclusive of shell heat transfer and utility system and equipment, and are quite accurate in predicting the envelope load and system performance. The application
of these programs requires large scale computer systems, input preparation time, and computer usage costs. Additionally, these programs do not evaluate the biomass fueled energy systems.

Heat Loss from Basement

The calculation of basement heat loss is fundamentally more complex than predicting losses through above grade walls. One-dimensional theory is certainly not adequate, and thermal lag measured in weeks or months should be considered. A number of new methods for calculating basement heat loss have been developed in recent years (Shipp, 1982; Yard et al., 1984; Mitalas, 1983; Akridge and Poulos, 1983), ranging from empirical correlations to three-dimensional finite element and finite difference programs.

Overview of basement heat loss prediction methods

The Latta Boileau (1968) method, reported by ASHRAE Handbook (1985), is the most widely used method for predicting peak heat loss to the ground. This model assumes radial heat flow from wall and floor elements. This method is restricted to predicting the peak heat losses.

Shipp (1982) utilized a regression equation to calculate the seasonal heating or cooling impact of a basement as a function of heating degree days, cooling degree days, and basement thermal resistance. The regression coefficients were developed using a
validated transient, two-dimensional finite difference program. The method contains implicit assumptions of 22.8 °C basement temperature and 21% soil moisture content. The major strength of the method is the ability to consider different insulation configurations, while the major limitations are the invariant basement temperature and soil moisture content.

Mitalas (1983) used finite element analysis to develop a set of factors that are used to predict monthly heat loss for a variety of basement configurations. The method predicts the heat loss through specific basement segments to get the total basement heat loss. This method is restricted to shallow basements or to poorly insulated cases where the soil thermal conductivity is substantially different from the reference cases (0.8 W/m °k and 1.2 W/m °k).

Akridge and Poulos (1983) developed the decremented average ground temperature method for predicting heat loss from below grade walls. This method does not consider heat loss through the basement floor; therefore it is restricted to shallow basements.

Yard et al. (1984) used overall floor and wall conductances as well as effective ground temperatures to predict basement heat loss. These effective parameters were determined from a two dimensional finite element analysis. Curves fitted to results from the finite element analysis are presented in terms of nondimensional parameters. The effective ground temperature accounts for energy storage in the
ground as well as seasonal temperature variations and is calculated from long-term average values of air temperature. This method can accept a wide range of soil thermal properties, basement temperatures, and insulation values.

MacDonald et al. (1985) compared the above described methods for predicting the basement heat loss. Their study for cold climates revealed that the Mitalas method almost always predicts the greatest heat loss, usually followed by Yard, Shipp, Latta-DD, and Akridge.
DEVELOPMENT OF COMPUTER PROGRAM FOR THERMAL LOAD ANALYSIS
OF BUILDING ENVELOPE (THERM)

After extensive literature search, the multiple measure model (modified bin method) was selected to achieve the objectives of this research, for the following reasons:

1. It uses all the elements essential for energy calculations, such as climatic data, building construction characteristics, infiltration and ventilation, and internal heat gain due to lighting, people, equipment, and appliances.

2. It can be programmed on a microcomputer.

3. It can be modified to incorporate the effects of biomass fueled energy systems in predicting seasonal fuel requirements.

4. It uses the cooling load temperature difference concept which takes into account the building thermal mass that has been completely ignored in single measure models.

5. It predicts seasonal energy load within 15% of those predicted by the DOE-2 detailed simulation program for single story masonry construction buildings (Kusuda, 1981).

Theoretical Basis

THERM is based on the modified bin method developed by ASHRAE TC 4.7, and the simplified dimensionless relations for heat loss from
basements developed by the solar energy laboratory, Madison, Wisconsin. THERM, like the modified bin method, performs quasi-steady state calculations at different outdoor temperatures. The calculations account for a large number of factors affecting the building load and energy usage. The loads and energy usages at other outdoor temperatures were obtained by interpolation. The sum of the product of the energy requirements at different temperatures and the number of occurrences of each of the temperatures gave the annual energy requirements of the building.

THERM expressed the building loads as a function of outdoor temperature and makes the following simplifying assumptions.

1. All exterior loads were expressed as a linear function of outdoor temperature. The exterior loads include transmission (including structural storage effects), infiltration, and solar loads. The transmission and infiltration loads are assumed to be a "piecewise linear" function of outdoor temperature, while the solar load is assumed to have a linear dependence on outdoor temperature over the entire outdoor temperature range for the location (Figure 1).

2. On a daily basis, the interior loads were averaged over the "system on" or "system off" time periods. Time dependencies resulting from scheduling are either averaged over a selected period or multiple calculation periods are established. The
Figure 1. Assumption of variation of exterior loads with outdoor temperature (Sud and Kusuda, 1982)
duration of a calculated period determined the number of bin hours included in that bin. Normally two calculation periods, representing occupied and unoccupied hours, were used. The occupied period is defined as the operating period when the systems are operating normally and provide heating. The "unoccupied" period is the operating mode when the heating has been set back to a lower temperature.

THERM, like the modified bin method, involves performing average or diversified calculations at four outdoor temperature conditions. These temperatures represent the mid-point of bins that are judged to be of some significance for the location and operation of a particular building and represent the following conditions.

- Peak Cooling ($T_{pc}$): This is usually the mid-point of the highest temperature bin occurring at the location.

- Intermediate Cooling ($T_{ic}$): This represents the lowest temperature bin in which the envelope transmission and outdoor air sensible loads impose cooling loads on the building. It is generally taken to be 25 °C.

- Intermediate Heating ($T_{ih}$): This represents the midpoint of that temperature bin where the net building loads change from heating to cooling loads. It is near the balance point temperature of the building. This is generally taken as 11.1 °C.
- Peak Heating ($T_{ph}$): This is the mid point of the lowest temperature bin occurring at the location.

THERM considered all heat gains to be positive, and all heat losses to be negative. The net load is the algebraic sum of all the individual component loads.

**Subbuilding or Zone Selection**

THERM has the capability to predict the thermal loads of perimeter zones and interior zones separately and net thermal load is the sum of the loads of the two zones. This was done in recognition of the fact that for large buildings "core" interior spaces may be experiencing a net cooling load, while the exterior spaces may be experiencing a net heating load, but residence buildings usually consist only of a perimeter zone.

**Components of THERM**

The components of THERM, which were used to predict the diversified or time averaged load are:

- solar gain through fenestrations
- solar gain through walls and roof
- transmission load through walls, roof, and fenestration.
- interior load
- infiltration
Figure 2 presents the energy interactions of a house envelope. Each load component shown in Figure 2 was developed as a linear function of outdoor temperature. This permits definition of a total load profile which is the sum of the individual components.

**Solar load through fenestration**

THERM calculates the solar contribution for the glass area in summer and winter for the perimeter zone. To predict the seasonal variation of the solar load a linear relationship of solar load with outside air temperature was assumed. Diversified solar heat gain for summer was computed using the following relationship:

\[
Q_{\text{SOL, JUL}} = \frac{\sum_{i=1}^{N\text{EXP}} (M\text{SHG}\text{FJ}_i \times A\text{G}_i \times S\text{C}_i \times CL\text{FTOT}_i \times J\text{PPS})}{t \times A_P}
\]  

where

- \(Q_{\text{SOL, JUL}}\) = average solar contribution for July, W/m²
- \(N\text{EXP}\) = number of different glass exposures
- \(M\text{SHG}\text{FJ}_i\) = maximum solar heat gain factor for \(i\)th orientation for July at the specified latitude, W/m²
- \(A\text{G}_i\) = glass area for \(i\)th exposure, m²
- \(S\text{C}_i\) = shading coefficient of glass for \(i\)th exposure
- \(CL\text{FTOT}_i\) = 24 hour sum of cooling load factor for \(i\)th orientation
- \(J\text{PPS}\) = percent of possible sunshine for July
- \(t\) = run time of air conditioning system, hours
Figure 2. Energy interactions for a house envelope
Diversified solar heat gain for winter was computed using the following relationship.

\[
Q_{\text{Sol,Jan}} = \sum_{i=1}^{N_{\text{EXP}}} \left( \frac{\text{MSHGFA}_i \cdot \text{AG}_i \cdot \text{SC}_i \cdot \text{CLFTOT}_i \cdot \text{APPS}}{24 \cdot A_F} \right)
\]  

where

- \( Q_{\text{Sol,Jan}} \) = average solar contribution for January, W/m^2
- \( \text{MSHGFA}_i \) = maximum solar heat gain factor of \( i^{th} \) orientation for January at the specified latitude, W/m^2
- \( \text{APPS} \) = fraction of possible sunshine for January

During the cooling season, the HVAC systems are usually operated only during the occupied periods. Since the entire solar load is removed during this time, the value of \( t \) is taken to be the number of hours in the occupied time period. In the heating mode, the building usually experienced a heating load during the occupied period with some heating usually provided during the unoccupied period. Therefore, the winter diversified solar load is averaged over a 24-hour time period (Sud and Kusuda, 1982).

The summer and winter diversified loads calculated above provide two points for establishing a linear solar load profile. The summer diversified load is assigned to \( T_{ps} \) and the winter diversified solar load to \( T_{ph} \). As shown in Figure 1, the diversified solar load at any intermediate temperature was obtained by linear interpolation using the following equation.
\[ Q_{\text{SO}_\text{L}} = Q_{\text{SO}_\text{L}, \text{JAN}} + M \ast (T_{\text{O}} - T_{\text{ph}}) \]  

where

\[ M = \frac{(Q_{\text{SO}_\text{L}, \text{JUL}} - Q_{\text{SO}_\text{L}, \text{JAN}})}{(T_{\text{pC}} - T_{\text{ph}})} \]

\[ TO = \text{outside air temperature, } ^{\circ}\text{C} \]

**Solar gain through walls and roof**

The diversified contribution from the opaque surfaces in July, expressed in watt per m\(^2\) of building conditioned area, is given by:

\[ Q_{\text{T}_{\text{SUEL}}} = \sum_{\text{wall,roof}}^{\text{NEXP}} (A_i \ast U_i \ast CLTDJ \ast K \ast APPS) / A_F \]  

where

\[ A_i = \text{surface area of } i^{\text{th}} \text{ exposure, } m^2 \]

\[ U_i = \text{overall heat transfer coefficient for } i^{\text{th}} \text{ surface, } W/m^2 \degree\text{C} \]

\[ CLTDJ = \text{24-hour average solar component of cooling load temperature difference} \]

\[ K = \text{color correction factor for July} \]

The solar component from the opaque surfaces in January, expressed in watt per m\(^2\) of building conditioned area, is given by:

\[ Q_{\text{T}_{\text{SJEAN}}} = \sum_{\text{wall,roof}}^{\text{NEXP}} (A_i \ast U_i \ast CLTDA \ast K \ast APPS) / A_F \]  

where

\[ CLTDA = \text{24-hour average solar component of cooling load temperature difference for January, } ^{\circ}\text{C} \]

The relationship of \(Q_{\text{T}}\) with other temperatures was established using following relationship.
QTS = M1*(T0-Tph) + QTS, [6]

where

\[ M1 = \frac{(QTS_{JUL} - QTS_{JAN})}{(T_{pc} - T_{ph})} \]

Transmission load

The transmission load through walls, roof, and fenestrations, expressed in watt per m² of building conditioned area, is given by:

\[ QT = eN_{wall, roof} \times (A_{1i} U_{i} (T_{0} - T_{1}) / A_{F}) [7] \]

where

\[ T_{1} = \text{inside temperature, } ^{\circ}C \]

Interior loads

For some building types, loads due to lights, people, and equipment constitute a very significant proportion of the total loads. This is particularly true for commercial buildings. Even for residences, interior loads exist due to the use of lights, refrigerators, freezers, ranges and waterbed heaters. The diversified interior load, per unit of building area, from a particular source is given by:

\[ QI = \frac{(AU \times I_{MAX} \times HF)}{A_{F}} [8] \]

where

\[ AU = \text{average usage during the occupied and unoccupied time periods, expressed as a fraction of the maximum load} \]

\[ I_{MAX} = \text{connected load for lighting and other internal} \]
equipment, or maximum number of occupants

\[ HF = \text{factor for converting a unit of maximum load to watts} \]

THERM has the ability to calculate the interior load separately for the occupied and unoccupied period.

**Infiltration and ventilation**

THERM computes the diversified outdoor infiltration air loads at three \((T_{ph}, T_{lh}, T_{ic})\) outdoor temperatures for occupied and unoccupied periods using average infiltration rates at these temperatures, and it interpolates between these values for the rest of the temperature bins. The diversified sensible load due to infiltration, expressed in watt per \(\text{m}^2\), is given by:

\[
\text{Sensible load} = \left(1.232 \times V_I \times (T_o - T_i)\right) / A_p
\]

where:

\[ V_I = \text{average outdoor infiltration air entering the building or space during occupied or unoccupied periods, L/s} \]

The winter latent loads can be ignored if humidification is not provided (Sud and Kusuda, 1982).

THERM also predicts the diversified load due to ventilation for occupied period by substituting \(V_V\) with \(V_I\), and \(T_S\) with \(T_o\) in the above equation.

where:

\[ V_V = \text{the amount of ventilation air entering the building during occupied period, L/s} \]
TSA = supply air temperature, °C

**Prediction of basement heating load**

THERM uses the Yard method to predict the basement heat loss for the following reasons.

1. It can accommodate a wide range of soil thermal properties, basement temperatures, insulation values, and variable width/depth ratios.

2. It can use different insulation values for walls and floor.

3. It can predict peak heat loss as well as seasonal heat loads.

4. It uses equations and correlations rather than tabular values for predicting basement heat loss; therefore it is more suitable for developing a microcomputer program.

THERM calculates the heat flow from a basement using the following conduction equation:

\[ q = U_f A_f (T_b - T_{gf}) + U_w A_w (T_b - T_{gw}) \]  \[10\]

where

- \( q \) = basement heat loss, W
- \( U_f \) = basement floor & overall ground conductance, W/m² °C
- \( U_w \) = basement wall and overall ground conductance, W/m² °C
- \( A_f \) = basement floor area, m²
- \( A_w \) = basement wall area, m²
- \( T_b \) = basement space temperature
- \( T_{gf} \) = effective ground temperature for the basement floor, °C
$T_{gw} =$ effective ground temperature for the basement wall, °C

The conductances are defined as the steady state values for the basement-ground-ambient air combination. The effective ground temperature accounts for energy storage in the ground and the seasonal temperature variations.

Yard et al. (1984) predicted heat transfer coefficients and the effective ground temperature using a finite element conduction program. The predicted values were correlated as a function of readily available physical parameters in non-dimensional form. The dimensionless equation describing the wall conductance is given by:

$$\frac{U_{WD}}{K_s} = C_1 \times (D/R_f \times K_s)^{C_2} + C_3$$  \hspace{1cm} [11]$$

where

- $U_w =$ basement wall overall heat transfer coefficient, w/m² °C
- $D =$ basement depth, m
- $K_s =$ soil thermal conductivity, w/m °k
- $R_f =$ thermal resistance of basement floor, m² °c/w
- $R_w =$ thermal resistance of basement wall, m² °c/w
- $C_1 = -0.23 \ln[D/R_f \times K_s + 0.0078] + 3.3$
- $C_2 = 0.1584$
- $C_3 = -2.568 + 0.176 \ln[D/R_f \times K_s + 0.007$ and the floor conductance is given by:

$$\frac{U_f \times D}{K_s} = [C_4 \times (D/R_f \times K_s)^{C_5} + C_6] \times f(W/D)$$  \hspace{1cm} [12]$$

where
\( U_f = \text{basement floor overall heat transfer coefficient, } \text{w/m}^2 \degree\text{C} \)

\[ C_4 = 0.029 \ln[(D/R_\text{K}) + 0.63] - 0.45 \]

\[ C_5 = -0.27 \]

\[ C_6 = -0.055 \ln[(D/R_\text{K}) + 0.63] + 0.809 \]

\[ \text{and } f(W/D) \text{ function is:} \]

\[ f(W/D) = C_7 \ln(D/R_\text{K}) + C_8 \]

where

\[ C_7 = 0.3764 (W/D)^{-1.02} - 0.0832 \]

\[ C_8 = (-0.0968 (W/D)^{-0.83} + 0.0298) \ln(D/R_\text{K}) + 1.61(W/D)^{-0.39} + 0.08 \]

The above relations are valid for non-dimensional floor and wall surface resistances ranging from 0.025 to 4.

The effective ground temperature over any period of time were predicted using following equation:

\[
\bar{T}_g = \bar{T}_a - \frac{B_g (365)^2}{2\pi(n_2-n_1)\times360}[\cos \left(\frac{n_2-n_1}{365} * 360 - \phi\right) - \cos \left(\frac{n_1-n_1}{365} * 360 - \phi\right)]
\]

[13]

where

\( \bar{T}_g = \text{average effective ground temperature, } ^\circ\text{C} \)

\( \bar{T}_a = \text{yearly average air temperature, } ^\circ\text{C} \)

\( B_g = \text{amplitude of effective ground temperature curve, } ^\circ\text{C} \)

\( \phi = \text{phase lag between ambient temperature curve and effective} \)
ground temperature curve, degree

\( n_1 \) = the day number of the year on which the time period of interest begins

\( n_2 \) = first day number of the year after the time period of interest ends

\( n_{\text{c}} \) = the day number of the year on which the ambient temperature curve crosses the mean value; it is approximately 110 days for U.S. locations.

The amplitude and phase lag of the effective ground temperature for the wall can be expressed as:

\[
\frac{B_g,w}{B_a} = -0.035 \, \text{FO}^{-0.37} + 1.01 \\
\phi_{w} = 22.0 \, \text{FO}^{-0.54} - 0.68
\]

and for the floor

\[
\frac{B_g,f}{B_a} = -0.73 \, \text{FO}^{-0.172} + 1.12 \\
\phi_{f} = 289.3 \, \text{FO}^{-0.104} - 176.
\]

where

\( B_a \) = the amplitude of the ambient temperature curve;

\( B_a \) varies from location to location

The Fourier modulus (FO) is the non-dimensional time and is defined as:

\[
\text{FO} = \frac{\alpha \theta}{D^2}
\]

where

\( \theta \) = period, one year
\( \alpha = \text{thermal diffusivity, } m^2/s \)

\( D = \text{basement depth, } m \)

THERM predicts the monthly heat loss from basement using the above algorithm, and then regresses the monthly basement heating load with the average monthly temperature to develop a relation that can be used to predict the basement heating load at various temperature bins.

**Description of THERM**

The computer program for thermal load analysis of residences (THERM) was written in FORTRAN F77L on an IBM-compatible microcomputer. Figure 3 is a flow chart of THERM. Input data to the computer program consist of building orientation, use and occupancy, physical dimensions, climatic data, and indoor load.

THERM has the following capabilities:

- predict design as well as seasonal energy requirements of the buildings;
- predict the thermal loads of the perimeter and interior zones separately;
- predict the thermal load for both occupied and unoccupied periods separately;
- predict the below grade basement heating load.

THERM consists of one main program and nine subroutines. The program listing is presented in Appendix A, and the program output is
START

READ INPUT DATA

DOES PERIMETER ZONE EXIST

NO

SOLAR

CALL SOLAR

YES

COMPUTE SOLAR HEAT GAIN THROUGH GLASS IN JULY & JAN.

TRANS

CALL TRANS

COMPUTE SOLAR COMPONENT THROUGH WALLS AND ROOF

CONDUC

CALL CONDUC

COMPUTE CONDUC. LOAD THROUGH WALLS AND GLASS

INTL

CALL INTL

COMPUTE INTERIOR LOAD DUE TO LIGHTS, EQUIP. & OCCUPANTS

DOES INTERIOR ZONE EXIST

NO

YES

Figure 3. Flow chart of THERM
Figure 3. (Continued)
Figure 3. (Continued)
presented in Appendix B. A brief description of the various subroutines follows:

SOLAR

Subroutine SOLAR computes the solar contribution for the glass area in summer and winter for the perimeter zone.

TRANS

Subroutine TRANS computes the solar contribution from opaque surfaces for July and January.

CONDUC

Subroutine CONDUC computes the transmission load through walls, roof, and fenestrations.

INTL

Subroutine INTL computes building interior load due to people, lights, and equipment.

IZONE

Subroutine IZONE computes solar load through opaque roof, and transmission load due to conduction from roof of the interior zone.

HLOAD

Subroutine HLOAD computes hourly baseboard heating loads for each temperature bin.

BASE

Subroutine BASE computes monthly basement heating load and then regresses the monthly basement heating load with the average monthly
temperature to predict the basement heating load at various
temperature bins.

DESIGN

Subroutine DESIGN computes the design heating load of the
building.

SLOAD

Subroutine SLOAD computes the seasonal heating load of the
building.
DATA COLLECTION AND ANALYSIS

Description of House Envelope

The residence building of the McNAY Memorial Research Center is state owned, and is situated near Chariton, Iowa. Chariton is 304 meters above sea level, at 41.01° North latitude and 93.18° West longitude. The two-story brick house is located in a rural area. It has a basement and is surrounded by a small number of trees. It has a conditioned floor area of 118.0 m² and a leakage area of 1768 cm², and is oriented north and south. Figure 4 presents the overall view of the house. The average indoor temperature during the winter season of 1989-90 was 21.0 °C, with no night setback. Table 1 presents the main house parameters.

Data Collection

To understand the house and its usage and to calculate the thermal properties of the house components, the following data were collected:

- Data on house dimensions and material characteristics of the walls, windows, and roof at the site;
- Data on the use of appliances and equipment, lighting levels, occupancy levels, and other related parameters (by consultation of house resident);
- Data on indoor air temperature and energy delivered to the
Figure 4. A overall view of the McNay Memorial Research center residence
Table 1. House parameters

<table>
<thead>
<tr>
<th></th>
<th>Area, m²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior above-grade walls</strong></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>59.80</td>
</tr>
<tr>
<td>East</td>
<td>50.20</td>
</tr>
<tr>
<td>South</td>
<td>64.24</td>
</tr>
<tr>
<td>West</td>
<td>42.35</td>
</tr>
<tr>
<td><strong>Glass above grade area</strong></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>16.50</td>
</tr>
<tr>
<td>East</td>
<td>14.50</td>
</tr>
<tr>
<td>South</td>
<td>12.05</td>
</tr>
<tr>
<td>West</td>
<td>22.34</td>
</tr>
<tr>
<td><strong>&quot;U&quot;- value</strong></td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td>1.47</td>
</tr>
<tr>
<td>Windows</td>
<td>2.84</td>
</tr>
<tr>
<td>Roof</td>
<td>0.364</td>
</tr>
<tr>
<td>Basement</td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>3.541</td>
</tr>
<tr>
<td>Walls</td>
<td>1.77</td>
</tr>
<tr>
<td><strong>Interior loads</strong></td>
<td></td>
</tr>
<tr>
<td>Number of occupants</td>
<td>3</td>
</tr>
<tr>
<td>Lights (watts)</td>
<td>1460</td>
</tr>
<tr>
<td>(for 16 hours with 30% use)</td>
<td></td>
</tr>
<tr>
<td>Refrigerator (watts hrs/day)</td>
<td>4700</td>
</tr>
<tr>
<td>Freezer (watts hrs/day)</td>
<td>4600</td>
</tr>
<tr>
<td>Range (watts hrs/day)</td>
<td>3300</td>
</tr>
<tr>
<td>Waterbed (watts hrs/day)</td>
<td>1200</td>
</tr>
<tr>
<td>(30% utilization)</td>
<td></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>41° - 02'</td>
</tr>
<tr>
<td>Longitude</td>
<td>93° - 20'</td>
</tr>
<tr>
<td>Elevation (above sea level)</td>
<td>304 meter</td>
</tr>
</tbody>
</table>
house from the biofueled boiler. These data were recorded by using an on-site computerized data-acquisition system from December 16, 1989 to March 31, 1990. Energy consumed from November 1, 1989, to December 15, 1989, was computed from gasmeter readings.

- Data required to compute the house infiltration rate by performing an on-site blower door test. Appendix C presents the results of the blower door test and other procedures used to predict the infiltration rate.

- Weather data for the winter season of 1989-90 at McNAY Memorial Research Center from records at the Department of Agricultural Meteorology, The University of Nebraska-Lincoln. A computer program BIN was written, which directly reads the hourly weather data from the diskette and converts it to various temperature bins. Appendix D presents the listing of computer program BIN. Figure 5 shows the occurrence of the various temperature bins for Des Moines (1878-1977) and Chariton, Iowa (April 1989 - March 1990), whereas Appendix E presents a tabulated form. Procedures adopted for computing the thermal transmittance of various components of the house solar heat gain factor, cooling load factor, and cooling load temperature difference are presented in Appendix F.
Figure 5. Frequency of outdoor temperature for Chariton and Des Moines, IA
RESULTS AND DISCUSSION

Comparison of Monthly Heating Load

To validate THERM, the monthly predicted heating loads were compared with those measured. Table 2 presents the average indoor house and basement temperatures, and predicted and measured loads for the months of November 1989 through March 1990. Appendix E presents additional input data and operating details of THERM. Figure 6 presents a comparison between the measured and predicted loads. It can be seen that the program overpredicted by about 18.9% and 8.4% for the months of November and February, respectively; whereas it underpredicted about 7.3%, 21.6%, and 15% for the months of December, January, and March, respectively. The largest discrepancies exist for the months of November, January, and March. The average wind velocity (3.73 m/s) over the period of the study was used for predicting the infiltration rate. During January and March, wind speed was above average, which may have resulted in a high infiltration rate, and consequently have increased the actual heating load. On the other hand, during November, wind speed was below average, which decreased the heating load.

Figure 7 plots the monthly measured heating load vs the monthly predicted heating load. The slope of the regressed line between the measured and predicted results is 1.06. The 95% confidence estimates
Table 2. Measured and predicted loads for the period of November 1989 - March 1990

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Temperature (°C)</th>
<th>Load (kWh)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>House</td>
<td>Basement</td>
<td>Measured</td>
</tr>
<tr>
<td>November</td>
<td>19.5</td>
<td>19.3</td>
<td>5523</td>
</tr>
<tr>
<td>December</td>
<td>19.5</td>
<td>19.3</td>
<td>17085</td>
</tr>
<tr>
<td>January</td>
<td>21.5</td>
<td>21.0</td>
<td>12960</td>
</tr>
<tr>
<td>February</td>
<td>21.5</td>
<td>21.0</td>
<td>9842</td>
</tr>
<tr>
<td>March</td>
<td>22.5</td>
<td>22.0</td>
<td>8396</td>
</tr>
</tbody>
</table>
Figure 6. Comparison between measured and predicted monthly heating loads for McNay Memorial Research Center residence.
Figure 7. Measured vs predicted heating loads for McNay Memorial Research Center residence
of the slope are 0.56 and 1.55. The 95% confidence lines are also shown in Figure 7. It can be seen that the 95% confidence interval estimates of the slope brackets the value of 1.0. This means that the predicted load was in good agreement with the measured load for November, December, January, February, and March.

Comparison of Seasonal Heating Load

Figure 8 shows the comparison of predicted seasonal load using both the Chariton weather data 1989-90, and the Des Moines published bin weather data (U.S. Air Force Manual 88-29, 1978) with the measured seasonal load. It can be seen that the measured seasonal loads (November 1989 to March 1990) were 53807 kWh, whereas the predicted seasonal load using 1989-90 Chariton weather data was 50371 kWh. This signifies that the program underpredicted the seasonal load by only 6.5%.

Kusuda et al. (1981), using the modified bin method, predicted the seasonal load of single-story masonry-construction buildings and compared those results with the DOE-2 results. The results obtained using the modified bin method fell within 15 percent of the DOE-2 results. The THERM seasonal predicted load was within 6.5% of the measured load. Good agreement between measured and predicted loads was achieved because THERM predicts the basement heating load in addition to the house envelope load. If the basement load had not
Figure 8. Comparison between measured and predicted seasonal heating load for McNay Memorial Research Center residence.
been accounted for, the predicted results might have fallen 26.5% below the measured results because the basement made up around 20% of the total house envelope load.

Figure 8 presents a comparison of predicted seasonal load using the Des Moines published bin weather data with the measured seasonal load. This comparison was made to determine how much variation between measured and predicted results may exist as a result of using published bin weather data for a 100-year period from a close location. It can be seen from Figure 8 that the predicted seasonal load was 56110 kWh, as compared with the measured seasonal load of 53807 kWh. The THERM program therefore overpredicted about 4.5%. The predicted seasonal load using the Des Moines published bin data was also in good agreement with the measured results.

Energy Saving Measures

Figure 9 plots the seasonal load of the McNAY Memorial Research Center residence versus various indoor temperature settings. The basement temperature was assumed to be 20°C. It can be seen that by increasing the indoor temperature setting from 22°C to 25°C, the seasonal load will increase from 67,000 kWh to 79,000 kWh. In other words, by increasing the indoor temperature setting only 3°C, a corresponding increase of 12,000 kWh in seasonal load is possible. Thus by setting indoor temperature to 22°C instead of to 25°C, one
Figure 9. Seasonal load vs indoor temperature for McNay Memorial Research Center residence
can save about 12,000 kWh (15% reduction in energy use) per heating season. This translates into a savings of $420.0 for users of the LPG system (assuming $0.16/L LPG price and 65% boiler efficiency) and a savings of $750.0 for users of a wood fired system (assuming $75/ton wood fuel price, 45% MC of fuel, and 40% wood fired boiler efficiency). One can save even more with night-time thermostat setback.
CONCLUSION

1. A Microcomputer Program for Thermal Load Analysis of a Building Envelope (THERM) was developed to predict the hourly heating load at various bin temperatures and design as well as seasonal energy requirement of the building envelope. The predicted hourly heating loads at various bin temperatures would be used for simulating a biofueled boiler (in the second part of this dissertation).

2. To validate THERM the measured heating loads for November, December, January, February, and March were compared with the predicted heating loads. The slope of the regressed line between the measured and predicted results was 1.06. The 95% confidence estimates of the slope were computed as 0.56 and 1.55, which bracket the value of 1.0. This means that THERM predictions were in good agreement with measured results.

3. The seasonal predicted load was compared with the measured seasonal load. The THERM prediction of seasonal load was also in good agreement (within 6.5%) with the measured seasonal load. THERM was consequently determined to be suitable for estimating the seasonal load of residence buildings.

4. The parametric analysis revealed that by setting the indoor temperature at 22 °C instead of at 25 °C up to a 15% reduction in seasonal energy consumption of a two-story house may result.
REFERENCES


PART II. A SIMULATION MODEL FOR PREDICTING THE SEASONAL EFFICIENCY OF BIOFUELED BOILERS
INTRODUCTION

The seasonal efficiency of wood fired space heating boilers is well below the efficiency obtainable under continuous full load operations. This is because boiler capacity must be well above average heat demand. Figure 1 presents a typical duration curve of heating demand for a residence building of McNAY Memorial Research Center, Chariton, Iowa. It shows that heating loads greater than 50% of the maximum load occur for only 1000 hours/heating season, and only 10 percent of the seasonal energy is provided at loads greater than 50% of maximum building envelope load. Because of this wide variation in heating demand, the boiler output is always larger than the load and the boiler operates cyclically. This results in reduced efficiency.

An accurate determination of seasonal efficiency is not only imperative to evaluate the seasonal performance of biofueled boilers, but it is also an important parameter in estimating the seasonal fuel requirement, and for economic analysis of the biofueled energy system. The measured steady state efficiency of a wood fired space heating boiler of 80% in the laboratory can drop to 35% (seasonal) when the design and operation of the system are poor (USDA, 1982). Numerous investigators have developed various methods for predicting the seasonal performance of residential gas and oil fired heating systems (Chi and Kelley, 1978; Kweller and Mullis, 1981; ASHRAE,
Figure 1. A duration curve of heating demand of a McNay Research Center residence
1982; Kelly et al., 1978; Kusuda et al., 1982). But no attempt has been made to predict the seasonal performance of biomass fueled boilers.

At the present time the determination of seasonal performance of wood fired boilers is based solely on experiments, which are often difficult and expensive to conduct. In addition, little quantitative knowledge of how the seasonal efficiency of a wood fired boiler is affected by design and operating variables exists.

To develop a better understanding, a computer model was developed to simulate boiler operation and to predict the seasonal efficiency of wood fired boilers. Confidence in the model predictions was established by comparing them with the measured results. About one hundred runs of the computer program were made to predict the performance of wood fired boilers at various combinations of design and operating variables. The results were plotted to be easily accessible to wood fired boiler designers and operators, to assist them in obtaining higher boiler efficiency.
REVIEW OF LITERATURE

Biomass Fuel Characteristics

Simulation modelling of a biofueled energy system requires a full understanding of the chemical and physical properties of biomass fuel. Many different sources of biomass fuel exist, including agricultural residues, forest residues, woody biomass, and crops grown specifically for energy. In this work the major thrust has been given to wood biomass. However, where data were available for other forms of biomass, these were also included.

Chemical composition of wood

Wood is composed of a variety of substances. The chief constituents are cellulose, lignin, hemicellulose, extractive and various ash-forming minerals. The ranges of composition of each of the components is as follows: cellulose, 40-50%; hemicellulose, 15-35%; lignin, 20-35% (Miller et al. 1985). The cellulose and hemicellulose are often considered together as "holocellulose" and will typically made up 60-80% of total dry wood mass. In pyrolysis, the energy content of the fuel is distributed to varying degrees between the char and volatile fractions depending on the composition of the fuel and the reaction condition employed. Volatilization is enhanced by high carbohydrate and extractive content in the fuel and elevated reaction temperatures (Shafizadeh and Degroot, 1977).
Proximate and ultimate analysis

The proximate analysis is valuable in analyzing wood combustion. It determines the percentage of moisture, ash, volatile matter, and permits calculating the percentage of fixed carbon by difference. The quantity of volatile matter indicates the amount of gaseous fuel present; during combustion the volatiles burn in the gaseous phase with flaming combustion. The fixed carbon is the combustible residue left after the volatile matter distills off. It consists mainly of carbon, but contains some hydrogen and oxygen, and a minute amount of sulfur and nitrogen not driven off with the gases (Schwieger, 1980). During combustion, the fixed carbon burns in the solid phase with glowing combustion.

Ultimate analysis generally reports carbon, hydrogen, nitrogen, sulfur, and oxygen (by difference) in the solid fuels. For certain biomass materials like municipal solids and animal waste, the determination of chlorine is important because it represents possible pollutants and corrosive agents in a gasification and combustion system. Graboski and Bain (1981) documented well the proximate and ultimate analysis of various biomass materials. The typical values of proximate and ultimate analysis of bark, wood, and coal were presented in Table 1. The extremely low percentage of nitrogen, sulfur and ash present in the wood and bark makes them highly desirable fuel from the standpoint of combustion pollution control.
Table 1. Typical values of proximate and ultimate analysis of a bark, wood, and coal^a

<table>
<thead>
<tr>
<th>Fuel Characteristics</th>
<th>Proximate Analysis</th>
<th>Ultimate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bark (Douglas fir)</td>
<td>Wood Wyoming</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile matter</td>
<td>70.6</td>
<td>86.2</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>27.2</td>
<td>13.7</td>
</tr>
<tr>
<td>Ash</td>
<td>2.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Ultimate Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Carbon</td>
<td>56.2</td>
<td>52.3</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Oxygen</td>
<td>36.7</td>
<td>40.5</td>
</tr>
<tr>
<td>Ash</td>
<td>1.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

^aSchwieger, 1980.
Moisture content

Wood is hygroscopic; it absorbs and adsorbs water. The absorbed water is known as free water, while the adsorbed water is called "bound water" (Tillman, 1981). The Fiber Saturation Point (FSP) for wood ranges from 23 to 25% moisture content green basis with water being adsorbed below the FSP and absorbed above the FSP.

The moisture content of wood is expressed on the wet basis and dry basis. The moisture content on wet basis is the weight of water in the wood sample divided by the weight of dry wood plus the weight of water. The moisture content on dry basis is the fractional water content or the weight of water divided by the sample weight when dried. The conversion from dry basis to wet basis and from wet basis to dry basis is given by the following equations.

\[ M.C. (wb) = \frac{M.C.(db)}{(M.C.(db) + 1)} \]  
\[ M.C. (db) = \frac{M.C.(wb)}{(1 - M.C.(wb))} \]

Throughout this study the moisture content of wood refers to wet basis unless it is specified otherwise.

Table 2 presents green moisture content for the various parts of several forest tree species (Howlett and Gamache 1977). It can be seen that large variations exist among the moisture contents of various parts of a tree. The foliage contains maximum moisture content followed by roots, stem and branches.
Table 2. Green moisture contents of tree parts for several speciesa

<table>
<thead>
<tr>
<th>Species</th>
<th>Moisture Content (%, wet basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foliage</td>
</tr>
<tr>
<td>Red spruce</td>
<td>53</td>
</tr>
<tr>
<td>Balsam fir</td>
<td>59</td>
</tr>
<tr>
<td>White pine</td>
<td>58</td>
</tr>
<tr>
<td>Eastern hemlock</td>
<td>54</td>
</tr>
<tr>
<td>Northern white</td>
<td></td>
</tr>
<tr>
<td>Cedar</td>
<td>56</td>
</tr>
<tr>
<td>Slash pine</td>
<td>61</td>
</tr>
<tr>
<td>Loblolly pine</td>
<td>51</td>
</tr>
<tr>
<td>White birch</td>
<td>60</td>
</tr>
<tr>
<td>Red maple</td>
<td>62</td>
</tr>
<tr>
<td>Aspen</td>
<td>55</td>
</tr>
</tbody>
</table>

aHowlett and Gamache (1977).
Moisture content affects not only the combustion process and its efficiency, but also greatly affects the net heating value of wood fuel, as well as the selection of equipment for combustion.

**Heating value of wood**

There are two different heating values, namely Higher Heating Value (HHV) and Lower Heating Value (LHV). The HHV is the experimentally determined value of heat released during the combustion per unit weight of fuel using an oxygen bomb calorimeter (ASTM standard D2015-85). It is important to note here that in the products of combustion the water formed is in the liquid phase, and therefore, the heat of vaporization for the water is not subtracted from the heating value. The LHV is defined for product water in vapor phase. The HHV for various species are presented in Table 3 (USDA, 1982).

The lower heating value can be calculated by subtracting the latent energy of vaporization of water from the higher heating value. The higher heating value of moist fuel is (Mcgowan et al., 1980):

\[
HHV \text{ (moist fuel) } = HHV \text{ (dry fuel) } (1-MC) \tag{3}
\]

Where the MC is the fractional moisture content on wet basis. The lower heating value is then (Ebeling and Jenkins, 1985).

\[
LHV = HHV(1-MC) - (\lambda) (MC) - (1-MC) (\lambda) (18H /200) \tag{4}
\]

The variable \( H \) is the hydrogen concentration in the fuel, percent by weight dry basis and \( \lambda \) is the latent energy of
vaporization for water. The second term on the right hand side represents the latent energy of fuel moisture. The third term is the energy loss due to formation of water from fuel hydrogen. Rearranging Equation 4,

\[ \text{LHV} = (1-MC) (\text{HHV} - \lambda (MC/1-MC + 0.09H)) \]  

Figure 2 shows the relationship between the moisture content and the higher and lower heating values. Figure 2 clearly indicates that the heating values (both HHV and LHV) of wood fuel are very sensitive to the moisture content.

**Wood Combustion**

Combustion is a fast and highly exothermic chemical reaction between fuel and an oxidant. In complete combustion of wood, hydrogen and carbon in the fuel react with oxygen in the air producing water (H\textsubscript{2}O) and carbon dioxide (CO\textsubscript{2}). Sulfur is generally ignored in the direct combustion of biomass fuels because of the low sulfur content of biomass materials. The following equations summarize the combustion of carbon and hydrogen with oxygen (Leppa and Saarni, 1982).

\[ \text{C + O}_2 \rightarrow \text{CO}_2 + 32.8 \text{ MJ/kg C} \ (14,100 \text{ Btu/lb C}) \]

\[ \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} + 141.9 \text{ MJ/kg H} \ (61,000 \text{ Btu/lb H}) \]

Combustion largely involves free radical reactions where gaseous compounds are converted into radicals by homolytic cleavage, and these radicals react with each other and with oxygen in the
Table 3. Heating values of various biomass fuels

<table>
<thead>
<tr>
<th>Species</th>
<th>Higher Heating Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MJ/kg (Btu/lb)</td>
</tr>
<tr>
<td>Wood&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Ash, white</td>
<td>20.73 (8920)</td>
</tr>
<tr>
<td>Elm</td>
<td>20.47 (8810)</td>
</tr>
<tr>
<td>Hickory</td>
<td>20.15 (8670)</td>
</tr>
<tr>
<td>Maple</td>
<td>19.94 (8580)</td>
</tr>
<tr>
<td>Oak, black</td>
<td>19.00 (8180)</td>
</tr>
<tr>
<td>Oak, white</td>
<td>20.19 (8690)</td>
</tr>
<tr>
<td>Poplar</td>
<td>20.73 (8920)</td>
</tr>
<tr>
<td><strong>Other Biomass Fuels&lt;sup&gt;b&lt;/sup&gt;</strong></td>
<td></td>
</tr>
<tr>
<td>Corn cobs</td>
<td>26.32 (11,330)</td>
</tr>
<tr>
<td>Rice hulls</td>
<td>16.51 (7,106)</td>
</tr>
<tr>
<td>Rice Straw</td>
<td>15.19 (6,540)</td>
</tr>
<tr>
<td>Cotton gin trash</td>
<td>15.15 (6,520)</td>
</tr>
<tr>
<td>Feedlot manure</td>
<td>15.12 (6,508)</td>
</tr>
<tr>
<td>(aged/composted)</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>USDA (1982).
<sup>b</sup>Lepori and Soltes (1985).
Figure 2. Relationship between the heating values and moisture contents of wood fuel
combustion air in a complex series of pathways. There are numerous intermediate compounds such as OH, CH\text{3}, C\text{6}H\text{6}, CH\text{2}, HOO, CO, etc., while CO\text{2} and H\text{2}O are the final products.

Wood Combustion can take place in the gaseous phase, called flaming combustion, or in the solid phase, called glowing combustion. Figure 3 summarizes the different reactions or reaction zones of wood combustion as (Edward, 1974, reported by Tillman, 1981):

1. Heating and drying
2. Solid phase pyrolysis
3. Precombustion gas phase pyrolysis reactions
4. Gas phase oxidation reactions, and
5. Char oxidation reactions

Heating and drying

The first stage of wood combustion is the evaporation of water in the wood. This is an endothermic process in which energy must be supplied to vaporize the water. Drying typically occurs at a temperature of 100 to 150 °C. The drying reactions can be represented by the following expression:

\[
\text{wet wood + energy} \rightarrow \text{dry wood + H}_2\text{O}
\]

The rate of drying is governed by: (1) initial fuel moisture content, (2) particle size and shape, (3) specific heat of wood, and (4) the thermal conductivity of wood.
Figure 3. Different reactions and reaction zones of wood combustion (Edwards, 1974 reported by Tillman, 1981)
Solid phase pyrolysis

Pyrolysis is an endothermic irreversible chemical degradation of wood in which virgin wood is transformed into char and combustible vapors (Kanury, 1972). All biomass gasification and combustion processes involve pyrolysis as a necessary first step, because the complex structures such as cellulose and lignin can not be oxidized directly (Milne, 1981). When the biomass material is heated in the presence of substoichiometric air, the principal gaseous products include hydrogen, carbon monoxide, carbon dioxide, nitrogen, methane, and small amounts of other hydrocarbons. This can be represented by the following expression (Lepa and Saarni, 1982):

\[
\text{Dry wood } \rightarrow \text{ CO}_2 + \text{ CO} + \text{ CH}_4 + \text{ C}_2\text{H}_6 + \text{ C}_3\text{H}_8 + \text{ CH}_3\text{COOH} + \\
\text{CH}_3\text{CHO} + \text{ tars } + \ldots \text{char (typically C}_4\text{H}_6\text{)}
\]

Products of solid wood pyrolysis vary by wood component. The rate of pyrolysis is governed by: (1) heat transfer rates, (2) particle temperature, (3) particle size and geometry. The distribution of pyrolysis products is also affected by particle size, moisture content, and temperature. Large particles, wet particles, and low temperature will produce relatively more char. Small, dry, and high temperature particles will yield relatively more condensible volatiles, which can be further reacted to noncondensible gaseous compounds or passed through the process as potential pollutants (depending upon residence time and combustion air penetration).
Precombustion gas phase reactions

This sequence of events involves the volatile products of solid-phase pyrolysis. Among these reactions are further degradation of such components as acetic acid and acetaldehyde by decarboxylation and decarbonylation, shown by the following equations:

\[
\begin{align*}
    \text{CH}_3\text{COOH} & \rightarrow \text{CH}_4 + \text{CO}_2 \\
    \text{CH}_3\text{CHO} & \rightarrow \text{CH}_4 + \text{CO}
\end{align*}
\]

Gas-phase oxidation reactions

Gas-phase reactions involve both chain propagation and chain termination. Chain propagation reactions produce two key intermediates, including the highly reactive hydroxy radical, which tend to govern the subsequent chain termination reactions.

Char oxidation

The residue remaining after pyrolysis is a highly reactive carbonaceous char. Oxidation of this char in solid phase gives glowing combustion which has a relatively slower rate of combustion than flaming combustion. If the intensity of the heat flow or combustion gases (oxygen supply) fall below a minimum level, smoldering combustion takes place in which unoxidized volatile products and aerosol particles are emitted as smoke (Nikoo, 1985).

It can be concluded that wood combustion is a highly complex physical and chemical phenomenon with numerous reaction steps and pathways. Understanding and manipulation of those pathways can
maximize combustion efficiency, rates of combustion, heat release, and minimizing formation of airborne emissions.

**Combustion Technologies**

Wood fuels, in general, differ greatly in composition, moisture content, and particle-size as well as method of utilization. Numerous furnace designs exist for the direct combustion of biomass fuels. Each design has its unique characteristics, but most were developed for burning fossil fuels (Lepori and Soltes, 1985). These systems are generally classified as grate burners, pile burners, suspension burners, and fluidized bed combusters. Due to space limitation only brief descriptions of these systems are presented below, while these are well documented by Shafizadeh, 1982.

**Grate burners**

The fuel is spread upon the grates by some combination of gravity feed and pneumatic or mechanical feed (a spreader stoker). Air flow through the grates: (1) provides oxygen for combustion of fixed carbon, (2) cools the grates, (3) promotes turbulence in the fuel bed, and (4) contributes to drying the fuel.

**Pile burners**

Pile burners consists of primary and secondary combustion chambers. Primary combustion chamber dry and partially burn the fuel and boil off the volatiles prior to complete burning in a secondary combustion chamber (O'Grady, 1980). The prototype of this design is
the dutch oven boiler. A modern variation of the dutch oven design, which incorporates features of grate burning and pile burning, is the boiler produced by American Fyr-Feeder and Weiss (McNay biomass boiler is the example of this type). This type must be selected where a high moisture fuel must be burned. Firing of low moisture fuels may cause increased NO\textsubscript{x} emissions due to hot spots and long retention time in the furnace (USDA, 1982).

**Suspension burners**

Suspension burners are of two types: (1) injection type, where fuel and air are mixed in a turbulent jet inside the firebox, and (2) cyclonic type, where the fuel and air are mixed and burned in an external cyclone burner. Efficient, clean combustion with suspension burners is possible only with clean, dry, and finely divided wood waste such as sanderdust (Schwieger, 1980). Dry fuels may be fired without preparation. Wet fuels require pulverization and predrying, preferably using the flue gas from the boiler as a heat source for drying to improve the efficiency.

**Fluidized bed combustor**

The fluidized bed combustor is characterized by a bed of solid inert particles (e.g., sand) through which air is passed at sufficient velocity to float and move the particles in relation to each other--to "fluidize" the bed. Woodwaste or any other fuel
burns in suspension with the inert material. The primary functions of inert material are:

- to disperse incoming fuel particles throughout the bed
- to heat the fuel particles quickly to the ignition temperature
- to store thermal energy
- to provide sufficient residence time for complete combustion

The fluidized combustor provides a relatively complete combustion, controlled temperatures in the combustion zone, and can diminish emissions. Particulate, NO$_x$, and SO$_x$ emissions can be kept at a low level. On the other hand, it has a high power consumption and a poor turn-down ratio (Leppa and Saarni, 1982).

In addition to the above well known systems, Claar, Buchele, and Marley (1981) have designed and tested a concentric vortex cell furnace that provides staged combustion by controlling air injection at several points within the unit. They successfully substituted corn cobs for Liquefied Petroleum Gas (LPG) as fuel in a crop dryer. Many other investigators (Riley and Smith, 1984; Huff et al., 1976; Smith et al., 1980) conducted extensive research in developing and evaluating systems for using biomass fuels. But no attempt was made to predict the seasonal performance of these biomass fueled systems.

Lepori et al. (1985) reported that Lang (1983) stated that the main problem for burning biomass materials with high ash content in the wood fired systems is the creation of slag or ash scale deposits...
on the system components. Caution is necessary in extrapolating the feasibility of equipment designed for one biomass fuel to use with another. The chemicals in the ash, including basic and acidic constituents, are important in addition to the ultimate analysis for evaluating the suitability of biomass fuels for direct combustion.

**Modeling of Combustion Systems**

The seasonal efficiency of space heating boilers is considerably lower than the efficiency obtainable under continuous full load operations. This is because: (1) heat demand varies, and (2) boilers are usually sized on the basis of design load, which is larger than the average load.

Chi (1977) developed a computer model for predicting the seasonal performance of fossil fueled boilers. This model was also used to examine the effects of design and operating variables on the boiler performance and fuel economy. In addition, numerous investigators have developed various methods for predicting the seasonal performance of residential gas and oil fired heating systems (Chi and Kelly, 1978; Kweller and Mullis, 1981; ASHRAE, 1982; Kelly et al., 1978; Kusuda et al., 1982). But no attempt has been made to predict the seasonal performance of biomass fueled boilers.

Giese and Leesley (1981) developed a mathematical model of burning wood chips. In order to develop and solve governing
equations in this model, several simplifying assumptions have been made such as: (1) the temperature and the concentrations of solids and gases do not vary with the radial position, and that all transport of mass and energy along the axial direction of the furnace occurs only by virtue of the material moving, i.e., convection (these are also called plug-flow assumptions), (2) zero percent moisture content, and (3) cylindrical shaped particles. These assumptions have drastically reduced the applicability of this method to model the real world phenomena, where these assumptions could not be fulfilled.

Schneider (1984) conducted an efficiency study of a wood chip stoker central heating system. He reported that the heating system efficiency was approximately 45% over the 1981-82 heating season. Cleanliness of grate and heat exchanger was important for maintaining efficiency.

Finally, until now the determination of seasonal performance of space heating wood fired boilers has been based solely on experiments, which are difficult and expensive to conduct. Therefore, this work was undertaken to develop a simulation model for predicting the seasonal performance of biofueled boilers. This model will also serve as an inexpensive instrument for making parametric studies.
SIMULATION MODELING OF A BIOFUELED BOILER

Description of the System

The McNAY wood biomass boiler is the modern version of the dutch oven design, which incorporates features of grate burning and pile burning. Drying is completed on sloped grates prior to the introduction of fuel into the main area of the combustion. Sloped or stepped grates serve to facilitate drying and to convey the fuel to the combustion zone. Combustible gases are distilled from the fuel, mixed with preheated secondary air, ignited and burned in the combustion chamber. A standing column of raw fuel is maintained in the fuel feed hopper by a level control which activates the fuel transfer conveyor from the storage wagon. A schematic diagram of the McNAY wood-fired boiler system is shown in Figure 4.

The fuel (wood chips) supplies input energy to the boiler. Water circulates at a constant rate around the heat exchanger tubes and delivers the heat to the building envelope. In addition, there are a number of sensible and latent losses involved in this process of energy conversion.

The three modes of operations of a wood fired boiler under various load conditions are shown in Table 4. At low load (i.e., when the required energy for the building is less than the medium heat output of the boiler) the temperature of the supply water rises
Figure 4. A schematic diagram of the McNay wood-fired boiler system
Table 4. Various modes of operation of biofueled boiler

<table>
<thead>
<tr>
<th>Various Modes</th>
<th>Induced Draft Fan</th>
<th>Primary Air Damper</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON1</td>
<td>ON</td>
<td>Closed</td>
</tr>
<tr>
<td>ON2</td>
<td>ON</td>
<td>Open</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>Closed</td>
</tr>
</tbody>
</table>

until it reaches the upper limit of the controlled range, at which temperature a control device shuts off the Induced Draft (ID) fan and reduces the firing rate. During the subsequent off cycle, hot water continues supplying the required heating energy to the building. As the temperature of supply water drops below the upper temperature limit, the control device switches on the ID fan and increases the firing rate.

At high load (i.e., when the required energy for the building is more than the medium heat output of the boiler) the temperature of the supply water decreases until it reaches the lower limit of the controlled range, at which temperature a control device opens the Primary Air Damper (PAD), and increases the firing rate. During this second stage of the on period, hot water is continuously supplying the required heating energy to the building. As the temperature of
the supply water reaches the minimum operating limit, the control device closes the primary air damper.

Model Components

To study the seasonal performance of biofueled boilers, a simulation model which can be described by simple mathematical relations was established. In order to describe the simulation procedure and mathematical formulation, this subject is divided into three parts:

1. A mathematical relation was developed to predict the duration of three modes of operation.

2. Principles of conservation of mass and the first law of thermodynamics were applied to predict the steady state efficiencies under three modes of operation.

3. An analytical and numerical approach was developed and used to predict the energy losses through the flue gases during the on and off cycling operation of the system.

Prediction of Boiler Operation Time under Three Modes of Operation

As described earlier the wood fired automatically fed boiler has three modes of operation under various load conditions. To predict the seasonal efficiency it is important to predict the boiler operation time under various modes of operation. The time under
various modes of operation was predicted by simulating the boiler tank. To achieve this, it was assumed that the boiler is an ideal storage unit with an evenly distributed temperature, receiving energy from burning of wood chips and delivering energy to the system at a constant rate.

The energy storage capacity of a hot water boiler at uniform temperature operating over a finite temperature difference is given by;

$$ Q_b = (m \times C_p) \Delta T_b $$

where $Q_b$ the total heat capacity for a cycle operating through the temperature range $\Delta T_b$, with $m$ kilograms of water in the boiler tank. An energy balance on the boiler tank yields.

$$ (m \times C_p)_b \left( \frac{dT_b}{dt} \right) = Q_{in} \times SSE - L $$

where $Q_{in}$ and $L$ are rates of addition of energy from wood chips, and removal to the building load. SSE is the steady state efficiency, which converts the input energy to the actual useful energy and also takes care of ambient losses.

The above equation can be written in finite difference form and can be solved for the boiler temperature at the new time.

$$ T_{b'} = T_b + \left( \frac{\Delta T}{m \times C_p} \right) [Q_{in} \times SSE - L] $$

Inserting the appropriate constants, with a given time increment (15 seconds), the temperature of the boiler tank at the end of the
time increment was calculated from its temperature at the beginning of that time increment, from the known inputs and outputs.

Subroutine SIMBLR was written to predict the boiler operating time under various modes of operation using the above mathematical formulation. Figure 5 presents the flow chart of subroutine SIMBLR, and logical decisions which were made to predict the boiler operation time under three modes of operations.

Application of Principle of Conservation of Mass

To determine the mass flow rate and composition of flue gas, the principle of conservation of mass was used, in addition to the knowledge of chemical reactions taking place in the boiler furnace. The principal combustible constituents are elemental carbon, hydrogen, and their compounds. These can be represented by the chemical reactions (Babcock and Wilcox, 1978):

\[ \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \]
\[ \text{C} + 0.5 \text{O}_2 \rightarrow \text{CO} \]
\[ \text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O} \]

In the above reactions, the reactants combine on a mole basis. The amount of nitrogen oxides NO\textsubscript{x} was assumed negligible in the products of combustion.

First, the input rate (on a mass basis) of each constituent entering the boiler furnace was calculated, followed by the
Figure 5. Flow chart of subroutine SIMBLR
Figure 5. (Continued)
Figure 5. (Continued)
Figure 5. (Continued)
calculations of moles of each constituent. Finally, according to the above chemical reactions the total number of moles of constituents of the product of combustion was calculated, and then converted back to the mass basis.

1. Input rate of various constituents in the fuel, kg/s

The input rate (on mass basis) of each substance in the fuel was determined by the following relationships:

\[ IR_{\text{conf}} = \frac{(AX_{\text{conf}} \times IR_{\text{waf}})}{100}. \]  

where

- \( IR_{\text{conf}} \) = input rate of various constituents
- \([\text{H}_2\text{O}, \text{C}, \text{O}_2, \text{H}_2, \text{N}_2, \text{S}, \text{Dirt}, \text{ASH}]\) in the fuel, kg/s
- \( AX_{\text{conf}} \) = constituents present in the fuel on as fired basis, %
- \( IR_{\text{waf}} \) = input rate of wood fuel on as received basis, kg/s

The input rate of carbon that remained unburned and carbon burned were calculated as follows:

\[ IR_{\text{unbc}} = \frac{(X_{\text{unbc}} \times IR_{\text{c}})}{100}. \]  

\[ IR_{\text{bc}} = IR_{\text{c}} - IR_{\text{unbc}} \]  

where

- \( IR_{\text{unbc}} \) = input rate of unburned carbon, kg/s
- \( X_{\text{unbc}} \) = percent unburned carbon
- \( IR_{\text{bc}} \) = input rate of carbon burned, kg/s
The input rate of carbon burned to carbon monoxide and carbon dioxide was calculated using following equations:

\[
IR_{\text{cco}} = \frac{(X_{\text{cco}} \times IR_{bc})}{100}. \quad [12]
\]
\[
IR_{\text{ccO}_2} = \frac{(X_{\text{ccO}_2} \times IR_{bc})}{100}. \quad [13]
\]

where

\[
IR_{\text{cco}} = \text{input rate of carbon burned to carbon monoxide, kg/s}
\]
\[
IR_{\text{ccO}_2} = \text{input rate of carbon burned to carbon dioxide, kg/s}
\]
\[
X_{\text{cco}} = \frac{(X_{\text{CO}_{dg}})}{(X_{\text{CO}_{dg}} + X_{\text{CO}_2_{dg}})} \times 100.
\]
\[
X_{\text{ccO}_2} = \frac{(X_{\text{CO}_2_{dg}})}{(X_{\text{CO}_{dg}} + X_{\text{CO}_2_{dg}})} \times 100.
\]

where

\[
X_{\text{cco}} = \text{carbon burned to carbon monoxide, } \%
\]
\[
X_{\text{ccO}_2} = \text{carbon burned to carbon dioxide, } \%
\]
\[
X_{\text{CO}_{dg}} = \text{carbon monoxide in dry flue gases, } \%
\]
\[
X_{\text{CO}_2_{dg}} = \text{carbon dioxide in dry flue gases, } \%
\]

2. The mole rate of various constituents of fuel entering the boiler furnace were predicted by the following relationship:

\[
MR_{\text{conf}} = \frac{IR_{\text{conf}}}{MW_{\text{conf}}}. \quad [14]
\]

where

\[
MR_{\text{conf}} = \text{mole rate of various constituents of fuel}
\]
\[
MW_{\text{conf}} = \text{molecular weight of constituents of fuel}
\]
3. The mole rate of various constituents of the combustion air were calculated using the equation:

\[
MR_{\text{cona}} = \frac{IR_{\text{da}} \cdot Y_{\text{cona}}}{MWA}
\]  \[15\]

where

- \(MR_{\text{cona}}\) = mole rate of various constituents \([\text{A},\text{CO,CO}_2,\text{N}_2,\text{O}_2,\text{H}_2\text{O}]\) of the combustion air
- \(Y_{\text{cona}}\) = various constituents of the combustion air on fractional basis
- \(MWA\) = molecular weight of dry air
- \(IR_{\text{da}}\) = input rate of dry combustion air, kg/s

The input rate of dry combustion air was computed by the following relationship (ASME test code, 1985):

\[
IR_{\text{da}} = \frac{((28.02 \cdot X_{\text{N}_2}) \cdot ((IR_c - + (12.01/32.07) \cdot IR_g)) / (12.01 \cdot (X_{\text{CO}_2} + X_{\text{CO}_2})) - IR_H) / 0.7685}{11.51 \cdot IR_c + 34.3 \cdot (IR_H - IR_{\text{o}_2} / 7.937) + 4.335 \cdot IR_g}
\]  \[16\]

Where the theoretical air required for complete combustion was predicted using the equation:

\[
RT_{\text{da}} = 11.51 \cdot IR_c + 34.3 \cdot (IR_H - IR_{\text{o}_2} / 7.937) + 4.335 \cdot IR_g
\]  \[17\]

The mole rate of flue gas was determined using the equation:
\[ \text{MR}_{\text{conc}} = \text{MR}_{\text{ona}} + \text{MR}_{\text{conf}} \]  

where

\[ \text{MR}_{\text{conc}} = \text{mole rate of constituents} \]

\[ \{\text{AR, CO, CO}_2, \text{N}_2, \text{H}_2\text{O}, \text{O}_2, \text{S}\} \]

in the products of combustion, kg-mole/s

After calculating the mole rates of the constituents of the flue gas, the mole fractions of the constituents were computed. Finally, the molecular weight and mass rate of flue gases were predicted using the mole rate and mole fractions of the products of combustion.

**Application of First Law of Thermodynamics**

The first law of thermodynamics was used to balance the energy input and output of the boiler. It treats the boiler as a "black box" with fuel and combustion air entering and the products of combustion (flue gas and ash) leaving under steady state conditions. For a steady state process, the first law of thermodynamics can be stated as:

\[ \text{Energy Input} = \text{Energy output} + \text{Energy losses} \]

A structure of a boiler model under steady state condition was shown in Figure 6. Each part of the foregoing equation was worked out for the boiler.
Figure 6. A schematic diagram of the wood-fired boiler simulation model
Energy input

The total input energy of fuel (wood chips) on as fired basis can be predicted by the equation, which is based on the assumption of complete combustion.

\[ Q_{in} = IR_{waf} \times AHHV \]  \[19\]

where

- \( Q_{in} \) = energy input rate of fuel, kJ/s
- \( IR_{waf} \) = input rate of fuel on as fired basis, kg/s
- \( AHHV \) = higher heating of fuel on as fired basis, kJ/kg

Energy losses

The energy that is not used to increase the temperature of flue gas or is lost to the environment was treated as energy loss. Following are the major losses that reduce the efficiency of the wood fired boiler.

1. Sensible losses
2. Latent losses
3. Combustion material loss
4. Radiation and unaccountable losses

Sensible losses The sensible losses are due to heating of combustion products and excess air to the flue gas temperature. They are briefly described below:

Energy loss caused by dry flue gas and excess air The largest of the losses is usually the energy content of the flue
gases. These energy losses are dependent on the flue gas temperature and the combined content of CO₂ and CO. These can be predicted by the following relationship (ASME Power Test Code, 1974):

\[ Q_{\text{dfg}} = M_{\text{dfg}} (h_{\text{dfg}} - h_a) \] \hspace{1cm} \text{[20]}

where

- \( Q_{\text{dfg}} \) = energy loss due to dry flue gases, kJ/s
- \( M_{\text{dfg}} \) = mass rate of dry flue gases, kg/s
- \( h_{\text{dfg}} - h_a \) = difference in enthalpies of dry flue gas and air entering the system, kJ/kg

The enthalpy of an ideal gas is a function of the temperature only, and is independent of the pressure, it follows that:

\[ dh = C_p \, dt \]

Integrating above equation:

\[ h_{\text{dfg}} - h_a = \int_{\theta_1}^{\theta_2} C_p \, \theta \, d\theta \]

\[ = \int_{\theta_1}^{\theta_2} \frac{\theta}{\theta_1} \, C_p \, \theta \, d\theta \] \hspace{1cm} \text{[21]}

where

- \( \theta_1 \) = \( t_a /100 \).
- \( \theta_2 \) = \( t_{\text{dfg}} /100 \).
- \( t_a \) = temperature of air entering the system, °C
- \( t_{\text{dfg}} \) = temperature of flue gases, °C

Using Equation 21, the difference in enthalpies at various
temperatures for various constituents of combustion products were predicted using the empirical equations for \( \overline{C_p} \), given by Van Wylen and Sonntag (1986). The difference in enthalpies of flue gases was predicted by taking the weightage average of the difference in enthalpies of various constituents of the dry flue gases.

Energy loss due to sensible heat in flue dust

The amount of dirt carried with the fuel in the boiler furnace exits the furnace with the ash discharge at approximately the same temperature as the flue gas (Nikoo and Bushnell, 1987). The energy consumed in heating the dirt is a loss because it is not used in raising the temperature of the flue gas. This energy loss is calculated as:

\[
QL_{dirt} = IR_{dirt} \times CP_{dirt} \times (T_{drg} - T_f)
\]

where

- \( QL_{dirt} \) = energy loss due to heating of dirt, kJ/s
- \( IR_{dirt} \) = input rate of dirt to the boiler furnace, kg/s
- \( T_f \) = temperature of fuel entering the system, °C
- \( CP_{dirt} \) = heat capacity of dirt, 1.0 kJ/kg °C

Latent losses

The latent losses include energy loss due to hydrogen in the fuel, moisture in the fuel, and moisture in combustion air. They are briefly presented below:

Energy loss due to moisture in fuel

If green (moist) wood chip fuel is used in a furnace, moisture evaporates. Generally, all
vapor is released in flue gases during combustion and the vapor heat is lost (USDA, 1977).

Energy loss due to moisture in wood fuel is a function of moisture content and stack gas temperature because of the heat required to vaporize water and the heat lost when the vapor escapes from the boiler in stack gases. Energy loss due to moisture in fuel can be predicted by the following equation.

\[ Q_{L_{mf}} = IR_{H_2O} \cdot (h_{vfg} - h_{slf}) \]  

where

- \( Q_{L_{mf}} \) = energy loss due to moisture in fuel, kJ/s
- \( IR_{H_2O} \) = input rate of moisture, kg/s
- \( h_{vfg} - h_{slf} \) = difference in enthalpy of super heated vapor at flue gas temperature and enthalpy of saturated liquid at fuel temperature, kJ/kg

The enthalpy of super heated vapor at flue gas temperature, and the enthalpy of saturated liquid at fuel temperature were computed using the empirical equations, given by Irvine and Liley (1984).

**Energy loss due to moisture from burning of hydrogen**

Wood and bark generally contain about 6% hydrogen (dry weight basis). One kilogram of oven dried wood or bark contains about 0.06 kilogram of hydrogen. In the combustion process, hydrogen combines with oxygen and forms water vapor. Water is by weight 1 part hydrogen and 8.936 parts oxygen. Therefore, 0.06 kilogram of hydrogen in combustion
will form 0.536 kilogram of water. Energy in water vapor formed from hydrogen escapes from heat recovery systems via stack gases. This energy loss can be estimated using the following equation.

\[ Q_{\text{hf}} = 8.936 \times IR_{\text{H}_2} \times (h_{\text{vfg}} - h_{\text{s1f}}) \]  

where

- \( Q_{\text{hf}} \) = energy loss due to moisture produced from burning of hydrogen, kJ/s
- \( IR_{\text{H}_2} \) = input rate of hydrogen in the boiler furnace, kg/s

**Energy loss due to moisture in combustion air**

During the combustion process, the moisture in the combustion air changes to water vapor. These losses can be estimated using the equation.

\[ Q_{\text{ma}} = IR_{\text{da}} \times \text{SPH} \times (h_{\text{vfg}} - h_{\text{s1a}}) \]  

where

- \( Q_{\text{ma}} \) = energy loss due to moisture in combustion air, kJ/s
- \( IR_{\text{da}} \) = input rate of dry air to the boiler furnace, kg/s
- \( h_{\text{vfg}} \) = enthalpy of superheated vapor at flue gas temperature, kJ/kg
- \( h_{\text{s1a}} \) = enthalpy of saturated vapor at combustion air temperature, kJ/kg
- \( \text{SPH} \) = specific humidity of combustion air, kg of water per kg of dry air

**Energy required to bring the bound water to the energy level of free water**

This is the amount of energy required to bring the...
bound water to the energy level of the free water (could be called the energy required to break the bonds). The energy to vaporize this water from the free water level is already included in energy loss due to the moisture in the fuel. The energy required to break the bonds was computed using the equation (Skaar, 1972, reported by Nikoo and Bushnell, (1987)):

\[
Q_{bw} = IRBW \times 1.055 \times \left[ \frac{(1/MC)}{4.679415E2 \times MC} - 3.23141E1 \times MC^2 + 1.04078667 \times MC^3 + 4.68014E-2 \times MC^4 - 6.588278 \times E-3 \times MC^5 + 2.569851667E-4 \times MC^6 - 3.48937E-6 \times MC^7 \right]
\]  

[26]

where

- \( Q_{bw} \) = energy used to remove the bound water, kJ/s
- \( IRBW \) = input rate of bound water, kg/s
- 1.055 = conversion factor for changing \( Q \) from Btu/s to kJ/s
- \( MC \) = moisture content of wood fuel on wet basis, %

If the moisture content of the wood is higher than the Fiber Saturation Point (FSP), \( MC \) would be equal to 23.08 which is the FSP (the moisture content of the wood at which all the capillary water has been evaporated but no water from the cell wall has been lost is termed the Fiber Saturation Point. If the moisture content of the wood is less than FSP, then FSP would be equal to the moisture content of the wood in "percent" wet basis.
Combustion material loss Losses of combustible material include fuel in the ash and combustible material in the flue gas, such as:

**Energy loss due to formation of carbon monoxide** Each kilogram of carbon monoxide, when it goes through complete combustion to produce CO₂, releases about 10178 kJ of energy. Therefore, for each kilogram of carbon monoxide generated there is a loss of 10178 kJ of heat. The heat loss due to generation of CO was calculated as:

\[ Q_{L, CO} = 10178 \times IR_{cco} \]  

where

- \( Q_{L, CO} \) = energy loss due to formation of carbon monoxide, kJ/s
- \( IR_{cco} \) = input rate of carbon burned to carbon monoxide, kg/s

**Energy loss due to unburned carbon** For each kilogram of carbon that is burned to carbon dioxide, about 33747 kJ heat is released. Therefore, for each kilogram of carbon that is not burned (remains in the ash), this amount of energy is lost. This can be estimated using the equation.

\[ Q_{L, unbc} = 33747 \times IR_{unbc} \]  

where

- \( Q_{L, unbc} \) = energy loss due to unburned carbon, kJ/s
- \( IR_{unbc} \) = input rate of carbon remaining unburned in the ash, kg/s
Radiation and unaccounted-for loss These losses are mainly due to radiation and incomplete combustion resulting in hydrogen and hydrocarbons in the flue gas. These losses are relatively small, and difficult to accurately determine. In practice, these losses range from 3 to 5% for large size steam generating units (Li and Priddy, 1985), and 5 to 8% for small size space heating units (Oswald, 1980).

Steady state efficiency

The boiler steady state efficiency is defined as the ratio of boiler output compared to the heat input of the fuel under steady state operation. This can be predicted by the following equation.

\[
SSE = \left(\frac{Q_{in} - QL}{Q_{in}}\right) \times 100. \tag{29}
\]

where

\[
SSE = \text{boiler steady state efficiency, \%}
\]

\[
QL = \text{total energy losses, kJ/s}
\]

Prediction of Energy Losses Through the Flue Gases During ON and OFF Cycling Operation

A method for estimating the on and off period flue gas losses for residential gas and oil fired heating systems was developed by Chi and Kelley (1978). They derived various heat loss equations for predicting on and off period heat losses. A similar approach was used to predict the energy losses through the flue gases during on and off cycling operations of a biomass fueled boiler. During the on
and off cycling operations of a biofueled boiler the sensible energy losses through flue gases were divided into on-period sensible energy loss and off-period sensible energy loss.

**On-period sensible energy loss**

The on-period sensible energy loss, is due to the heating of combustion products and excess air from off-period flue gas temperature to on-period flue gas temperature. The sensible energy loss can be predicted by the equation.

$$L_{s, ON} = L_{s, ss} - \left[ (100 \times C_p) / (Q_{in} \times t_{on}) \right] \times \int_{0}^{t_{ON}} M_{F, ON} \times f(t) \, dt$$

[30]

where

- $L_{s, ON}$ = on-period loss expressed as a percentage of the boiler input rate during ON1 period, %
- $L_{s, ss}$ = sensible heat loss during ON1 period steady state operation, %
- $C_p$ = specific heat of air, 1.0 kJ/kg°C
- $M_{F, ON}$ = mass flow rate of flue gasses during ON1 period, kg/s
- $f(t)$ = flue gas temperature during heat up period (from off period to ON1 period), °C

The mass flow rate of flue gases during ON1 period can be expressed as:
\[ M_{F,\text{ON}} = \left( \frac{Q_{\text{IN}}}{\text{HHV}} \right) \left[ 1.0 + R_{TF} \times \left( \frac{A}{F} \right) \right] \]  \[ \text{[31]} \]

where

\[ R_{TF} = \text{ratio of combustion air to stoichiometric air in the flue during ON1 period} \]

\[ A/F = \text{mass ratio of stoichiometric air to fuel} \]

By examining the experimental data, it was possible to develop an equation to predict flue gas temperature from off period to ON1 period of biomass fueled boiler, similar to oil and gas fired boilers. The following expression can be written for flue gas temperature during the heat up period.

\[ \theta_{F}(t) = \theta_{F,\text{SS}} \times e^{-t/\tau_{\text{ON}}} \]  \[ \text{[32]} \]

where \( \theta_{F}(t) = T_{F,\text{SS}} - T_{F}(t) \), \( T_{F,\text{SS}} \) denotes flue gas temperature at steady operation of ON1 period, and \( \theta_{F,\text{SS}} \) and \( \tau_{\text{ON}} \) are constant. By measuring the flue gas temperature at two different times \( t_1 \) and \( t_2 \) during the heat up period, time constant \( \tau_{\text{ON}} \) can be obtained as follows:

\[ \theta_{F}(t_1) = T_{F,\text{SS}} - T_{F}(t_1) = \theta_{F,\text{SS}} \times e^{-t_1/\tau_{\text{ON}}} \text{ at } t = t_1 \]  \[ \text{[33]} \]

and

\[ \theta_{F}(t_2) = T_{F,\text{SS}} - T_{F}(t_2) = \theta_{F,\text{SS}} \times e^{-t_2/\tau_{\text{ON}}} \text{ at } t = t_2 \]  \[ \text{[34]} \]

Solving both equations simultaneously gives:

\[ \tau_{\text{ON}} = \frac{t_2 - t_1}{\ln \left( \frac{T_{F,\text{SS}} - T_{F}(t_1)}{T_{F,\text{SS}} - T_{F}(t_2)} \right)} \]  \[ \text{[35]} \]
The initial constant values, $\theta_{F,0,x}$, can be defined using the measured flue gas temperatures at $t_1$ to obtain:

$$\theta_{F,0,x} = \theta_F(t_1) e^{t_1/\tau_{ON}} = [T_{F,SS} - T_F(t_1)] e^{t_1/\tau_{ON}} \quad [36]$$

Figure 7 shows typical experimental results obtained for the flue gas temperature as the flue gas temperature increased from off-period to ON1 period, and back from ON1 period to off period.

Park et al. (1979) stated that when the heat up period is finite, the pattern of the flue gas temperature changes with respect to time. Due to the finite length of time of on- and off-periods, the initial values of the exponential function become smaller due to the fact that the unit may never cool down to the off-period flue gas temperature. Therefore, they introduced a correction factor such that for the heat up period,

$$\theta_F(t) = C_{t,ON} \cdot \theta_{F,0,x} e^{-t/\tau_{ON}} \quad [37]$$

where

$$C_{t,ON} = \frac{1 - \psi_{F,0}}{\frac{T_{F,SS} - T_{F,OFF}(t_5)}{\frac{T_F(t_5)}{\frac{T_{F,SS} - T_{F,OFF}(t_5)}}} \frac{T_{F,SS} - T_{F,OFF}(t_5)}{2e^{-[t_{ON}/\tau_{ON} + t_{OFF}/\tau_{OFF}]}} \psi_{F,0} \quad [38]$$

where $\psi_{F,0}$ and $\tau_{OFF}$ are defined in the section on off-period losses.

The complete derivation of correction factor $C_{t,ON}$ is presented in (Park et al., 1979).
Figure 7. Temperature profile during ON1 and OFF-period of wood-fired boiler (operating at 45% MC of wood fuel)
After substituting the value of \( \theta_\text{F} (t) \) and \( M_{\text{F,ON}} \) in Equation 30 and then solving the integral the final equation for predicting the on period sensible energy loss can be written as:

\[
L_{S,ON} = L_{S,SS} - \frac{100*C_p*\theta_{F,OFF}*C_{t,ON}[1 + R_{TF}(A/F)](1 - e^{-t_{ON}/t_{ON}})}{\text{AHHV} \left(\frac{t_{ON}}{t_{ON}}\right)}
\]  

[39]

**Off-period sensible heat loss**

This sensible heat loss is a measure of the energy flow through the flue during the transitional period (from ON1 steady state condition to off-period steady state condition). Figure 7 also shows the sensible heat loss during off period.

The off-period sensible energy loss can be predicted by taking the product of flue gas mass flow, specific heat of air, and temperature rise above off-period steady state temperature of flue gases integrated over the boiler off-cycle period. This loss can be expressed by the following equation.

\[
L_{S,OFF} = \left[\frac{(100*C_p)}{Q_{IN}*t_{ON}}\right]*\int_{t_0}^{t_{OFF}} M_{S,OFF}*(T_{s,OFF}(t) - T_{F,OFF}(t))\ dt
\]  

[40]

where

\( L_{S,OFF} = \) sensible heat loss during transitional period, expressed as a percentage of the boiler input rate during ON1 period, %

\( T_{s,OFF} = \) flue gas temperature during any time \( t \), of the cool down period, °C
\[ M_{g,\text{OFF}} = \text{mass flow rate of flue gases during the transitional period, kg/s} \]

The sensible off period energy loss can be predicted by knowing the time histories of flue temperature, and mass flow rate during the transitional cool down period. An equation to predict the flue gas temperature during the transitional period can be developed similar to the equation for the heat up period. The following equation can be written for flue gas temperature during the cool down period.

\[
\psi_F(t) = \psi_{F,0,x} e^{-t/\tau_{\text{OFF}}} \tag{41}
\]

where \( \psi_F(t) = T_F(t) - T_{F,\text{OFF}}(t_5) \), and \( \psi_{F,0,x} \) and \( \tau_{\text{OFF}} \) are constants. \( \tau_{\text{OFF}} \) can be obtained by measuring the flue gas temperature at two different times \( t_3 \) and \( t_4 \) during the transitional period.

\[
\psi_F(t_3) = \psi_{F,0,x} e^{-t_3/\tau_{\text{OFF}}} \quad \text{at } t = t_3 \tag{42}
\]

\[
\psi_F(t_4) = \psi_{F,0,x} e^{-t_4/\tau_{\text{OFF}}} \quad \text{at } t = t_4 \tag{43}
\]

These two equations when solved simultaneously yield.

\[
\tau_{\text{OFF}} = \frac{t_4 - t_3}{\ln \left( \frac{T_F(t_4) - T_{F,\text{OFF}}(t_5)}{T_F(t_3) - T_{F,\text{OFF}}(t_5)} \right)} \tag{44}
\]

The initial constant \( \psi_{F,0,x} \) can be defined using the measured flue gas temperature at \( t_3 \), to obtain:

\[
\psi_{F,0,x} = \psi_F(t_3) e^{t_3/\tau_{\text{OFF}}} = [T_F(t_3) - T_{F,\text{OFF}}(t_5)] e^{t_3/\tau_{\text{OFF}}} \tag{45}
\]
The flue gas temperature any time during the off-period can be calculated using the equation.

\[ T_{F,\text{OFF}}(t) = T_{F,\text{OFF}}(t_0) e^{-t/T_{OFF}} + T_{F,\text{OFF}}(t_5) \]  \[ \text{[46]} \]

The quantity \( C_{T,\text{OFF}} \) is a correction factor for the relative length of the off-periods and is given by (Chi and Kelley, 1979).

\[ C_{T,\text{OFF}} = \frac{1 - e^{-t_{\text{ON}}/\tau_{\text{ON}}}}{T_{F,\text{SS}} - T_{F,\text{OFF}}(t_5)} \]

\[ \text{[47]} \]

The time histories of flue flow rates during the off period can be calculated from consideration of the hydrostatic pressure difference between the flue gas and the boiler room temperature and the basic theory of turbulent flow. The resulting equation was given by Park et al. (1979).

\[ M_{F,\text{OFF}} = DF \cdot M_{F,\text{ON}} \left( \frac{T_{F,\text{OFF}} - T_{\text{BRA}}}{T_{F,\text{SS}} - T_{\text{BRA}}} \right)^{0.56} \left( \frac{T_{F,\text{SS}} + 273.15}{T_{F,\text{OFF}} + 273.15} \right)^{1.19} \]  \[ \text{[48]} \]

where

- \( DF \) = average off cycle draft factor for flue gases
- \( T_{\text{BRA}} \) = boiler room temperature, °C
By substituting the value of $M_{F,\text{off}}$, the off period loss equation becomes:

$$L_{S,\text{OFF}} = \frac{100 \cdot C_p \cdot DF \cdot M_{F,\text{ON}}}{Q_{\text{in}} \cdot t_{\text{ON}}} \cdot \frac{(T_{F,\text{SS}} + 273.15)^{1.19}}{(T_{F,\text{SS}} - T_{\text{BRA}})^{0.56}} \cdot \int_{0}^{t_{\text{OFF}}} \frac{(T_{F,\text{OFF}} - T_{\text{BRA}})^{0.56}}{(T_{F,\text{OFF}} + 273.15)^{1.19} \cdot (T_{F,\text{OFF}} - T_{F,\text{OFF}(t)}) \, dt} \quad [49]$$

The above equation can be simplified to:

$$L_{S,\text{OFF}} = \frac{100 \cdot C_p \cdot DF \cdot (1 + R_{TF}(A/F))}{AHHV \cdot t_{\text{ON}}} \cdot \frac{(T_{F,\text{SS}} + 273.15)^{1.19}}{(T_{F,\text{SS}} - T_{\text{BRA}})^{0.56}} \cdot \int_{0}^{t_{\text{OFF}}} \frac{(T_{F,\text{OFF}(t)} - T_{\text{BRA}})^{0.56}}{(T_{F,\text{OFF}(t)} + 273.15)^{1.19} \cdot (T_{F,\text{OFF}(t)} - T_{F,\text{OFF}(t)}) \, dt} \quad [50]$$

It is difficult to solve the above integral analytically; therefore subroutine RAMBRG was written to solve this integral numerically.

**Prediction of Seasonal Efficiency**

The wood chip fired automatically-fed boiler has three modes of operation. The times under three modes of operation were predicted by simulating the boiler tank. By knowing the time, steady state efficiency, and the input rate under each mode of operation, the part load efficiency was predicted by the following procedure:
1. If the boiler was operating only at ON1 mode then:

\[ PEFF = SON1 \]

where

\[ PEFF = \text{part load efficiency, \%} \]
\[ SON1 = \text{steady state efficiency during ON1 mode, \%} \]

2. If the boiler was operating at ON2 mode only, then:

\[ PEFF = SON2 \]

where

\[ SON2 = \text{steady state efficiency during ON2 mode, \%} \]

3. If the boiler was operating at off and ON1 mode, then the cyclic efficiency for the ON1 period can be predicted by:

\[ CEON1 = 100 - QLLP1 - QLCP1 - QLRP1 - [L_{s,ON} + L_{s,OFF}] \quad [51] \]

where

\[ CEON1 = \text{efficiency of ON1 mode during on and off operation of boiler, \%} \]
\[ QLLP1 = \text{latent losses during ON1 mode, \%} \]
\[ QLCP1 = \text{combustion material losses during ON1 mode, \%} \]
\[ QLRP1 = \text{radiation, convection, and unaccountable losses during ON1 mode, \%} \]

By knowing the cyclic efficiency for the ON1 period, the average part load efficiency during on and off operations of the boiler can be predicted by the equation.
PEFF = \frac{(t_{ON1}^*CEON1^*QIN_{ON1} + t_{OFF}^*SOFF^*QIN_{OFF})}{(t_{ON1}^*QIN_{ON1} + t_{OFF}^*QIN_{OFF})} \quad [52]

where

- \(t_{ON1}\) = boiler operating time under ON1 mode, s
- \(QIN_{ON1}\) = input rate of energy during ON1 mode, kJ/s
- \(QIN_{OFF}\) = input rate of energy during OFF mode, kJ/s
- \(t_{OFF}\) = boiler operating time under OFF mode, s
- \(SOFF\) = steady state efficiency during OFF mode, %

4. If the boiler was operating under both ON1 and ON2 modes then;

PEFF = \frac{(t_{ON1}^*SON1^*QIN_{ON1} + t_{ON2}^*SON2^*QIN_{ON2})}{(t_{ON1}^*QIN_{ON1} + t_{ON2}^*QIN_{ON2})} \quad [53]

After computing the part load efficiency against various outside temperature bins, the seasonal efficiency was predicted by the following expression:

\[
SE = \frac{\sum_{i=1}^{N} PEFF_i \times FREQ_i}{\sum_{i=1}^{N} FREQ_i} \quad [54]
\]

where

- \(FREQ_i\) = frequency occurrence of the hours of the \(i^{th}\) temperature bin
- \(N\) = number of temperature bins
- \(PEFF_i\) = part load efficiency for the \(i^{th}\) temperature bin, %
- \(SE\) = seasonal efficiency of the boiler, %
Description of the Simulation Program

The simulation program for predicting the seasonal efficiency of biofueled boilers was written in FORTRAN F77L on an IBM-compatible microcomputer. Figure 8 is a flow chart of the computer program. Input to the model consists of the space-heating load for each temperature bin, an elemental analysis of fuel, input rates of fuel under three modes of operation, moisture contents of fuel, a flue gas analysis on a dry basis, input parameters describing the behavior of the flue gases during ON and OFF periods of operation, boiler-tank storage capacity, maximum and minimum temperature settings, etc. The model has the following capabilities:

- predicts steady-state efficiency in addition to sensible losses, latent losses, and combustion material losses under three modes of operation;
- simulates dynamic behavior of the boiler in response to building heating load;
- predicts part-load efficiency in response to varying heating load;
- predicts seasonal efficiency of the boiler;

The simulation program is composed of one main program, eight subroutines, and three subprogram functions. A listing of the computer program is presented in Appendix A. A typical output of the
Figure 8. Flow chart of simulation model for predicting the seasonal efficiency of biofueled boiler (SIMPSE)
Figure 8. (Continued)
Figure 8. (Continued)
Figure 8. (Continued)
A brief description of the various subroutines follows:

**RATE**

Subroutine RATE computes the input rate (kg/s) of various constituents of biomass fuel from an oven-dry basis to an as fired basis.

**FLUE**

Subroutine FLUE predicts the flue gas analysis on a wet basis, the input rate of actual dry air into the boiler furnace, the mass ratio of stoichiometric air to fuel, the mass rate of flue gases, the ratio of combustion air to stoichiometric air, etc.

**STDEFF**

Subroutine STDEFF predicts sensible losses, latent losses, combustion material losses, and steady-state efficiency of the biofueled boiler. This subroutine calls three subprogram functions, namely HVAP, HSLIQ, and HGAS, to predict the enthalpy of vapors as a function of flue gas temperature, the enthalpy of a saturated liquid as a function of fuel temperature, and the enthalpy of flue gases as a function of flue temperature, respectively.

**SIMBLR**

Subroutine SIMBLR predicts boiler-operating time under three modes of operation, by using the mathematical and logical
formulations presented in a section entitled "prediction of boiler operation time under three modes of operation."

TIME

Subroutine TIME computes the time constants and correction factors for the relative length of the ON and OFF periods.

ROMBRG

Subroutine ROMBRG solved the integral presented in the section entitled "off-period sensible loss," by using the Romberg integration technique.

LOSS

Subroutine LOSS predicts sensible losses during ON and OFF periods.

PROFIL

Subroutine PROFIL predicts the temperature profile during transitional periods (heat-up and cool-down).
RESULTS AND DISCUSSION

To validate the model, the results of the computer simulation were first compared with those of the experiments. The comparison was followed by a parametric analysis performed to develop the design principles of wood-fired boiler optimization and to explore the possibilities of energy savings.

Validation of Model

Comparison of part-load efficiency

The part-load efficiency of a wood-fired boiler was measured during the winter season of 1989-1990 (Chaudhary, 1990). The data regarding part-load efficiency were collected for test runs of three hours duration by measuring the wood fuel consumed and the energy delivered to the building envelope. Thermal efficiencies of the boiler at various loads were computed using the input-output method. Part-load efficiency was then predicted using a computer program under the same conditions (measured load as input parameter). The other input parameters for the computer program were collected under the same conditions. Appendix C presents the input parameters and operating details of SIMPSE.

Table 5 outlines the measured and predicted efficiencies at 45% wood fuel moisture content at various hourly loads ranging from 19.55 kWh to 38.54 kWh. Figure 9 shows the plot of measured efficiency vs
Table 5. Measured and predicted efficiencies at various hourly loads

<table>
<thead>
<tr>
<th>Boiler room temperature °C</th>
<th>Fuel consumed (kg/hr)</th>
<th>Load kWh</th>
<th>Measured efficiency (%)</th>
<th>Predicted efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.2</td>
<td>21.24</td>
<td>19.55</td>
<td>30.5</td>
<td>33.41</td>
</tr>
<tr>
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<td>21.17</td>
<td>21.24</td>
<td>33.24</td>
<td>34.24</td>
</tr>
<tr>
<td>23.7</td>
<td>26.51</td>
<td>23.42</td>
<td>29.25</td>
<td>34.92</td>
</tr>
<tr>
<td>23.7</td>
<td>25.00</td>
<td>24.37</td>
<td>32.35</td>
<td>35.35</td>
</tr>
<tr>
<td>21.2</td>
<td>28.29</td>
<td>25.69</td>
<td>30.09</td>
<td>35.63</td>
</tr>
<tr>
<td>21.2</td>
<td>24.23</td>
<td>26.30</td>
<td>35.97</td>
<td>36.38</td>
</tr>
<tr>
<td>21.2</td>
<td>26.25</td>
<td>26.93</td>
<td>33.99</td>
<td>36.38</td>
</tr>
<tr>
<td>21.2</td>
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<td>27.17</td>
<td>33.34</td>
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</tr>
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<td>18.7</td>
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<td>29.30</td>
<td>36.98</td>
<td>37.54</td>
</tr>
<tr>
<td>18.7</td>
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<td>30.25</td>
<td>35.68</td>
<td>38.15</td>
</tr>
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<td>34.27</td>
<td>39.17</td>
<td>40.32</td>
</tr>
<tr>
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<td>32.67</td>
<td>34.47</td>
<td>34.96</td>
<td>40.41</td>
</tr>
<tr>
<td>12.7</td>
<td>30.50</td>
<td>34.75</td>
<td>37.75</td>
<td>40.55</td>
</tr>
<tr>
<td>12.7</td>
<td>32.96</td>
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<td>37.08</td>
<td>38.76</td>
<td>41.87</td>
</tr>
<tr>
<td>10.2</td>
<td>32.67</td>
<td>38.54</td>
<td>40.45</td>
<td>42.67</td>
</tr>
</tbody>
</table>
Figure 9. Measured vs predicted efficiency at various building envelope loads
predicted efficiency. The slope of the regressed line between measured and predicted results was 0.92. The 95% confidence estimates of the slope were computed as 0.825 and 1.02. The 95% confidence lines are also shown in Figure 9. It can be seen that the 95% confidence interval estimates of the slope bracket the value of 1.0. This means that the predicted part-load efficiency was in good agreement with the measured part-load efficiency.

Table 5 also reveals that variation exists in the measured efficiency. This may be due to errors involved in the measurement of fuel consumption. During data collection, before recording the weight of the fuel wagon the standing column of the raw fuel was leveled and marked at the beginning of each test, and at the end of the test it was leveled to the pre-marked position. The fact is, however, that fuel does not move down to the furnace continuously, but instead the fuel flows intermittently to the furnace. This intermittent flow makes it difficult to precisely measure wood fuel consumption for 3-4 hour tests.

Moisture content data were collected randomly, and an average value of 45% was established. A sensitivity analysis was performed to see the effect of variation in moisture content on the model predictions. Figure 10 presents the plots of measured vs predicted efficiency at 42.5%, 45.0%, and 47.5% moisture content. The slopes of the regressed lines were 0.88, 0.92, and 0.96 at 42.5, 45.0, and
Figure 10. Measured vs predicted efficiency at three moisture contents of fuel
47.5% moisture content, respectively. This signifies that the agreement between the measured and predicted results was better at 47.5% moisture content than at the other two moisture contents.

**Comparison of seasonal efficiency**

To compare seasonal efficiency, the wood-fired boiler system was monitored during the winter season of 1989-90. The fuel consumed and the actual energy delivered to the building envelope were measured. The computer model was used to predict boiler efficiency for the months of December, January, February, and March. The predicted house load (from Part 1 of this dissertation) at various temperature bins was used as input parameter for the computer program, and the workshop load was 8.5 kW (average value from measured data). The other input parameters are presented in Appendix C.

Figure 11 presents a comparison of measured and predicted efficiencies. Clearly the predicted results are within 3% of the measured results. This means that the model's predictions were in good agreement with measured results. Predicted efficiencies for the months of December, January, February, and March were about 2.7, 1.4, 2.6, 2.32% higher than the measured efficiencies, respectively. Thus the model overpredicted efficiency during all four months of operation. This discrepancy may exist for a number of reasons:
Figure 11. Comparison of measured vs predicted seasonal monthly efficiency of McNay biofueled boiler
1. The model does not account for the start-up and shutdown losses occurring when starting the fire in a cold boiler or when letting a hot boiler cool down for cleaning purposes.

2. To predict seasonal efficiency, the average difference between boiler room temperature and outdoor air temperature used was about 22 °C, which might have dropped when the boiler room was opened to fill the chip wagon. During this period, the combustion air temperature was approximately equal to the outdoor temperature, which resulted in reduced efficiency of the boiler.

From Figure 11 it can be seen that the measured efficiency of the boiler for the months of December, January, February, and March were only 37.3, 33.0, 32.06, and 31.0%, respectively. The reason for this low efficiency is well explained by the duration curve of the heating load of McNAY wood-fired boiler system (Figure 12). At the optimum setting, the maximum McNAY wood-fired boiler output is 60 kW (using feed rate 40 kg/hr, 45% MC of wood chips, and 50% efficiency). In Figure 12 it can be seen that the peak demand of more than 50% of capacity was for only 450 hours and that only five percent of the total energy was provided by loads more than 50% of maximum capacity during the period of study (December 15, 1989 to March 31, 1990). The boiler operated 72% of the total time at a load below its 50%
Figure 12. Duration curve of heating load of McNay wood-fired boiler system (1989–1990 winter season)
maximum capacity. Therefore, seasonal efficiency was well below the efficiency obtainable at full-load operation.

**Design Principles of Wood-Fired Boiler Optimization**

Wood fired-boiler performance is a function of the moisture content of the fuel, the flue gas temperature, and excess air. Proper adjustment of all three variables were imperative for the excellent performance of the wood-fired boiler. At the present time, little quantitative knowledge of how wood-fired boiler efficiency is affected by these design and operating variables exists. About 100 computer runs, using SIMPSE were made to predict the performance of a wood-fired boiler at various combinations of these design and operating variables. The results were plotted to be easily accessible to wood-fired boiler designers and to operators to assist them in obtaining higher boiler efficiency.

**Effect of moisture and hydrogen content of fuel on boiler performance**

In addition to moisture present physically, wood fuel contains about 6% hydrogen by dry weight which is converted to water during the combustion process. Evaporation of moisture in wet wood is an endothermic process, requiring approximately 2451.6 kJ per kg of water vaporized. Therefore, as the moisture content of wood increases, the higher and lower heating values of the fuel decrease. Because the net heating value of the wood decreases as moisture
content increases, the rate of fuel feed for a given boiler load must be increased, resulting in higher cost of fuel handling equipment and fuel transportation.

Energy losses due to moisture and hydrogen in wood fuel can be combined in terms of latent losses. Figure 13 shows the plot of latent losses versus moisture content of wood fuel at various flue gas temperatures. Evidently the latent losses were more sensitive to moisture content of the fuel in comparison with flue gas temperature. Going back to Figure 13, it can be seen that by increasing the moisture content from 10 to 50% at 148 °C flue gas temperature, the latent energy losses will rise from 9.05% to 21.34%. This means that there is an increase of 12.3% in latent energy losses. On the other hand, at 371.1 °C flue gas temperature, an increase of 14.28% is possible.

Figure 14 shows the plot of boiler steady state efficiency at various flue gas temperatures versus flue oxygen concentration at 50% wood fuel moisture content, whereas Figure 15 shows the plot of boiler steady state efficiency at various flue gas temperatures versus flue oxygen concentration at 10% wood fuel moisture content. It is revealed from these two figures that decreasing the wood fuel moisture content from 50% to 10% results an increase (14%) in steady state efficiency from 53% to 67% (at 371°C flue gas temperature and 5%
Figure 13. Latent losses vs moisture content of fuel at various flue gas temperatures
Figure 14. Boiler steady state efficiency at various flue-gas temperatures vs flue oxygen concentration at 50% fuel moisture content.
Figure 15. Boiler steady state efficiency at various flue gas temperature vs flue oxygen concentration at 10% fuel moisture content.
flue oxygen concentration). This means the wood fuel moisture content greatly affects the efficiency of the biofueled boilers.

In addition to higher latent energy losses, the high moisture content fuel causes large volumes of vapors to be evolved in the firebox, which results in a reduced rate of combustion and a low flame temperature and which increases particulate carryover into the stack (Oswald, 1980). It is therefore recommended that emphasis should be placed on designing and developing a wood-fired boiler able to operate efficiently under a wide range of moisture contents.

**Effect of moisture content on boiler output capacity**

The moisture content of wood fuel greatly affects the higher heating value of fuel and efficiency of the boilers. This consequently affects the boiler rated output capacity. Figure 16 shows the plot of boiler output capacity versus wood fuel at flue gas temperatures of 371°C and 260°C (at 39% excess air, 40 kg/hr feed rate and 22°C combustion air temperature). It can be seen from Figure 16 that by decreasing the wood fuel moisture content from 50% to 10% results an increase (73.5 kW) in boiler output capacity from 56.5 kW to 130.0 kW at 371°C flue gas temperature, provided fuel feed rate remains constant (40 kg/hr) for both moisture contents, whereas at 260°C flue gas temperature an increase of 77.0 kW (64.0 to 141.0 kW) in boiler output capacity is possible. This means great variation
Figure 16. Boiler output capacity vs wood fuel moisture content (at 39% excess air, 40 kg/hr feed rate and 22°C combustion air temperature)
exists in the rated output capacity of the biofueled boilers because of the variation in wood fuel moisture content.

**Effect of flue gas temperature and excess air on boiler performance**

The largest of the boiler losses is usually the energy content of the flue gases. High flue gas temperature indicates low efficiency. This may stem from a dirty heat-exchange surface, from poor heat-exchange-surface design, or both. Various studies (Oswald, 1980; Schneider, 1984) predicted and presented the effect of flue gas temperature on only a particular value of flue gas temperature and excess air. Those were not sufficient for the designers and the operators of the biofueled boilers. To properly design and monitor the wood-fired system they should have complete knowledge concerning the wide range of effects of flue gas temperature and of excess air supplied.

The energy loss due to flue gas temperature can be characterized as sensible losses. Another sensible loss is due to the heating of the dirt, but this loss is negligible in comparison with flue gas loss. The computer model was used to predict the sensible losses of a wood-fired boiler at various flue gas temperatures and flue oxygen concentrations. The results were plotted graphically (Figure 17). It can be seen that the sensible losses are functions of both flue gas temperature (distance between the lines) and flue oxygen concentrations (slope of the lines). The sensible losses increased
Figure 17. Sensible losses vs flue-oxygen concentration at various flue gas temperatures
slowly up to a flue oxygen concentration of 10%, but beyond this point, they increased drastically. This is due to the high percentage of excess air, because the percent excess air increased rapidly as the flue oxygen concentration increased above 10% (Figure 18).

Table 6 presents in a tabulated form the sensible losses at various flue gas temperatures and flue oxygen concentrations. Evidently by decreasing flue gas temperature from 371.1°C to 149°C at 2.5% flue oxygen concentration, there occurred a corresponding decrease (8.4%) in sensible losses from 13.02% to 4.61%, whereas at 17.5% flue oxygen concentration, the sensible losses decreased or boiler efficiency improved about 46% as a result of decreasing the flue gas temperature from 371.1°C to 149°C. This means that sensible losses were more sensitive to flue oxygen concentration (excess air) than to flue gas temperature. The proper adjustment of flue gas temperature and flue oxygen concentration may result in improving the boiler efficiency from 8 to 46% only by decreasing the sensible losses.

**Energy Saving Measures**

It was predicted that during the winter season of 1989-90, the peak demand of more than 50% capacity was for only 262 hours, and that only five percent of total energy was provided by loads more than 50% of maximum boiler capacity. The boiler was operated 89% of
Figure 18. Percent excess air vs flue-oxygen concentration (at 3% unburned carbon and zero % CO in flue gas)
Table 6. Sensible losses at various flue gas temperatures and flue oxygen concentration

<table>
<thead>
<tr>
<th>Flue oxygen concentration (%)</th>
<th>Flue gas temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>371.1</td>
</tr>
<tr>
<td>2.5</td>
<td>13.02</td>
</tr>
<tr>
<td>5.0</td>
<td>14.92</td>
</tr>
<tr>
<td>7.5</td>
<td>17.68</td>
</tr>
<tr>
<td>10.0</td>
<td>21.65</td>
</tr>
<tr>
<td>12.5</td>
<td>28.07</td>
</tr>
<tr>
<td>15.0</td>
<td>40.16</td>
</tr>
<tr>
<td>17.5</td>
<td>71.60</td>
</tr>
</tbody>
</table>
the time at a load which was below its 50% of its maximum capacity. Therefore, reducing the size of boiler may result in improved efficiency. Computer runs were made to predict the part-load efficiency and the seasonal efficiency of a proposed small unit with the existing large unit. The input data used for predictions were presented in Table 7. Data for case 1 were assumed on the following grounds.

The management decided to reduce the size of the burner to reduce the firing rate while keeping the same boiler. As the heat exchange surfaces remain the same while cutting down the firing rate, it is possible that the flue gas temperature will drop in comparison with that of the existing large unit. Therefore, the flue gas temperature was assumed less than that of the large unit while keeping CO₂ concentrations in the flues identical.

The input data for case 2 rested on the assumption that it may be possible that by cutting down the firing rate, the amount of excess air will increase. Therefore, CO₂ concentrations in the flue were lower than those in the existing large unit.

The input data for case 3 rested on the assumption that if the CO₂ concentrations in the flue were dropped, then it would also be possible for the flue gas temperature to drop. Therefore, both CO₂ concentrations and flue gas temperature) were taken less than the values of the existing large units.
Table 7. Assumed input data for future predictions of seasonal efficiency of large and small unit

<table>
<thead>
<tr>
<th>Modes of operation</th>
<th>CO₂ concentration in flue (%)</th>
<th>Flue gas temperature (°C)</th>
<th>Feed rate (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small Unit:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON1</td>
<td>4.25</td>
<td>232.0</td>
<td>17</td>
</tr>
<tr>
<td>ON2</td>
<td>14.0</td>
<td>315.5</td>
<td>30</td>
</tr>
<tr>
<td>OFF</td>
<td>2.6</td>
<td>177.0</td>
<td>7</td>
</tr>
<tr>
<td>Case 2:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ON1</td>
<td>3.0</td>
<td>232.0</td>
<td>17</td>
</tr>
<tr>
<td>ON2</td>
<td>10.0</td>
<td>315.5</td>
<td>30</td>
</tr>
<tr>
<td>OFF</td>
<td>2.0</td>
<td>177.0</td>
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<tr>
<td>Case 3:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ON1</td>
<td>3.0</td>
<td>204.0</td>
<td>17</td>
</tr>
<tr>
<td>ON2</td>
<td>10.0</td>
<td>288.0</td>
<td>30</td>
</tr>
<tr>
<td>OFF</td>
<td>2.0</td>
<td>149.0</td>
<td>7</td>
</tr>
<tr>
<td><strong>Large Unit:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>25</td>
</tr>
<tr>
<td>ON2</td>
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<td>40</td>
</tr>
<tr>
<td>OFF</td>
<td>2.6</td>
<td>204.0</td>
<td>13</td>
</tr>
</tbody>
</table>

Higher heating value of fuel = 19752 kJ/kg

Moisture content of fuel = 45%
In addition, house load was predicted by using Des Moines published weather data; house indoor temperature was assumed 22.5 °C; and a new workshop load was assumed at 17.0 kW. Predictions were made for five-month periods (November to March).

The comparison between predicted seasonal efficiencies of the large unit and all three cases of small units is presented in Figure 19. Small unit seasonal efficiencies were 9%, 4.34%, and 6.4% higher than those for the large unit for case 1, case 2, and case 3, respectively. Thus by reducing the boiler size, a maximum increase in boiler efficiency of up to 9% was possible. In case 2, the small-unit seasonal efficiency was only 4.34% higher than that of the large unit because of low flue CO$_2$ concentrations or because of increases in air supply. This means that when reducing the firing rate, the air supply to the boiler should be reduced at the same proportions. On the other hand, possibility of increased efficiency by cutting down the firing rate would be overruled. If the CO$_2$ concentration in the flue of the small unit has further dropped, as assumed in cases 2 and 3, then it may be possible that the seasonal efficiency of the small unit would have dropped close to the large unit.

Figure 20 presents the efficiency versus load curves of the large unit and all three cases of the small unit. The small unit had a higher efficiency level compared to the large unit. The small units can provide maximum energy at the rate of about 48 kW, whereas
Figure 19. Comparison of predicted seasonal efficiency of large unit and all the three cases of small unit.
Figure 20. Efficiency vs load curve of large unit and all the three cases of small unit.
the large unit can provide up to 60 kW. It can also be seen in Figure 17 that the efficiency of the small unit dropped after achieving maximum. Because the load is dependent on the outside air temperature, as the outside temperature dropped the boiler room temperature also dropped proportionally, thus causing reduced efficiency of the system.

The other energy saving measure which can be adopted at McNAY research center, is supplying heat to the workshop during occupied periods only (12 hours/weekday). In this way, about 39,000 kWh of energy can be saved during one heating season, by installing small units or by cutting down the firing rate of the large unit. Making load shifting arrangements, and cutting down the firing rate or size of the McNAY wood fired boiler for about 33%, accompanied by a pro-rated reduction of the supply of air will reduce fuel consumption from 100 metric tons (at 41% large unit efficiency, 123,000 kWh seasonal load, and 45% MC of fuel) to 56 metric tons (50% efficiency of small unit and 84,000 kWh seasonal load), which will save $3300 per heating season (at $75/ton, wood chip price).
CONCLUSIONS

1. A computer model was developed to simulate boiler operation and to predict the seasonal efficiency of wood fired boilers. The model is also capable of predicting steady-state efficiency in addition to sensible losses, latent losses, and combustion material losses under various modes of operation.

2. To validate the computer model, the measured part-load efficiency was compared with the predicted part-load efficiency. The slope of the regressed line between measured and predicted part-load efficiency was 0.92, and the 95% confidence interval estimates of this slope bracket a value of 1.0. Thus the predicted part-load efficiency by the computer model was in good agreement with the measured part-load efficiency.

3. The measured seasonal efficiencies for the months of December, January, February, and March were compared with the computer model predictions. The model predictions were in good agreement with the measured results (within 3% of the measured results).

4. During the winter of 1989-90 the peak demand of more than 50% capacity of the McNAY wood-fired boiler system was for only 450 hours, and only five percent of the total energy was provided by loads more than 50% of maximum capacity during the period of the study (December 15, 1989 to March 1990). The boiler was, therefore,
operated 72% of the total time at a load which was below its 50% maximum capacity.

5. Making load-shifting arrangements and cutting down the firing rate or size of the McNAY wood fired boiler about 33%, accompanied by a pro-rated reduction of the supply of air, will reduce seasonal fuel consumption from 100 to 56 metric tons, and $3300 per heating season will be saved.

6. To obtain the maximum efficiency of the wood-fired boiler, it is suggested that the boiler should be sized for only 50 to 60% of maximum demand. With this sizing method, the boiler runs most of the time with a high efficiency. A backup system, however, should be used to meet the peak heating demand.

7. Parametric analysis revealed that boiler latent losses were more sensitive to moisture content of the fuel than to flue gas temperature. An increase in moisture content from 10% to 50% will increase latent losses in the vicinity of 14%.

8. The proper adjustment of flue gas temperature and flue oxygen concentration may improve boiler efficiency from 8 to 46%, only by reducing the sensible losses.
REFERENCES


PART III. A COMPUTER MODEL FOR LIFE CYCLE COST ANALYSIS OF BIOFUELED ENERGY SYSTEMS
INTRODUCTION

Biofuels are possible alternatives to some of the increasingly scarce and costly traditional energy sources. The production of substantial quantities of energy from biofuels is technically feasible, but considerable uncertainty exists over economic feasibility. Therefore, an economic analysis is imperative to intelligently plan the use of renewable energy resources such as wood-biomass for energy production. Computers can serve as an excellent management tool in making this assessment.

Life cycle cost methodology has been used in industry and by the United States Department of Defense since 1970 in making purchase decisions (U.S. Department of Defense, 1970). In addition, it is the required mode of analysis for making evaluations of Potential Federal Energy Management and Planning Programs (Ruegg, 1980).

In view of the importance of life cycle cost for assessing renewable energy projects, a computer model for life cycle cost analysis of biofueled energy systems (CYCLE) was developed. CYCLE will assist the potential users of biomass energy, and has the following capabilities:

a. To evaluate the cost of wood fuel harvesting and chipping;

b. To calculate the present worth of lifetime expenses of both biomass and conventional energy systems;
c. To predict the savings to investment ratio, payback period, and life cycle savings before and after tax payments of the biomass energy system;

d. To perform a parametric analysis of the most critical and uncertain variables of the biomass energy system.
DEVELOPMENT OF COMPUTER MODEL FOR LIFE CYCLE COST
ANALYSIS OF BIOFUELED ENERGY SYSTEM

Previous Work

Ince (1983) developed a computer program "COMPARE" for analyzing investment alternatives in industrial wood and bark energy systems. COMPARE is only compatible with the Madison Academic Computer Center Version of the FORTRAN V language. Modifications are required to make it compatible with other systems. The program computes a benefit/cost ratio for each investment alternative. But it does not compute the other modes of analysis such as total life cycle cost or net life cycle savings.

Harpole et al. (1982) developed a wood and bark Fuel Economics Computer Program (FEP). FEP provides a means of assessing the relative energy values of fossil fuels and wood/bark fuels, and to provide a means for pre-engineering assessments of the potential investment that may be justified by benefits gained through modification of systems to burn wood/bark fuels. FEP does not perform a life cycle cost analysis of a wood energy system. The author also suggested that this program is only for preliminary assessments of wood/bark fuel use opportunities and more engineering and financial analyses should be used for further evaluation if FEP analysis indicates favorable results.
In recognizing the value of computer software packages, the Council of Great Lakes Governors and the Iowa Natural Heritage Foundation (1987) have developed a software package to aid farmers and potential energy producers in examining the appropriateness of a proposed crop residues energy system. This program uses the payback period as a criterion of selection. The program does not take into account the timing of cash flows and the magnitude of the total benefits.

Finally, it can be stated that until now no software package has been available to perform a life cycle cost analysis of a biofuel energy system. An attempt was made to fill this gap.

**Life Cycle Cost Models**

Life Cycle Costing (LCC) is an evaluation approach which takes into account relevant costs over the life of a system. It incorporates initial investment costs, operation and maintenance costs, insurance and tax costs, fuel costs, and salvage or resale values, adjusting them to a consistent time basis and combining them in a single cost effectiveness measure that makes it easy to compare alternative energy projects (Ruegg, 1975).

Total Life Cycle Cost (TLCC) is the sum of all significant costs of a system, discounted to present values, and can be expressed by the following mathematical model (Li and Priddy, 1985):
MODEL I.

\[
TLCC = INV - S \cdot (PWF)_1^N_E + \sum_{i=1}^{N_E} (PWF)_1^i \cdot APTi_1
\]

\[
+ \sum_{i=1}^{N_E} (PWF)_1^i \cdot AF_1 + \sum_{i=1}^{N_E} (PWF)_1^i \cdot AOM_1
\]  \[1\]

where

- **TLCC** = total life cycle cost, discounted to present value
- **INV** = capital investment
- \(PWF_i\) = single payment present worth factor in \(i^{th}\) year and is equal to \(1/(1+D)^{**i}\)
- **D** = market discount rate
- **APTI_i** = annual property tax and insurance cost for the \(i^{th}\) year
- **AF_i** = annual fuel cost in the \(i^{th}\) year
- **AOM_i** = annual operation & maintenance cost in the \(i^{th}\) year
- **NE** = period of analysis in years (this may be economic life of the energy system)
- **S** = remaining value of the system at the end of the period of analysis, % of investment.

If the system is on mortgage then the total life cycle cost can be expressed by the following mathematical model:

MODEL II.

\[
TLCC = DP - S \cdot (PWF)_1^N_E + \sum_{i=1}^{N_E} (PWF)_1^i \cdot AMP_i
\]

\[
+ \sum_{i=1}^{N_E} (PWF)_1^i \cdot APTi_1 + \sum_{i=1}^{N_E} (PWF)_1^i \cdot AF_1
\]

\[
+ \sum_{i=1}^{N_E} (PWF)_1^i \cdot AOM_1
\]  \[2\]
where

\[ DP = \text{down payment, } $ \]

\[ AMP_i = \text{annual mortgage payment cost in the } i^{\text{th}} \text{ year} \]

**Capital Investment**

Capital investment items include the delivered price of the biomass fueled boiler. The cost of pumps, pipes, heat exchangers, ductwork or plumbing were not included, because these are often the same for both the biofueled and conventional system. The initial investment is considered to be made at the start of the first year. All other costs are assumed to occur at the end of whatever year in which they come (USDA, 1978). If the system is on mortgage, then the annual payments on the mortgage amount can be expressed by the following equation:

\[
AMP = \frac{MA}{(\frac{1}{MI-MINF})*\left(1-\left(\frac{1+MINF}{1+MI}\right)^{NFIN}\right)}
\]

where

\[ AMP = \text{annual payment on the mortgage amount, } $ \]
\[ MA = \text{mortgage amount, } $ \]
\[ MI = \text{mortgage interest rate, } \% \]
\[ MINF = \text{mortgage inflation rate} \]
\[ NFIN = \text{number of years for which the system is financed.} \]
Operation and Maintenance Cost

The annual operation and maintenance expenses include the labor cost associated with maintenance and operation of a biofueled boiler such as inspection visits to the boiler room, cleaning of the boiler, and ash handling. In fact, the biomass fueled systems require more labor than do oil or gas fired systems, which have very little operation and maintenance cost. These expenses could be estimated for the first year of operation but uncertain inflation rates make future expenses uncertain (Skog, 1979). By assuming a reasonable inflation rate the magnitude of the future annual expenses can be predicted by the following relationship.

\[
AOM_i = FYOM^* (1+IFOP)^{i-1}
\]

where

FYOM\(_i\) = first year operation and maintenance cost

IFOP = inflation rate for operation and maintenance cost

Property Taxes and Insurance Cost

The property taxes and insurance are assessed on the remaining (depreciated) values of the energy system, in other words, they are levied as a percentage of the market value of the system. The property tax and insurance rates vary with the life of the system because of uncertain inflation rates. The magnitude of the future
annual expenses incurred for property taxes and insurance can be reasonably predicted by the following expression.

$$\text{APTI}_i = \text{PTI}_1 \times (1 + \text{IFPI})^{i-1} \times (\text{RV}_1 - \text{DEP}_{i-1})$$  \[5\]

where

- **PTI** = first year property tax and insurance cost
- **IFPI** = inflation rate for property taxes and insurance cost
- **RV** = remaining value of the system at the beginning of the i\(^{th}\) year
- **DEP** = annual depreciation for the i-1 year using the straight line method

**Fuel Cost**

If whole tree chipping is an integral part of the biomass energy system, then in order to predict the cost of wood chips, an economic analysis of the entire harvesting system is required. If tree chipping is not an integral part of the biomass energy system, then the market price of the woodchips can be used as an input variable.

**Cost analysis of harvesting system**

A typical whole tree harvesting system consists of felling, skidding, chipping, loading, and transportation to the boiler site (Massey et al., 1981). A fully mechanized whole tree harvesting system uses feller-bunchers, grapple skidders, whole tree chippers,
bulldozers, tractors or trucks, chipvans and conveyors. In order to investigate the cost of woodchipping, the following algorithm was used.

The annual average depreciation of various machines of the harvesting system was estimated by the following expression.

\[ Y_{DEP} = \sum_{i=1}^{N} NU_i * FU_i * (P_i - S_i) / E_i \]  \[ \text{[6]} \]

where

- \( Y_{DEP} \) = yearly depreciation of various machines of the Harvesting System (HS)
- \( NU_i \) = number of units of \( i \)th machine in HS
- \( FU_i \) = fractional use of \( i \)th machine for chipping operation
- \( P_i \) = purchase price of the \( i \)th machine
- \( S_i \) = salvage value of the \( i \)th machine
- \( E_i \) = economic life of the \( i \)th machine
- \( N \) = number of machines involved in the chipping operation

The yearly interest on investment was calculated by:

\[ Y_{INT} = \sum_{i=1}^{N} (NU_i * FU_i * (P_i + S_i) / 2) * IRS / 100 \]  \[ \text{[7]} \]

where

- \( IRS \) = real interest rate, %

The yearly taxes, insurance, and housing costs were lumped together as 1% of the purchase price (Edwards, 1985).
The yearly total fixed cost was obtained by adding yearly depreciation, interest on investment, taxes, insurance and housing cost. Among the variable costs, the repair and maintenance cost of various machines was estimated by the following expression.

\[ YTTH = \sum_{i=1}^{N} 0.01 \times (NU_i \times FU_i \times P_i) \]  \[ \text{[8]} \]

where

\[ R_i = \text{repair & maintenance cost of } i^{th} \text{ machine, % of purchase price for 100 hours} \]
\[ APU_i = \text{annual potential use of } i^{th} \text{ machine, hrs} \]

The yearly fuel cost was predicted by the following expression.

\[ YFC = \sum_{i=1}^{N} NU_i \times HFC_i \times FU_i \times APU_i \times FC \]  \[ \text{[10]} \]

where

\[ HFC_i = \text{hourly fuel consumption of } i^{th} \text{ machine, L/hr} \]
\[ FC = \text{fuel cost, $/L} \]

The yearly lubrication cost could be estimated as 15% of the yearly fuel cost (Kepner et al., 1982). The labor cost varies from location to location and also depends upon the degree of mechanization. Labor cost can be estimated by collecting data for a particular biomass energy project. The summation of all the above costs was treated as the total yearly cost of the harvesting system.

The cost of chipping was predicted by the following expression.

\[ PWC = \frac{YTC}{YPHS} + CC \]  \[ \text{[11]} \]
where

\[ PWC = \text{price of wood chips, \$/ton} \]

\[ YTC = \text{yearly total cost of harvesting system, \$} \]

\[ YPHS = \text{yearly total production of harvesting system, tons} \]

\[ CC = \text{carrying cost (land and management cost of wood production) of woody biomass, \$/ton} \]

**Prediction of future annual fuel expenses**

The future annual fuel expenses can be determined by the following expression.

\[ \text{AF}_1 = \left( \frac{SL \cdot PWC}{1000 \cdot SE \cdot AHHV} \right) \cdot (1 + IFF)^{t-1} \]  \[12\]

where

\[ SL = \text{seasonal load, kJ} \]

\[ SE = \text{seasonal efficiency of biomass energy system} \]

\[ AHHV = \text{higher heating value of the biomass fuel on as received basis, kJ/kg} \]

\[ IFF = \text{inflation rate for biomass fuel cost} \]

The above algorithm presented for predicting the life cycle cost of a biofueled energy system can also be used for predicting the life cycle cost of a conventional energy system (LPG, oil, and natural gas) by incorporating the appropriate parameter values.
Net Life Cycle Savings

The Life Cycle Savings (LCS) of a biomass energy system can be predicted by taking the difference between the total life cycle cost of a conventional system and a biomass system (savings can be negative; they are then losses). This concept is similar to the concept of solar savings as outlined by Beckman et al. (1977).

The LCS can be expressed as:

\[ \text{LCS} = \text{TLCC}_{\text{bio}} - \text{TLCC}_{\text{con}} \]  

where

\[ \text{LCS} = \text{life cycle savings of biomass energy system} \]
\[ \text{TLCC}_{\text{bio}} = \text{total life cycle cost of biomass energy system discounted to present value} \]
\[ \text{TLCC}_{\text{con}} = \text{total life cycle cost of conventional system discounted to present value} \]

Cash Flow Analysis

The cash flow analysis determine the amount and timing of positive and negative cash flows associated with each alternative. It is necessary to take account of the timing of the cash flows because money has a time value, and therefore, expenditures made at different times do not have the same value. The before taxes cash flow was predicted by subtracting the yearly cost associated with the conventional system from the yearly cost of the biomass energy
system. To compare the systems, the yearly cash flow were discounted to today's dollar value. The positive values of yearly cash flow were treated as yearly cost savings.

The after taxes yearly cash flow was determined by subtracting the yearly tax payments from the yearly cost savings. The taxable amount for the $i^{th}$ year can be predicted by following expression:

$$Y_{TA_i} = \text{Effective tax rate} \times Y_{TA_i}$$  \[14\]

where the $Y_{TA_i}$ is the taxable amount for the $i^{th}$ year, and can be predicted by the following relationship.

$$Y_{TA_i} = Y_{CS_i} - D E_{P_i} - Y_{INT_i}$$  \[15\]

where

- $Y_{CS_i} = \text{yearly cost savings before taxes for the } i^{th} \text{ year}$
- $D E_{P_i} = \text{annual depreciation allowance for the } i^{th} \text{ year}$
- $Y_{INT_i} = \text{yearly interest payments for the } i^{th} \text{ year}$

The accelerated depreciation methods provide for a higher depreciation allowance during the early years of an assets life and a correspondingly lower allowance in later years (White et al., 1977). The tangible property (having a life of more than 15 years) used for the production of income may be depreciated, at a rate of 150 % using the declining balance method (Internal Revenue Service, 1987). A modified straight line method for the first tax year is permitted if that method, when applied to the adjusted basis at the beginning of
the year, will yield a larger deduction. Therefore, an election may be made to use the straight line method over the recovery period.

Sometimes the taxpayers can claim a tax credit for investments in certain depreciable property. This means they can deduct from their tax liability an amount up to a percentage of their investment in qualified property. All of these situations were incorporated in the computer model.

Payback Period

The payback period is the elapsed time between the initial investment and the time at which cumulative savings in energy costs are just sufficient to offset the initial investment cost. If differences in the timing of the cash flows are taken into account, the mode is called "discounted payback." If timing differences are not taken into account, the mode is called "simple payback." These can be predicted by the following relation:

\[
PB = \frac{\Delta IC}{\Delta FC - \Delta O&M - \Delta PTIC}
\]  

[16]

where

\(\Delta IC\) = differential initial investment cost

\(\Delta FC\) = reduction in fuel cost

\(\Delta O&M\) = differential operation and maintenance cost

\(\Delta PTIC\) = differential property tax and insurance cost

For discounted payback period all costs are in present values.
Saving to Investment Ratio

The Savings to Investment Ratio (SIR) can be computed by the following expression:

$$\text{SIR} = \frac{\Delta FC - \Delta O&M}{\Delta IC - \Delta S + \Delta R}$$  \[17\]

where

$\Delta S =$ differential salvage values

$\Delta R =$ differential replacement costs

All costs are in present values.

To be economical, a biomass energy system must have a SIR that exceeds 1.0 when compared to the base case. This means that the present worth of all the savings must exceed the original investment over the assumed lifetime (25 years for this case).

Description of Computer Program

A computer program for life cycle cost analysis of biomass energy systems (CYCLE) was written in FORTRAN 77L with the mathematical formulation described above. CYCLE can be used to analyse the following investment alternatives.

1. both biomass and competing energy systems were on full payment (paid for when installed).

2. both biomass and competing energy systems were on mortgage (down payment plus annual mortgage payment).
3. biomass system was on full payment, while the competing system was on mortgage.

4. biomass system was on mortgage, while the competing system was on full payment.

Figure 1 show a flow chart for the program. CYCLE is composed of 1 main program, and 9 subroutines, which perform the necessary calculations. A complete listing of the computer program is presented in Appendix A. It starts by reading in the input variables of the biomass energy system, the competing or conventional energy system, and the harvesting system if the cost of wood chipping is desired. A brief description of the various subroutines follows:

CHIP

The subroutine CHIP predicts the cost of woodchips for the whole tree harvesting system. The input parameters for this subroutine are the purchase price, salvage value, economic life, gasoline/diesel consumption, annual use, and repair and maintenance cost of various machines included in the harvesting system. The other major input variables are interest on the investment, annual labor cost, and annual production of the harvesting system.

TAX

The subroutine TAX computes the property tax and insurance cost for various years of the economic analysis period. The input parameters of this subroutine are the first year property tax and
CALL TAX, FUEL, OPMAIN, MORTGA TO COMPUTE FOR COMPETING SYSTEM

CALL TAX

CALL FUEL

CALL OPMAIN

IS SYSTEM ON MORTGAGE

YES

NO

Figure 1. Flow chart of life cycle cost analysis model (CYCLE)
Figure 1. (Continued)
insurance cost, and their inflation rate, initial investment, salvage value, and economic life of the energy systems.

**FUEL**

The subroutine FUEL predicts the annual fuel cost for the various years of the economic analysis period. The input parameters are seasonal load, seasonal efficiency of the energy systems, fuel higher heating value, fuel price, and fuel inflation rate.

**OPMAIN**

The subroutine OPMAIN computes operation & maintenance cost for various years of the economic analysis period. This subroutine uses first year operation and maintenance cost, and inflation rate as input parameters.

**MORTGA**

The subroutine MORTGA ascertained the annualized mortgage payments, if the system is on mortgage. The main input variables are initial investment of the energy systems, percent financed, and interest rate on the mortgage amount.

**WORTH**

The subroutine WORTH performed the life cycle cost analysis of both the biomass and conventional energy system in accordance with the algorithm of life cycle models.
AWORTH

The subroutine AWORTH computes the after tax life cycle savings and yearly cash flow for the biomass energy system, if it is for commercial application.

PBACK

The subroutine PBACK predicts both simple and discounted payback periods for before and after tax payments. The input variables for this subroutine are initial investment of both energy systems and yearly before and after taxes cash flow.

CYCLE computes the future costs of property tax, insurance, fuel, and operation and maintenance, for both systems. These costs were then, used to predict the yearly cash flow before and after income taxes, life cycle costs of both systems, life cycle savings for the biomass system, fuel savings, savings to investment ratio, and payback periods (simple & discounted). A listing of the computer program output is presented in Appendix B.
RESULTS AND DISCUSSION

Life Cycle Cost Analysis of McNAY Biofueled Energy System

The McNay Memorial Research Center located in Lucas county is comprised of approximately 810 hectares of which 63 are existing timber and 21 hectares are being planted as an energy plantation (Honeyman et al., 1987). The project includes an integrated wood fired hot-water system for heating a residence, farm office, shop, and for drying grain.

The whole tree harvesting system of the McNay Memorial Research Center was semi-mechanized; trees were felled by chain saws and the entire tree was skidded to the chipper manually. When necessary, large limbs were partially sawn through to make it easier to feed the largest trees into the chipper throat. The chips were blown directly into a waiting wagon. When full, the wagon was hauled to the boiler site and unloaded.

To perform the life cycle cost analysis of the McNay biomass energy project and to predict the cost of woodchips, data were collected during the winter season of 1989-90. Table 1 shows the purchase price, annual use, economic life, repair and maintenance cost, and fractional use of various machines included in the harvesting system. Listings of labor costs for woodchipping and
Table 1. Parameters of harvesting system machines used for predicting the cost of wood chipping

<table>
<thead>
<tr>
<th>Machine Name</th>
<th>A</th>
<th>B</th>
<th>G</th>
<th>D</th>
<th>N</th>
<th>R</th>
<th>S</th>
<th>P</th>
<th>F</th>
<th>APU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chipper</td>
<td>100</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>1</td>
<td>1.5</td>
<td>1100</td>
<td>11000</td>
<td>0.2</td>
<td>500</td>
</tr>
<tr>
<td>Grapple Skidder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feller Buncher</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tractor 1</td>
<td>100</td>
<td>10</td>
<td>0.0</td>
<td>11.34</td>
<td>1</td>
<td>1.2</td>
<td>4000</td>
<td>40000</td>
<td>0.10</td>
<td>1000</td>
</tr>
<tr>
<td>Tractor 2</td>
<td>80</td>
<td>10</td>
<td>0.0</td>
<td>3.78</td>
<td>1</td>
<td>1.2</td>
<td>2500</td>
<td>25000</td>
<td>0.08</td>
<td>1000</td>
</tr>
<tr>
<td>Chip Van</td>
<td>60</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>1</td>
<td>1.25</td>
<td>0.0</td>
<td>2000</td>
<td>0.15</td>
<td>400</td>
</tr>
<tr>
<td>Pickup Truck</td>
<td>40</td>
<td>10</td>
<td>11.34</td>
<td>0.0</td>
<td>1</td>
<td>5.8</td>
<td>350</td>
<td>3500</td>
<td>0.10</td>
<td>400</td>
</tr>
<tr>
<td>Chain saw</td>
<td>90</td>
<td>10</td>
<td>1.13</td>
<td>0.0</td>
<td>2</td>
<td>25.25</td>
<td>0.0</td>
<td>440</td>
<td>0.45</td>
<td>200</td>
</tr>
<tr>
<td>Conveyor</td>
<td>20</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>1</td>
<td>1</td>
<td>0.0</td>
<td>900</td>
<td>0.02</td>
<td>1000</td>
</tr>
</tbody>
</table>

A = annual use for chipping operations, hours
B = economic life, years
G = gasoline consumptions, L/hr
D = diesel consumptions, L/hr
N = number of units in the system
R = repair and maintenance cost, % of original price per 100 hours
S = salvage value, $
F = purchase price, $
F = fractional use of machine for wood chipping
APU = annual potential use of machines, hrs
Table 2. Labor cost for wood chipping of 100 tons per season\(^a\)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Labor (hrs)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Felling with chainsaw, skidding</td>
<td>180</td>
<td>1800</td>
</tr>
<tr>
<td>2. Chipping</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>3. pick up truck</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>4. Chipvan</td>
<td>40</td>
<td>400</td>
</tr>
<tr>
<td>5. Conveyer</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>380</strong></td>
<td><strong>3800</strong></td>
</tr>
</tbody>
</table>

\(^a\)Jim Secor, Superintendent, McNay Research Center.
### Table 3. Operating and maintenance cost of a wood fired boiler system\(^a\)

<table>
<thead>
<tr>
<th>Boiler operation</th>
<th>hrs/year</th>
<th>cost/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Starting the fire</td>
<td>5</td>
<td>$50.0(^b)</td>
</tr>
<tr>
<td>2. Check up visits in the boiler room</td>
<td>75(^c)</td>
<td>$750.0</td>
</tr>
<tr>
<td>3. Cleaning of boiler &amp; ash handling</td>
<td>80(^d)</td>
<td>$800.0</td>
</tr>
<tr>
<td>4. Miscellaneous (parts &amp; labor)</td>
<td></td>
<td>$150.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$1750.0</strong></td>
</tr>
</tbody>
</table>

\(^a\)Jim Secor, Superintendent of McNAY Research Center.  
\(^b\)Labor rate used, $10.0/hr.  
\(^c\)One person spend 15 minutes twice a day for a period of 5 months.  
\(^d\)Two persons spend 4 hrs twice a month for a period of 5 months.
maintenance of the biofueled boiler are presented in Table 2 and Table 3 respectively. Appendix C lists the various input parameters used for life cycle cost analysis of McNay biomass energy system.

The economic data from the life cycle cost analysis for the McNay biomass energy system are presented in Table 4. The analysis revealed that the Life Cycle Costs (LCC) of the biomass energy and competing systems were 179.36 and 98.06 thousands of dollars, respectively. The biomass energy system is not competitive with the competing systems using the present costs. This is primarily due to the high cost of raw wood energy price at $7.0/million kJ ($75.90/ton) and the higher initial cost of the biomass system.

As revealed from Table 2, felling & skidding were done manually, at a labor cost of $18/ton. The total labor cost for woodchipping was $38/ton. This cost could be reduced as low as $5.60/ton (Massey et al., 1981) by (1) fully mechanizing the operation of felling and skidding, and (2) by increasing the seasonal production of woodchips. This would only be possible if the woodchips were produced on a commercial scale.

Sensitivity analysis

The process of determining how much the economic results will change as a result of a change in one of the input factors, other factors being held constant, is known as "sensitivity analysis" (Brown and Yanuck, 1985).
## Table 4. Economic figures of McNAY biomass energy system\(^a\)

<table>
<thead>
<tr>
<th>Cost of woodchips</th>
<th>$75.90/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of raw wood energy</td>
<td>$7.0/million kJ(^b)</td>
</tr>
<tr>
<td>Cost of competing fuel (LPG)</td>
<td>$0.211/L</td>
</tr>
<tr>
<td>Present worth of life cycle cost</td>
<td>$8.4/million kJ</td>
</tr>
<tr>
<td>(25 years) for McNAY biomass</td>
<td></td>
</tr>
<tr>
<td>energy system</td>
<td></td>
</tr>
<tr>
<td>Present worth of life cycle cost</td>
<td>$179,358.0</td>
</tr>
<tr>
<td>for competing system</td>
<td></td>
</tr>
<tr>
<td>Present worth of life cycle</td>
<td>$98,063.0</td>
</tr>
<tr>
<td>savings</td>
<td>$-81,296.0(^c)</td>
</tr>
<tr>
<td>Discounted cumulative fuel</td>
<td>$-30,322.7</td>
</tr>
<tr>
<td>savings</td>
<td></td>
</tr>
<tr>
<td>Savings to investment ratio</td>
<td>-2.30</td>
</tr>
<tr>
<td>No simple or discounted payback</td>
<td></td>
</tr>
<tr>
<td>period</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Predicted using CYCLE.
\(^b\)$/million kJ = Cost per unit/(higher heating value, million kJ/unit * (1.0-moisture content, %/100)).
\(^c\)Negative savings mean loss.
The sensitivity analysis was carried out to determine the effect of the most critical and uncertain variables such as wood energy price, competing fuel (Liquefied Petroleum Gas (LPG)) price, inflation rate, and the seasonal efficiency of the biomass energy system.

Figure 2 shows the effect of raw wood energy prices on the LCC of the McNay biomass energy system at its various seasonal efficiencies. The LCC is sensitive to both raw wood energy price (slope of the lines), and seasonal efficiency (distance between lines) of biomass energy system. A wood energy price increase of $1/million kJ ($10.87/ton at 45% Moisture Content (MC)) results in an increase of $16,920 at 40% seasonal efficiency (Figure 2). The LCC increase can be reduced to $13,536 (20% reduction), and $11,280 (33.37% reduction) by increasing the system efficiency to 50% and 60%, respectively. The LCC of the biomass energy system is very sensitive to the wood energy prices as well as the seasonal efficiency of the system.

Figure 3 shows the effect of conventional (LPG) energy prices on the LCC of the competing system at various inflation rates. An increase of $1/million kJ ($0.025/L) in LPG energy prices (at a 4% inflation rate) increases LCC by $10,970. The LCC would increase to $12,460 (13.62% increase), and $15,460 (41% increase) at inflation
Figure 2. Life cycle cost vs wood energy price at three efficiencies of the McNay biofueled energy system
Figure 3. Life cycle cost vs LPG energy price at three inflation rates for the competing system.
rates of 6\%, and 8\%, respectively. The LCC of the competing (LPG) system is sensitive to the LPG prices and their inflation rates.

Life cycle savings of the McNay biomass energy system can be estimated at various raw wood energy prices, LPG energy prices, biomass system efficiencies, and inflation rates of LPG prices by using Figures 2 and 3. For example, the LCC of a biomass energy system is $123,472 when the wood energy price is $3.68/million kJ ($40/ton at 45\% MC), and the system efficiency is 40\% (Figure 2). The LCC of an LPG system is $143,390 when the price of LPG is $8.4/million kJ ($0.21/L) and the fuel inflation rate is 8\%. Life cycle savings can be predicted by taking the difference of the costs. For this example, the biomass energy system life cycle savings are $19,918.

Figure 4 demonstrates the effect of competing fuel (LPG) price and wood energy price on the life cycle savings of the biomass energy system. The life cycle savings was most sensitive to increase in LPG prices (the distance between the curves). It was also sensitive to the wood energy price (the slope of the lines). The graphs indicate that at LPG prices of $6.4, $8.4, and $10.4/million kJ, the breakeven points exist at $0.924, $2.15 and $3.38/million kJ for raw wood energy respectively.

Figure 5 shows a graph of discounted fuel savings vs wood energy price at various prices of LPG. The graphs indicate that by
Figure 4. Life cycle saving vs wood energy price at three LPG energy prices for the McNay biofueled energy system.
Figure 5. Fuel savings vs wood energy price at three LPG energy prices for the McNay biofuelled energy system.
decreasing the wood energy price by $1/million kJ, the corresponding increase in fuel savings was $16,900. With an increase in LPG price of $2.0/million kJ ($0.05/L), at constant wood energy price, the fuel savings increased $21,500. The biomass energy fuel savings were sensitive to the wood energy prices as well as to conventional (LPG) fuel prices.

Figure 6 demonstrates the effect of seasonal efficiency of the biomass fueled system on life cycle savings at a fixed price of LPG ($8.4/million kJ). The effect of seasonal efficiency increases with an increase in raw wood energy price. With an increase in seasonal efficiency from 40 % to 60 %, there was an increase in breakeven price of raw wood energy from 2.15 to 3.23 $/million kJ. Increasing seasonal efficiency has a positive impact in making the biomass energy system economically viable, because less fuel is required at higher boiler efficiency.

Figure 7 shows life cycle savings vs raw wood energy price at three inflation rates of competing fuel (LPG) price. By changing inflation rates of LPG prices from 4 to 8 %, at 4% woodchip price inflation, the breakeven price of raw wood energy changes from 2.15 to 4.82 $/million kJ. The inflation rate of LPG price has a significant effect on the cost effectiveness of a system.

Figure 8 shows a graph of life cycle savings vs wood energy price at various seasonal loads of the biofueled boiler, assuming 50%
Figure 6. Life cycle savings relative to LPG system vs wood energy price at three seasonal efficiencies of the McNay energy system.
Figure 7. Life cycle savings relative to LPG system vs. wood energy price at three inflation rates of competing fuel (LPG) price.
Figure 8. Life cycle savings vs wood energy price at three seasonal loads, at 50% boiler efficiency.
system efficiency. The seasonal load of 318,600 kWh (1147 million kJ) is based on the assumption that the McNAY biofueled boiler should provide an average of 0.32 million kJ/hr for a five month period to the building envelope, whereas the seasonal load of 506,400 kWh (1823 million kJ) is based on the assumption that the same boiler is providing an average of 0.32 million kJ/hr for an 8 month period to a small scale industry. It can be seen from Figure 8 that the life cycle saving is very sensitive to seasonal load. With an increase in current connected seasonal load of 123,000 kWh (443 million kJ) to 318,600 kWh (1147 million kJ) there was an increase in the breakeven price of raw wood energy from 2.69 to 5.0 $/million kJ. By further increasing seasonal load to 506,400 kWh (1823 million kJ) the breakeven price will increase to 5.54 $/million kJ.
CONCLUSIONS

1. A computer model for life cycle analysis of biofueled energy systems (CYCLE) was developed. CYCLE is a very useful tool for making economic comparisons and performing the parametric analysis of a biofueled energy system.

2. The life cycle cost analysis of the McNay biomass energy system revealed that economics are not favorable for the present situation. The high cost of the biomass system and relatively high wood chip cost make the biomass system uneconomic at current costs of competing fuel. But the sensitivity analysis revealed that the:
   a. LCC of the biomass energy system was sensitive to raw wood energy prices and to the seasonal efficiency of the system;
   b. LCC of the competing system was sensitive to LPG prices and their inflation rates;
   c. life cycle savings of the biomass energy system were also sensitive to the raw wood energy price, LPG energy price and their inflation rates, seasonal load, and the seasonal efficiency of the biomass energy system.

3. The biomass energy system may become economically viable:
   a. by reducing the cost of woodchips;
   b. by increasing the seasonal efficiency and seasonal load of the biomass energy system;
   c. by an increase in the cost of competing fuel;
d. if the prices of competing fuels inflates at a rate of about 8% annually for the next 25 years.
REFERENCES


Honeyman, M. S. et al. 1987. Unpublished proposal for a wood-fired furnace and timber management research and demonstration system at the Iowa State University McNay Memorial Research Center Lucas County, Iowa. Iowa Agricultural Experiment Station, Ames Iowa.


Secor, J. Consultation. McNay Memorial Research Center, Chariton, Iowa.


GENERAL SUMMARY

A simulation model of a biofueled energy system (BIOMOD) was developed to assist the potential users of biofuel energy and to perform the parametric analysis of the most critical and uncertain variables (fuel moisture, excess air, flue gas temperature, seasonal load, fuel price, etc.) of biofueled energy system. BIOMOD consists of three submodels, namely, THERM, SIMPSE, and CYCLE.

THERM is based on the modified bin method developed by ASHRAE TC 4.7, and simplified dimensionless relations for heat loss from basements developed by the Solar Energy Laboratory, Madison, Wisconsin. THERM predicts the hourly heating load at various bin temperatures, and design as well as seasonal energy requirement of the building envelope. The predicted hourly heating loads at various bin temperatures were used for simulating a biofueled boiler. Likewise, the seasonal energy requirement of the building envelope provides a base for estimating the seasonal fuel requirement of the system. To validate the THERM submodel the measured seasonal load (November 1989 - March 1990) of the McNAY Research Center residence was compared with the predicted heating load. The THERM prediction of seasonal load was in good agreement (within 6.5%) with the measured load. THERM was consequently determined to be suitable for estimating the seasonal load of residence buildings.

The submodel SIMPSE simulates dynamic behavior of the boiler in
response to building heating load, predicts steady-state efficiency in addition to sensible losses, and latent losses under various modes of boiler operation, and predicts the seasonal efficiency of biofueled space heating boilers. To validate SIMPSE, measured seasonal efficiencies of the McNAY biofueled boiler for the months of December, January, February, and March were compared with the SIMPSE predictions. The model predictions were within 3% of the measured results. SIMPSE was found very suitable for predicting the seasonal thermal performance of the biofueled boilers.

About 100 computer runs, using SIMPSE were made to predict the performance of a wood-fired boiler at various combinations of the design and operating variables (moisture and hydrogen content of fuel, flue oxygen concentration (excess air), and flue gas temperature). The results were plotted to be easily accessible to wood-fired boiler designers and to operators to assist them in obtaining higher boiler efficiency. This parametric analysis revealed that: (a) The latent losses (energy losses due to moisture and hydrogen in wood fuel) were greatly affected by fuel moisture content. By increasing the moisture content from 10 to 50% at 149°C flue gas temperature, the latent energy losses rise from 9.05% to 21.34% of the fuel energy input, a difference of 12.3%. On the other hand, at 371°C flue gas temperature, this difference increases to 14.3% because of the greater enthalpy of the water vapors; (b) by
decreasing the flue gas temperature from 371°C to 149°C at a constant 2.5% flue oxygen concentration, sensible heat losses decreased from 13.02% to 4.61% (8.4% difference), whereas at 17.5% flue oxygen concentration, the sensible losses decreased from 71.6% to 25.63% (46% difference) as a result of decreasing the flue gas temperature from 371°C to 149°C. For a given boiler design, flue gas temperature and oxygen concentration are related to excess air; sensible heat losses increase with an increase in excess air. Therefore, proper control of excess air is imperative for obtaining higher efficiency of biofueled boilers.

During the winter of 1989-1990 a heating load of more than 50% of the capacity of the McNAY wood-fired boiler system occurred for only 450 hours, and only five percent of the total energy was provided at loads more than 50% of maximum capacity during the period of the study (December 15, 1989 to March 1990). The boiler was therefore operated 72% of the time at a load which was below 50% of its maximum capacity. This reduced seasonal efficiency of the McNAY biofueled boiler, because boiler efficiency increases with higher loads. It is suggested that the biofueled boiler should be sized for only 50 to 60% of maximum demand. With this sizing, the boiler would run most of the time at a high load and with a high efficiency. A backup system, however, would be required to meet the peak heating demand.
The parametric analysis of the McNAY biofueled energy system revealed that by installing a smaller unit or by reducing the firing rate (about 33%) of the existing wood fired boiler, accompanied by a proportional reduction of the supply of air, the seasonal efficiency will go from 41% to 50% at 45% wood fuel moisture content. In addition, energy can also be saved by supplying heat to the workshop during occupied periods only (12 hours/week day). In this way, about 39,000 kWh of energy can be saved during one heating season. By reducing the size of boiler and by eliminating unnecessary heating, the seasonal fuel consumption can be reduced from 100 metric tons (at 41% predicted efficiency of the existing unit for the 1990-91 heating season, 123,000 kWh seasonal load, and 45% moisture content of fuel) to 56 metric tons (50% efficiency of a smaller unit and 84,000 kWh seasonal load), which will save $3300 per heating season (at $75/ton, wood chip price).

CYCLE was developed to: (a) evaluate the cost of wood fuel harvesting and chipping; (b) perform life cycle cost analysis of a biofueled energy system; (c) predict the savings to investment ratio, payback period, and life cycle savings before and after tax payments of the biomass energy system. The life cycle cost analysis of the McNAY biomass energy system revealed that economics are not favorable for the present situation. The high cost of the biomass system and relatively high woodchip cost ($75.9/ton) make the biomass system
uneconomic at current costs. The sensitivity analysis revealed that
the McNAY biofueled energy system may become economically viable by:
(a) reducing the cost of wood chips; (b) increasing the seasonal
efficiency and seasonal load of the system; (3) an increase in the
cost of competing fuel.

Finally it can be concluded that BIOMOD is a very useful
software package for: (a) predicting the seasonal energy requirements
of a building envelope; (b) predicting the seasonal thermal
performance of biofueled space heating boilers; (c) and for
performing the life cycle cost analysis of biofueled energy systems.
Further work is required to make BIOMOD user friendly.
LITERATURE CITED


Colletti, J. P. Consultation. Department of Forestry, Iowa State University, Ames, IA.


Honeyman, M. S. et al. 1987. Unpublished proposal for a wood-fired furnace and timber management research and demonstration system at the Iowa State University McNay Memorial Research Center Lucas County, Iowa. Iowa Agricultural Experiment Station, Ames, Iowa.


I dedicate this work to my father who passed away just two months after I left home for studies in the United States of America. May his soul rest in peace.

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PART I. APPENDIX A. LISTING OF COMPUTER PROGRAM FOR THERMAL LOAD ANALYSIS OF BUILDING ENVELOPE
MICRO-COMPUTER PROGRAM FOR THERMAL LOAD ANALYSIS
OF BUILDING ENVELOPE (THERM).

DEVELOPED AND PROGRAMMED AT IOWA STATE UNIV., AMES, IOWA.

AUTHOR: MUNIR AHMAD, 1990

DEFINITION OF REAL VARIABLES:

ABF = area of basement floor, m²
ABW = area of basement walls, m²
ABWG = area of ith exposure of above grade basement walls, m²
ACLTD = twenty four hour averaged solar component of Cooling Load Temperature Difference (CLTD) for roof in January
ACLTDW = twenty four hour averaged solar component of CLTD for wall in January
AF = building conditioned floor area, m²
AG = glass area for ith exposure, m²
ABG = glass area for ith exposure of above grade basement, m²
AIZ = area of interior zone, m²
ALPHA = soil thermal diffusivity, m²/s
AMSHGF = maximum solar heat gain factor for January at the specified latitude
APPS = percent possible sunshine for January
APZ = area of perimeter zone, m²
ASC = shading coefficient of glass for January
AR = total roof area, m²
ARP = roof area for perimeter zone, m²
ARI = roof area for interior zone, m²
AVEL = average usage of light in perimeter zone for occupied period
AVEE = average usage of equipment in perimeter zone for occupied period
AVELUN = average usage of light in perimeter zone for unoccupied period
AVEUN = average usage of equipment in perimeter zone for unoccupied period
AW = opaque wall area, m²
BA = amplitude of expected daily average temperature curve in degree C
BSS = dummy variable.
BT = bin temperature in degree C
CLFTA = twenty four hour sum of Cooling Load Factor (CLF) for each exposure for January
CLFTJ = twenty four hour sum of CLF for each exposure for July
D = depth of basement, m
DEN = density (persons per 100 m²)
DM = days of the months of the year
F2 = heat loss coefficient, W/m² degree C per m of perimeter
FB = the average amount of infiltration air entering the building at respective bin-temperature, L/s m²
FIC = the amount of infiltration air entering the building at TIC, L/s m²
FIH = the amount of infiltration air entering the building at TIH, L/s m²
FPH = the amount of infiltration air entering the building at TPH, L/s m²
FREQOC = frequency of occurrence of each bin temperature for occupied period, hrs
FREQUN = frequency of occurrence of each bin temperature for unoccupied period, hrs
HF = heat factor (converting unit of load to watts)
HQHOC = hourly bin heating load for occupied period, kWh
HQHUN = hourly bin heating load for unoccupied period, kWh
JCLTDW = twenty-four hour averaged solar component of CLTD for wall in July
JCLTD:

- twenty-four hour averaged solar component of CLTD for roof in July

JMSHGF:

- maximum solar heat gain factor for July at the specified latitude

JPPS:

- percent possible sunshine for July

JSC:

- shading coefficient of glass for each exposure for July

KR:

- color correction factor for roof

KS:

- soil thermal conductivity, W/m degree C

KW:

- color correction factor for wall

L:

- length of basement, m

MQT:

- basement heating load for each month of the year, kWh

NI:

- the day number on which the ambient temperature curve crosses the mean value (NI = 110 days).

ODT:

- outdoor design temperature in degree C

P:

- perimeter or exposed edge of floor, m

PN:

- dummy variable

QDHL:

- design heating load, kWh

QHOCC:

- baseboard heating load for each bin-temperature for occupied period, W/m²

QHUNOC:

- baseboard heating load for each bin-temperature for unoccupied period, W/m²

QL:

- latent heat produced per person, W

QS:

- sensible heat produced per person, W

RF:

- overall R-value of the basement floor, m² degree C/W

ROW:

- soil volumetric thermal capacity, J/m³ degree C

RW:

- overall R-value of the basement walls, m² degree C/W

SQHOC:

- seasonal (total) heating load for occupied period, kWh

SQHUN:

- seasonal (total) heating load for unoccupied period, kWh

TA:

- annual average temperature in degree C

TAG:

- total glass area, m²

TABG:

- total glass area of above grade basement, m²

TAW:

- total wall area, m²

TABWG:

- total wall area of above grade basement, m²

TB:

- basement temperature in degree C

TBQHOC:

- total bin heating load for occupied period, kWh

TBQHUN:

- total bin heating load for unoccupied period, kWh

TIC:

- lowest temperature bin in which the envelope impose cooling load on the building, degree C
TID = inside temperature for computing the design load, degree C

TIH = mid point of a temp. bin where the net building loads change from heating to cooling loads, degree C

TIOCC = inside temperature during occupied period in degree C

TIUN = inside temperature during unoccupied period in degree C

TJ = run time for air-conditioned system in July, hr

TJA = run time for air-conditioned system in January, hr

TLOCP = total latent heat produced during occupied period in perimeter zone, W/m²

TLOCI = total latent heat produced during occupied period in interior zone, W/m²

TMM = mean monthly temperature of the year, °C

TPC = mid point of the highest temperature bin occurring at the location in degree C

TPH = mid point of the lowest temperature bin occurring at the location in degree C

TQB = total basement heating load, kWh (below grade + above grade)

TSA = supply air temperature in degree C

TSOCP = total sensible heat produced during occupied period in perimeter zone, W/m²

TSOCI = total sensible heat produced during occupied period in interior zone, W/m²

TSQH = total seasonal heating load, kWh

TSUNP = total sensible load during unoccupied period, W/m²

TSUNI = total sensible heat produced during unoccupied period in interior zone, W/m²

UG = overall heat transmission coefficient for glass, W/m² degree C

UGD = UG for design load calculations, W/m² degree C

URC = combined heat transmission coefficient for roof and ceiling, W/m² degree C

UW = overall heat transmission coefficient for wall, W/m² degree C

UWD = UW for design load calculations, W/m² degree C

VID = design volume of outdoor air (infiltration) entering building, L/s m²

VIOCCI = ventilation rate for occupied period for interior zone, L/s m²
VIOCCP = ventilation rate for occupied period for perimeter zone, L/s m²
VIUNI = ventilation rate for unoccupied period in interior zone, L/s m²
VIUNP = ventilation rate for unoccupied period for perimeter zone, L/s m²
W = width of basement, m
WID = humidity ratio of indoor air, kG H₂O/kG air
WOD = humidity ratio of outdoor air, kG/kG air
WFMEUN = equipment load for unoccupied period, W/m²
WPMLUN = lights load for unoccupied period, W/m²
WPMSE = equipment load for occupied period, W/m²
WPMSL = sensible light load, W/m²

INTEGER VARIABLES:

EXP = number of different glass exposures
IZ = interior zone, IZ=1, if it exists, IZ=0, if it does not exist
N = total number of bins
POCC = occupied period, POCC=1 if it exists, POCC=0 if it does not exist
PUNOC = unoccupied period, PUNOC=1 if it exists, PUNOC=0 if it does not exist
PZ = perimeter zone, PZ=1 if it exists, PZ=0 if it does not exist
BS = BS = 1, if basement exists, BS=0, if it does not exist
HP = heating period code: HP = 0 for seasonal heating load, HP = 1 to 12 for January to December
BSWG = BSWG = 1, if basement wall above grade exists, BSWG = 0, if it does not exist

**********************************************************

MAIN PROGRAM

COMMON /GAIN/ JMSHGF, JSC, CLFTJ, AMSHGF, ASC, CLFTA, TJ, TJA
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC
COMMON /WAI.T./ UW, JCLTDW, KW, URC, JCLTDR, KR, ACLTDW, + ACLTDR, UG, ARP, ARI
COMMON /BBB/ AVEL, WPMSL, HF, AVEE, WPMSE, DEN, QS, QL, + AVELUN, WPMLUN, WPMEUN, AVEUN
COMMON /LOAD/ M1,AQSOL,M2,M3,M4,AQTS,MI,AQTSR, QRI,PZ,IZ
COMMON /MENT/ D,W,L,KS,ROW,RW,RF,TA,BA,NI,TB,ABW,ABF,ABG,
+ ABWG,TMM
COMMON /DES/ ODT,AR,TAW,UWD,TAG,UGD,F2,P,VID,WID,WOD
COMMON /AAA/ TSOCP,TSOCI,TSUNP,TSUNI,TLOCP,TLOCI
COMMON /INFIL/ FPH, FIH, FIC

C
DECLARATION OF VARIABLES.

C
REAL JMSHGF(16), AG(16), JSC(16), CLFTJ(16), AMSHGF(16),
+ TSA, ASC(16), CLFTA(16), TJ, TJA, JPSS, APPS, TPC, TPH, AF
REAL AN(16), UW(16), JCLTDW(16), KW(16), AR, URC, JCLTDR, KR,
+ ACLTDW(16), ACLTDR, UG(16), ARI, ARP
REAL AVEL, WPMSL, HF, AVEE, WPMSE, DEN, QS, QL, AVELUN, WPMLUN,
+ WPMEUN, AVEUN, FPH, FIH, FIC
REAL M1, AQSOL, M2, AQTS, M3, TSOCP, TSUNP, TLOCP, APZ, TSOCI, TSUNI,
+ TLOC, AIZ, TIOCC, VIOPCP, VIOCI, TIUN, VIUP, VIUNI, MI, M4
REAL QHOCC(30), QHUNOC(30), BT(30), FREQOC(12,30),
+ FREQUN(12,30), HQHOC(30), HQHUN(30), SQHOC, SQHUN,
+ MQHOC(12), MQHUN(12), TMQH(12)
REAL DM(20), HQT(20), QBD, D, W, L, KS, ROW, RW, RF, TA, BA, NI, TB,
+ ABW, ABF, ODT, TAW, UWD, TAG, UGD, F2, P, VID, WID, WOD, ABG(8),
+ ABWG(8), QB(30), TG(12), TMF(12), QM(12)
REAL QLWOC(40), QLROC(40), QLIROC(40), QLWUN(40),
+ QLRUN(40), QLUN(40), QLVUN(40)

C
INTEGER EXP, IZ, N, POCC, PUNOC, PZ, BS, BSWG

C
INPUT DATA

C
OPEN(2,FILE = 'a:DESIGN.DAT')
C INPUT DATA FOR DESIGN LOAD CALCULATIONS.
READ(2,*) TID, AR, URC, ODT, TAW, UWD, TAG, UGD, F2, P, VID,
+ WID, WOD, TABG, TABWG
CLOSE(2,FILE='a:DESIGN.DAT')
C
OPEN(UNIT=5,FILE='a:EXPO.DAT')
READ(5,*) PZ, IZ, POCC, PUNOC, BS, BSWG
READ(5,*) EXP, JPSS, APPS, TPC, TPH, TIH, TIC, AF, TJ,
+ TJA, TSA, TIIOCC
READ(5,*) APZ, ARP, HF, DEN, QS, QL, AVEL, AVEE, WPMSL, WPMSE,
+ VIOPCP, FIH, FPH, FIC
IF(PUNOC .EQ. 1) THEN
READ(5,*) TIUN, AVELUN, AVEUN, WPMLUN, WPMEUN, VIUNP
END IF
CLOSE (UNIT = 5, FILE = 'a:EXPO.DAT')
IF (BS .EQ. 1) THEN
OPEN (UNIT = 5, FILE = 'a:BASE.DAT')
C INPUT DATA FOR BASEMENT LOAD CALCULATIONS.
READ (5, *) D, W, L, KS, ROW, RW, RF, TA, BA, NI, TB, ABW, ABF
READ (5, *) (DM(I), I = 1, 12)
READ (5, *) (TMM(I), I = 1, 12)
READ (5, *) (ABG(I), I = 1, EXP)
READ (5, *) (ABWG(I), I = 1, EXP)
CLOSE (UNIT = 5, FILE = 'a:BASE.DAT')
END IF
C OPEN (UNIT = 5, FILE = 'a:GLASS.DAT')
READ (5, *) (JMSHGF(I), I = 1, EXP)
READ (5, *) (AMSHGF(I), I = 1, EXP)
READ (5, *) (AG(I), I = 1, EXP)
READ (5, *) (UG(I), I = 1, EXP)
READ (5, *) (JSC(I), I = 1, EXP)
READ (5, *) (ASC(I), I = 1, EXP)
READ (5, *) (CLFTJ(I), I = 1, EXP)
READ (5, *) (CLFTA(I), I = 1, EXP)
IF (IZ .EQ. 1) THEN
READ (5, *) AIZ, ARI, VIOCCI, VIUNI
END IF
CLOSE (UNIT = 5, FILE = 'a:GLASS.DAT')
C OPEN (UNIT = 5, FILE = 'a:WALL.DAT')
READ (5, *) (AW(I), I = 1, EXP)
READ (5, *) (UW(I), I = 1, EXP)
READ (5, *) (KW(I), I = 1, EXP)
READ (5, *) (JCLTDW(I), I = 1, EXP)
READ (5, *) (ACLTDW(I), I = 1, EXP)
READ (5, *) KR, JCLTD, ACLTD
CLOSE (UNIT = 5, FILE = 'a:WALL.DAT')
C OPEN (UNIT = 5, FILE = 'a:BIN.DAT')
READ (5, *) N
READ (5, *) (BT(I), I = 1, N)
DO 2 I = 1, 12
READ (5, *) (FREQOC(I, J), J = 1, N)
2 CONTINUE
IF (PUNOC .EQ. 1) THEN
DO 3 I = 1, 12
READ (5, *) (FREQUN(I, J), J = 1, N)
3 CONTINUE
END IF
CLOSE(UNIT=5, FILE = 'a:BIN.DAT')
*****************************************************************************

CALL SUBROUTINES FOR CALCULATIONS
*****************************************************************************

IF (PZ .EQ. 1) THEN
CALL SOLAR(EXP, M1, AQSO, AG)
BSS = 0.0
CALL TRANS(EXP, M2, AQTS, AW, BSS)
CALL CONDUC(EXP, M3, AG, AW, BSS, M4)
CALL INTL(TSOC, TSUN, TLOC, APZ, POCC, PUNOC)
END IF
WORK OUT INTERIOR ZONE DIVERSIFIED LOAD, IF IT EXIST.

IF (IZ .EQ. 1) THEN
CALL IZONE(MI, AQTSR, QRI)
CALL INTL(TSOCI, TSUNI, TLOCI, AIZ, POCC, PUNOC)
ELSE
TSOCI = 0.0
TSUNI = 0.0
TLOCI = 0.0
END IF

IF (POCC .EQ. 1) THEN
PN = 1.0
CALL SUBROUTINE HLOAD TO COMPUTE HOURLY HEATING LOAD FOR
EACH BIN-TEMPERATURE FOR OCCUPIED PERIOD.
CALL HLOAD(QHOCC, BT, TIOCC, TSOC, N, VIOCC, VIOCCI, TSOCP, PN,
+ QLWOC, QLROC, QLIOC, QLVOC)
END IF

AGAIN CALL SUBROUTINE HLOAD TO COMPUTE HOURLY HEATING
LOAD FOR EACH BIN TEMPERATURE FOR UNOCCUPIED PERIOD.

IF (PUNOC .EQ. 1) THEN
PN = 2.0
CALL HLOAD(QHUNOC,BT, TIUN, TSUNP, N, VIUNP, VIUNI, TSUNI, PN, 
+ QLWUN, QLRUN, QLIUN, QLVUN)
END IF
C
IF (BS .EQ. 1) THEN
CALL BASE(DM, HQT, QBD, BSWG, EXP, BT, N, QB, TGW, TGF)
ELSE
QBD = 0.0
DO 4 I = 1, N
QB(I) = 0.0
4 CONTINUE
END IF
C
CALL DESIGN(TID, URC, QBD, QDHL, TB, TABG, TABWG)
C
CALL SUBROUTINE SLOAD TO COMPUTE HOURLY, MONTHLY, AND SEASONAL HEATING LOAD FOR OCCUPIED PERIOD.
C
IF (POCC .EQ. 1) THEN
CALL SLOAD(N, QHOC, FREQOC, HQHOC, MQHOC, SQHOC, QB)
END IF
C
CALL SUBROUTINE SLOAD TO COMPUTE HOURLY, MONTHLY, AND SEASONAL HEATING LOAD FOR UNOCCUPIED PERIOD.
C
IF (PUNOC .EQ. 1) THEN
CALL SLOAD(N, QHUNOC, FREQUN, HQHUN, MQHUN, SQHUN, QB)
ELSE
SQHUN = 0.0
END IF
C
IF (PUNOC .EQ. 1) THEN
DO 5 I = 1, 12
TMQH(I) = MQHOC(I) + MQHUN(I)
5 CONTINUE
TSQH = SQHOC + SQHUN
ELSE
DO 6 I = 1, 12
TMQH(I) = MQHOC(I)
6 CONTINUE
TSQH = SQHOC
END IF
C
OPEN(UNIT=9,FILE='a: THERM.RES')
WRITE(9,8)
FORMAT(10X,'OUTPUT OF'/
+ 17X,'MICRO-COMPUTER PROGRAM FOR THERMAL LOAD'/
+ 17X,'ANALYSIS OF RESIDENCES (THERM)')
IF(POCC .EQ. 1) THEN
WRITE(9,25)
FORMAT(//14X,'VARIOUS HOURLY HEAT LOSSES FOR OCCUPIED',
+ 'PERIOD'//10X,'BIN TEMP.',6X,'WALL',6X,'ROOF',6X,
+ 'INFILTR',6X,'VENTI'//14X,'C',10X,'kWh',8X,'kWh',8X,
+ 'kWh',9X,'kWh')
DO 30 I = 1,N
WRITE(9,27) BT(I),QLWOC(I),QLROC(I),QLIOC(I),QLVOC(I)
27 FORMAT(10X,F6.1,6X,F6.1,5X,F6.1,5X,F6.1)
30 CONTINUE
WRITE(9,32)
FORMAT(//15X,'HEATING LOAD FOR OCCUPIED PERIOD AGAINST'/
+ 'VARIOUS TEMPERATURE BINS')
WRITE(9,34)
FORMAT(//10X,'BIN TEMP',5X,'BASEBOARD',5X,'BASEMENT',5X,
+ 'HOURLY LOAD'//13X,'C',11X,'w/m2',9X,'w/m2',11X,'kWh')
DO 45 I = 1,N
WRITE(9,40) BT(I),QHOCC(I),QB(I),HQHOC(I)
40 FORMAT(10X,F6.2,6X,F7.2,7X,F6.2,7X,F8.2)
45 CONTINUE
END IF
WRITE(9,66)
FORMAT(//14X,'VARIOUS HOURLY HEAT LOSSES FOR UN-OCCUPIED',
+ 'PERIOD'//10X,'BIN TEMP.',6X,'WALL',6X,'ROOF',6X,
+ 'INFILTR',6X,'VENTI'//14X,'C',10X,'kWh',8X,'kWh',8X,
+ 'kWh',9X,'kWh')
DO 68 I = 1,N
WRITE(9,27) BT(I),QLWUN(I),QLRUN(I),QLIUN(I),QLVUN(I)
68 CONTINUE
WRITE(9,70)
FORMAT(15X,'HEATING LOAD FOR UNOCCUPIED PERIOD AGAINST'/
+ 'VARIOUS TEMPERATURE BINS')
WRITE(9,34)
DO 75 I = 1,N
WRITE(9,40) BT(I),QHUNOC(I),QB(I),HQHUN(I)
75 CONTINUE
CONTINUE
END IF
WRITE(9,80)
FORMAT(//'MONTHLY HEATING LOAD OF THE BUILDING'//
+ 'MONTH', 'HEATING LOAD'/'kWh')
WRITE(9,85) TMQH(1), TMQH(2), TMQH(3), TMQH(4), TMQH(5),
+ TMQH(6), TMQH(7), TMQH(8), TMQH(9), TMQH(10), TMQH(11),
+ TMQH(12)
FORMAT(21X,'JAN',12X,F8.2/21X,'FEB',12X,F8.2/
+ 'MARCH',10X,F8.2/21X,'APRIL',10X,F8.2/
+ 'MAY',12X,F8.2/21X,'JUNE',11X,F8.2/
+ 'JULY',11X,F8.2/21X,'AUG',12X,F8.2/
+ 'SEP',12X,F8.2/21X,'OCT',12X,F8.2/
+ 'NOV',12X,F8.2/21X,'DEC',12X,F8.2)
WRITE (9, 90) TSQH
FORMAT(//'SEASONAL HEATING LOAD OF BUILDING = ',
+ 'kWh')
WRITE(9,95) QDHL
FORMAT(//'DESIGN HEATING LOAD FOR BUILDING = ',
+ 'W')
IF (BS .EQ. 1) THEN
WRITE(9,100)
FORMAT(//'MONTHLY BELOW GRADE BASEMENT PARAMETERS'//
+ 'AVE TEMP', 'TGW', 'TGF', 'AVE HEAT LOSS'/'C', 'C', 'C', 'WATTS'//)
DO 110 I = 1,12
WRITE(9,105) I,TMM(I),TGW(I),TGF(I),HQT(I)
105 FORMAT(IIX,13,7X,F4.1,7X,F4.1,4X,F4.1,7X,F6.1)
110 CONTINUE
WRITE(9,112)
FORMAT(//'NOTE: TGW & TGF STAND FOR EFFECTIVE GROUND'//
+ 'WALL AND GROUND FLOOR TEMPERATURE IN DEGREE C'
+ 'RESPECTIVELY')
END IF
CLOSE(UNIT=9,FILE='a: THERM.RES')
STOP
END
SUBROUTINE SOLAR(EXP,M1,AQSOL,AG)

C THIS SUBROUTINE PREDICTS THE NECESSARY PARAMETERS, WHICH ARE USED TO COMPUTE THE DIRECT SOLAR GAIN FROM GLASS AREA.

DEFINITION OF VARIABLES:

AQSOL = solar heat gain through glass in January, W/m²
JQSOL = solar heat gain through glass in July, W/m²
M1 = slope of the linearized relation of direct solar gain from glass with outside air temperature

COMMON /GAIN/ JMSHGF,JSC,CLFTJ,AMSHGF,ASC,CLFTA,TJ,TJA
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC

REAL JMSHGF(16), AG(16), JSC(16), CLFTJ(16), AMSHGF(16),
     ASC(16), CLFTA(16), JPPS, APPS, TJ, TJA, AF, JQSOL,
     SQSOL(16), AQSOL, MQSOL(16), M1, TPC, TPH

INTEGER EXP

JQSOL = 0.0
DO 20 I = 1,EXP
SQSOL(I)= (JMSHGF(I) * AG(I) * JSC(I) * CLFTJ(I) * JPPS)
     / (TJ * AF)
JQSOL = JQSOL + SQSOL(I)
20  CONTINUE
AQSOL = 0.0
DO 30 I = 1,EXP
MQSOL(I)= (AMSHGF(I) * AG(I) * ASC(I) * CLFTA(I) * APPS)
     / (TJA * AF)
AQSOL = AQSOL + MQSOL(I)
30  CONTINUE

M1 = (JQSOL - AQSOL)/(TPC-TPH)
RETURN
END
SUBROUTINE TRANS (EXP, M2, AQTS, AW, BSS)

C **************************************************
C THIS SUBROUTINE PREDICTS THE PARAMETERS NEEDED FOR
C COMPUTING SOLAR GAIN THROUGH OPAQUE WALLS .
C
C DEFINITION OF VARIABLES :

C AQTS = solar gain through opaque walls and roof in
      January, W/m^2 .
C BSS = dummy variable, if BSS = 0.0, subroutine computes
      AQTS for wall and roof both, if BSS = 1.0 , it
      computes only for wall.
C JQTS = solar gain through walls and glass in July, W/m^2
C
C M2 = slope of the linear relation between solar gain
      through walls and outside air temperature
C
C **************************************************

COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TII, TIC
COMMON /WALL/ UW, JCLTDW, KW, URC, JCLTDR, KR, ACLTDW,
+ ACLTDR, UG, ARP, ARI

REAL AW(16), UW(16), JCLTDW(16), KW(16), ARP, URC, JCLTDR,
+ KR, ACLTDW(16), ACLTDR, UG(16), JPPS, APPS, TPC, TPH, AF,
+ SQ1(16), QTSW1, QTSR1, JQTS, QTSW2, SQ2(16), QTSR2,
+ AQTS, M2

INTEGER EXP

C COMPUTE SOLAR COMPONENT THROUGH OPAQUE WALLS IN JULY.
QTSW1 = 0.0
DO 15 I = 1, EXP
   SQ1(I) = (AW(I) * UW(I) * JCLTDW(I) * KW(I) * JPPS)/AF
   QTSW1 = QTSW1 + SQ1(I)
15 CONTINUE
IF (BSS .EQ. 0.0) THEN
   C COMPUTE QTS FOR ROOF FOR JULY.
   QTSR1 = (ARP * URC * JCLTDR * KR * JPPS)/AF
ELSE
   QTSR1 = 0.0
END IF
JQTS = QTSW1 + QTSR1

C COMPUTE SOLAR COMPONENT THROUGH OPAQUE WALLS IN JANUARY.
QTSW2 = 0.0
DO 20 I = 1, EXP
SQ2(I) = (AW(I) * UW(I) * ACLTDW(I) * KW(I) * APPS)/AF
QTSW2 = QTSW2 + SQ2(I)
20 CONTINUE
IF (BSS .EQ. 0.0) THEN
C COMPUTE QTS FOR ROOF IN JANUARY.
QTSR2 = (ARP * URC * ACLTDR * KR * APPS)/AF
ELSE
QTSR2 = 0.0
END IF
AQTS = QTSW2 + QTSR2
M2 = (JOTS -AQTS)/(TPC-TPH)
RETURN
END
C
SUBROUTINE CONDUC(EXP,M3,AG,AW,BSS,M4)
C ********************************************************************
C *
C THIS SUBROUTINE PREDICTS THE TRANSMITED LOAD DUE TO *
C CONDUCTION THROUGH OPAQUE WALLS, ROOF AND GLASS. *
C *
C DEFINITION OF VARIABLES: *
C *
C M3 = conduction through walls and glass, W/m² degree C *
C M4 = conduction load through roof, W/m² degree C *
C QG = conduction through glass, W/m² *
C QR = conduction through roof, W/m² *
C QW = conduction load through walls, W/m² *
C ********************************************************************
C
COMMON /GAIN/ JMSHGF,JSC,CLFTJ,AMSHGF,ASC,CLFTA,TJ,TJA
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC
COMMON /WALL/ UW,JCLTDW,KW,URC,JCLTDR,KR,ACLTDW,
+ ACLTDR,UG,ARP,ARI
C REAL JMSHGF(16),AG(16),JSC(16),CLFTJ(16),AMSHGF(16),ASC(16),
+ CLFTA(16)
REAL AW(16), UW(16),JCLTDW(16),KW(16),JCLTDR,ACLTDW(16),
+ UG(16),QW, SQ(16), QG,URC,ARP,AF,QR,M3,M4,SQG(16)
INTEGER EXP
C
QG = 0.0
DO 10 I = 1, EXP
SQG(I) = (AG(I)*UG(I))/AF
QG = QG+SQG(I)
10 CONTINUE
CONTINUE
QW = 0.0
DO 20 I = 1, EXP
SQ(I) = (AW(I) * UW(I))/AF
QW = QW + SQ(I)
20 CONTINUE
IF (BSS .EQ. 0.0) THEN
QR = (ARP * URC)/AF
ELSE
QR = 0.0
END IF
M3 = QW + QG
M4 = QR
RETURN
END

SUBROUTINE INTL(TSOC, TSUN, TLOC, AZ, POCC, FUNOC)

This subroutine calculate the interior load due to lights, equipment, and occupants.

Definition of variables:

EQU = interior load due to equipment for occupied period, W/m²
EQUN = interior load due to equipment for unoccupied period, W/m²
LI = interior load due to lights for occupied period, W/m²
LIUN = interior load due to lights for unoccupied period, W/m²
PEOL = interior latent load due to people, W/m²
PEOS = interior sensible load due to people, W/m²
TLOC = total latent heat produced during occupied period, W/m²
TSOC = sensible heat produced during occupied period, W/m²
TSUN = sensible heat produced during unoccupied period, W/m²
COMMON /BBB/ AVEL, WPMSL, HF, AVEE, WPMSE, DEN, QS, QL,
+ AVELUN, WPMLUN, WPMEUN, AVEUN
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC

REAL AVEL, WPMSL, AZ, HF, AVEE, WPMSE, DEN, QS, QL, AVELUN,
+ WPMLUN, AVEUN, WPMEUN, AF, LI, EQU, PEOS, PEOL, TSOC,
+ TLOC, LIUN, EQUN, TSUN
INTEGER POC, PUNOC

IF (POCC .EQ. 1) THEN
LI = (AVEL*WPMSL*AZ*HF)/AF
EQU = (AVEE * WPMSE * AZ * HF)/AF
PEOS = ((DEN/100) * QS * AZ*HF)/AF
PEOL = (DEN * QL * AZ)/AF
TSOC = LI + EQU + PEOS
TLOC = PEOL
END IF
IF (PUNOC .EQ. 1) THEN
LIUN = (AVELUN * WPMLUN * AZ * HF)/AF
EQUN = (AVEUN * WPMEUN * AZ *HF)/AF
TSUN = LIUN + EQUN
ELSE
TSUN = 0.0
END IF
RETURN
END

SUBROUTINE IZONE(MI, AQTSR, QRI)

***********************************************************************
C THIS SUBROUTINE PREDICTS THE NECESSARY PARAMETERS NEEDED *
C TO COMPUTE THE INTERIOR ZONE DIVERSIFIED LOAD *
C DEFINITION OF PARAMETERS:

AQTSR = solar gain through the roof of interior zone in *
    January, W/m2 *
JQTSR = solar gain through the roof of interior zone in *
    July, W/m2 *
MI = slope of the linear relation between solar gain *
    and outside air temperature for roof *
QRI = conduction load from the roof of interior zone, *
    W/m2 degree C *
***********************************************************************
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC
COMMON /WALL/ UW, JCLTDW, KW, URC, JCLTDR, KR, ACLTDW,
+ ACLTDR, UG, ARP, ARI
REAL UW(16), JCLTDW(16), KW(16), ACLTDW(16), UG(16),
+ ARI, URC, JCLTDR, KR, JPPS, AF, ACLTDW, APPS, MI,
+ AQTSR, QRI, JQTSR, TPC, TPH
C
JQTSR = (ARI * URC * JCLTDR * KR * JPPS)/AF
AQTSR = (ARI * URC * ACLTDR * KR * APPS)/AF
C COMPUTE SLOPE FOR LINEARIZED SOLAR CONTRIBUTION FROM ROOF
MI = (JQTSR-AQTSR)/(TPC-TPH)
C COMPUTE SLOPE FOR LINEARIZED CONDUCTION FROM ROOF
QRI = (ARI*URC)/AF
RETURN
END
C
SUBROUTINE HLOAD(QHC,BT,TI,TSP,N,VIP,VII,TSI,PN,QLW,QLR,
+ QLI,QLV)
C ***************************************************************
C THIS SUBROUTINE SIMULATE HOURLY BASEBOARD HEATING LOAD *
C OF THE BUILDING FOR EACH TEMPERATURE BIN *
C DEFINITION OF VARIABLES : *
C FQH = sensible load due to infiltration, W/m2 *
C QSOL= solar heat gain through glass area of perimeter *
C , W/m2 *
C QT = heat loss by conduction through wall and glass *
C area, W/m2 *
C QTC = hourly baseboard heating load for occupied and *
C unoccupied periods for both zones, W/m2 *
C QTI = hourly baseboard heating load for interior zone *
C at each bin temperature, W/m2 *
C QTP = hourly baseboard heating load for perimeter zone *
C at each bin temperature, W/m2 *
C QTR = heat loss by conduction through roof of the *
C perimeter zone, W/m2 *
C QTS = solar heat gain through opaque walls, W/m2 *
C QTV = sensible load due to ventilation, W/m2 *
C ***************************************************************
C COMMON /LOAD/M1,AQSOL,M2,M3,M4,AQTS,MI,AQTSR,QRI,PZ,IZ
COMMON /TEMP/JPPS,APPS,TPC,TPH,AF,TSA,THI,THC
COMMON /INFIL/ FPH, FIH, FIC

REAL BT(30), QHC(30), TI, TSP, VIP, VII, TSI, M1, AQSOL, M2, M3, AQTS,
+       M1, AQTSR, QR, TPH, AF, QSOL, QTS, QTP(30), QTSI, QTCI, QTIV,
+       QTI(30), TII, TIC, FPH, FIH, FIC, FB, FQH, QLW(40), QLR(40),
+       QLI(40), QLV(40), M4

INTEGER N, PZ, IZ

C INITIALIZE THE VARIABLES.
QSOL = 0.0
QTS = 0.0
QT = 0.0
QTV = 0.0
QTSI = 0.0
QTCI = 0.0
QTIV = 0.0
DO 30 I = 1, N
IF (PZ .NE. 1) GO TO 10
QSOL = M1 * (BT(I) - TPH) + AQSOL
QTS = M2 * (BT(I) - TPH) + AQTS
QT = M3 * (BT(I) - TI)
QTR = M4 * (BT(I) - TI)

C SENSIBLE LOAD DUE TO INFILTRATION.
IF (BT(I) .LE. TIH) THEN
FB = FIH + ((FPH - FIH) / (TIH - TPH)) * (TIH - BT(I))
END IF
IF (BT(I) .GT. TIH) THEN
FB = FIC + ((FIH - FIC) / (TIC - TIH)) * (TIC - BT(I))
END IF
IF (BT(I) .GT. TIC) FB = 0.0
FQH = 1.232 * FB * (TI - BT(I))
IF (FQH .LE. 0.0) FQH = 0.0

C LOAD DUE TO VENTILATION.
IF (PN .EQ. 1.0) THEN
QTV = 1.232 * VIP * (TI - TSA)
END IF
IF (PN .EQ. 2.0) THEN
QTV = 1.232 * VIP * (TI - BT(I))
END IF

C HOURLY HEATING LOAD FOR PERIMETER ZONE FOR EACH BIN TEMP.
QTP(I) = -1.0 * (QSOL + QTS + QT + QTR + TSP) + QTV + FQH
IF (QTP(I) .LE. 0.0) THEN
QTP(I) = 0.0
END IF
GO TO 15
10 QTP(I) = 0.0
Qt = 0.0
QTR= 0.0
FQH= 0.0
QTV= 0.0
15 IF (IZ .NE. 1) GO TO 20
C SOLAR CONTRIBUTION THROUGH OPAQUE ROOF FOR INTERIOR ZONE.
QTSI = MI*(BT(I)-TPH)+AQTSR
QTCI = QRI*(BT(I)-TI)
IF(PN .EQ. 1.0) THEN
QTIV = 1.232*VII*(TI-TSA)
ELSE
QTIV = 0.0
END IF
C HOURLY HEATING LOAD FOR INTERIOR ZONE FOR EACH BIN TEMP.
QTI(I) = -1.0*(QTSI+QTCI+TSX)+QTIV
IF(QTI(I) .LE. 0.0) THEN
QTI(I) = 0.0
END IF
GO TO 25
20 QTI(I) = 0.0
QTCI = 0.0
QTIV = 0.0
C HOURLY HEAT LOAD DURING OCCUPIED AND UNOCCUPIED PERIOD
C FOR BOTH ZONES, w/m2.
25 QHC(I) = QTP(I) + QTI(I)
C HOURLY HEAT LOSSES FROM HOUSE WALL AND ROOF AREA, AND
C DUE TO INFILTRATION, AND VENTILATION AIR, kWh.
QLW(I) = (-1*QT*AF)/1000.
IF (QLW(I) .LE. 0.0) QLW(I) = 0.0
QLR(I) = -1*(QTR+QTCI)*AF/1000.
IF(QLR(I) .LE. 0.0) QLR(I) = 0.0
QLI(I) = FQH*AF/1000.
QLV(I) = (QTV+QTCI)*AF/1000.
30 CONTINUE
RETURN
END
C
SUBROUTINE BASE(DM,HQT,QBD,BSWG,EXP,BT,N,QB,TGW,TGF)
C ***************************************************************
C *
C THIS SUBROUTINE SIMULATE BELOW GRADE AND ABOVE GRADE *
C BASEMENT HEATING LOAD *
C
DEFINITION OF VARIABLES:

QB = hourly above grade + below grade heating load at each bin temperature, W/m²
QBD = design heat loss from below grade basement, W
QCON = heat loss by conduction through above grade basement walls and glass
QSOL = solar heat gain through glass area of above grade basement wall, W/m²
QTS = solar heat gain through above grade opaque walls of basement, W/m²
QTP = hourly above grade basement heating load against each bin temperature, W/m²

COMMON /MENT/D, W, L, KS, ROW, RW, RF, TA, BA, NI, TB, ABW, ABF, ABG, + ABWG, TMM
COMMON /TEMP/ JPPS, APPS, TPC, TPH, AF, TSA, TIH, TIC

REAL D, W, L, KS, ROW, ALPHA, RW, RF, TA, BA, NI, TB, ABW, ABF, DM (20), + QBD, ABG (8), ABWG (8), M1, M2, M3, M4, BT (30)
REAL C1, C2, C3, OCW, C4, C5, C6, C7, C8, FWD, OCF, UBW, UBF, THETA, FO, + BGW, PHEW, BGF, PHEF, NA, N1, N2, TGW (12), TGF (12), QW (20), + QE (20), HQT (20), QTP (30), QB (30), TMM (12)

INTEGER N, BSWG, EXP

IF (BSWG .EQ. 1) THEN
COMPUTE THE SOLAR GAIN & HEAT TRANSFER THROUGH CONDUCTION FOR THE ABOVE GRADE BASEMENT WALL .
BSS = 1.0
CALL SOLAR (EXP, M1, AQSOL, ABG)
CALL TRANS (EXP, M2, AQTS, ABWG, BSS)
CALL CONDUC (EXP, M3, ABG, ABWG, BSS, M4)
ELSE
GO TO 7
END IF
DO 5 I = 1, N

SOLAR HEAT GAIN THROUGH GLASS OF BASEMENT WALL.
QSOL = M1*(BT(I) - TPH) + AQSOL
SOLAR HEAT GAIN THROUGH OPAQUE WALLS OF BASEMENT.
QTS = M2*(BT(I) - TPH) + AQTS
HEAT GAIN BY CONDUCTION THROUGH WALLS & GLASS.
QCON = M3*(BT(I) - TB)
C  HOURLY BASEMENT HEATING LOAD FROM ABOVE GRADE WALL, w/m2.
QTP(I) = (-1.0*(QSOL+QTS+QCON))
5 CONTINUE
7 CONTINUE
C *********************************************************************
C * THE NEXT PART OF SUBROUTINE COMPUTES THE HEAT LOSS *
C * THROUGH BELOW GRADE BASEMENT WALL. *
C *********************************************************************
C
C COMPUTE OVERALL CONDUCTANCE VALUES FOR WALL & ROOF
CI = -0.23*LOG((D/(RF*KS))+0.0078)+3.3
C2 = 0.1584
C3 = -2.568+0.176*LOG((D/(RF*KS))+0.0078)
OCW = CI*((D/(RW*KS))**C2)+C3
C
C4 = 0.029*LOG((D/(RW*KS)))+0.63)-0.45
C5 = -0.27
C6 = -0.055*LOG((D/(RW*KS)))+0.63)+0.809
C7 = 0.3764*(W/D)**(-1.02)-0.0832
C8 = ((-0.0968*(W/D)**(-0.83)+0.0298)*
     + LOG(D/(RW*KS))+1.61*(W/D)**(-0.39)+0.08
FWD = C7*LOG(D/(RF*KS))+C8
OCF = (C4*(D/(RF*KS))**C5+C6)*FWD
UBW = (OCW*KS)/D
UBF = (OCF*KS)/D
C CALCULATE THE FOURIER MODULUS FO
ALPHA = (KS/ROW)
THETA = (365.0*24.0*3600.0)
FO = (ALPHA*THETA)/D**2.0
C CALCULATE WALL AMPLITUDE AND PHASE LAG.
BGW = (-0.035*FO**(-0.37)+1.01)*BA
PHEW = 22.0*FO**(-0.54)-0.68
C CALCULATE FLOOR AMPLITUDE AND PHASE LAG.
BGF = (-0.73*FO**(-0.172)+1.12)*BA
PHEF = 289.0*FO**(-0.104)-176.0
C CALCULATE WALL GROUND & FLOOR GROUND TEMPERATURE FOR THE
C MONTHS OF JANUARY TO DECEMBER.
C INITIALIZE THE VARIABLES
NA = 1.0
N1 = 0.0
N2 = 1.0
DO 10 I = 1,12
N1 = N1+NA
N2 = N2+DM(I)
TGW(I) = TA - \left(\frac{BGW \times (365.0^{2.0})}{(2.0 \times 3.1416 \times (N2-N1) \times 360.0)}\right) \\
+ \cos\left(\frac{(N2-N1)/365.0 \times 360.0 - PHEW}{180.0}\right) \\
- \cos\left(\frac{(N1-N2)/365.0 \times 360.0 - PHEW}{180.0}\right)

\[C\]

TGF(I) = TA - \left(\frac{BGF \times (365.0^{2.0})}{(2.0 \times 3.1416 \times (N2-N1) \times 360.0)}\right) \\
+ \cos\left(\frac{(N2-N1)/365.0 \times 360.0 - PHEF}{180.0}\right) \\
- \cos\left(\frac{(N1-N2)/365.0 \times 360.0 - PHEF}{180.0}\right)

NA = DM(I)

10 CONTINUE

C CALCULATE THE HOURLY HEAT LOSS FROM BASEMENT WALL AND FLOOR
C FOR THE MONTHS OF JANUARY TO DECEMBER.

QBD = 0.0
DO 20 I = 1,12
QW(I) = UBW*ABW*(TB-TGW(I))
QF(I) = UBF*ABF*(TB-TGF(I))
C SUM UP THE HOURLY HEAT LOSSES FROM WALL AND FLOOR
HQT(I) = QW(I)+QF(I)
IF( HQT(I) .LE. 0.0) HQT(I) = 0.0
C DESIGN HEAT LOSS (WATTS) FROM THE BASEMENT.
QBD = MAX(HQT(I),QBD)
20 CONTINUE

C DEVELOP LINEAR RELATION BETWEEN AVERAGE OUTDOOR TEMP.
C AND HEAT LOSS FROM BELOW GRADE BASEMENT WALL AND FLOOR.

SXS = 0.0
SX = 0.0
SY = 0.0
SXY = 0.0
DO 25 I = 1,12
SXS = SXS+TMM(I)**2.
SX = SX+TMM(I)
SY = SY+HQT(I)/AF
SXY= SXY+TMM(I)*HQT(I)/AF
25 CONTINUE

C REGRESSION PARAMETERS.
B = (SXY-(SX*SY)/12.)/(SXS-(SX**2.)/12.)
XBAR = SX/12.
YBAR = SY/12.
BO = YBAR-B*XBAR
C HOURLY BASEMENT HEATING LOAD (ABOVE GRADE + BELOW GRADE), w/m2.
DO 30 I = 1,N
QB(I) = QTP(I) + (BO+B*BT(I))
IF(QB(I) .LE. 0.0) QB(I) = 0.0
30 CONTINUE
RETURN
SUBROUTINE DESIGN(TID, URC, QBD, QDHL, TB, TABG, TABWG)

C ***************************************************************
C *  
C THIS SUBROUTINE PREDICTS THE DESIGN HEATING LOAD OF  
C THE ENVELOPE  
C *  
C DEFINITION OF VARIABLES:  
C *********************************************  
C *  
C QBGD = design heat loss through above grade basement  
C     glass area, W  
C *  
C QBWD = design heat loss through above grade basement  
C     wall, W  
C *  
C QDHL = design heating load of the building, W  
C *  
C QGD = design heat loss by conduction through glass, W  
C *  
C QLID = design latent heat loss due to infiltration, W  
C *  
C QPD = design heat loss through floor perimeter, W  
C *  
C QRD = design heat loss by conduction through roof, W  
C *  
C QSID = design sensible heat loss due to infiltration, W  
C *  
C QWD = design heat loss by conduction through walls, W  
C *  
C ***************************************************************
C
COMMON /DES/ ODT, AR, TAW, UWD, TAG, UGD, F2, P, VID, WID, WOD

REAL QBD, QDHL, TID, ODT, TAW, UWD, TAG, UGD, AR, URC, F2, P, VID,  
     WID, WOD, QWD, QGD, QRD, QPD, QSID, QLID  

QMD = TAW*UMD*(TID-ODT)  
IF(QMD .LE. 0.0) QMD=0.0  
QGD = TAG*UGD*(TID-ODT)  
IF(QGD .LE. 0.0) QGD = 0.0  
QRD = AR*URC*(TID-ODT)  
IF(QRD .LE. 0.0) QRD = 0.0  

QBWD = TABWG*UWD*(TB-ODT)  
IF(QBWD .LE. 0.0 ) QBWD = 0.0  
QBGD = TABG*UGD*(TB-ODT)  
IF(QBGD .LE. 0.0) QBGD = 0.0  

HEAT LOSS FROM THE FLOOR PERIMETER, W  
QPD = F2*P*(TID-ODT)  
IF(QPD .LE. 0.0) QPD=0.0  

SENSIBLE HEAT LOSS DUE TO INFILTRATION, W  
QSID = 1.232*VID*(TID-ODT)
IF (QSID .LE. 0.0) QSID = 0.0
C LATENT HEAT LOSS DUE TO INFILTRATION, W
QLID = 3012*VID*(WID-WOD)
IF (QLID .LE. 0.0) QLID = 0.0
C TOTAL DESIGN HEATING LOAD, W
QDHL = (QBD+QWD+QGD+QBD+QRD+QPD+QSID+QLID)
C NOTE: HERE QBD IS DESIGN HEAT LOSS FROM THE BASEMENT, IT
C IS CALCULATED IN SUBROUTINE BASE.
RETURN
END
C
SUBROUTINE SLOAD(N,QHC,FREQ,HQH,MQH,SQH,QB)
---------------------------------------------------------------------
C THIS SUBROUTINE SIMULATES THE HOURLY HEATING LOAD OF THE
C BUILDING AT EACH BIN TEMPERATURE AND ALSO COMPUTES
C MONTHLY AND SEASONAL HEATING LOAD REQUIREMENTS OF THE
C ENVELOPE

C DEFINITION OF VARIABLES:

C HQH = hourly heating load of the building at each bin
C temperature, kWh
C MQH = monthly heating load of the building, kWh
C SQH = seasonal heating load of the building, kWh

C **********************************************************************
C COMMON /TEMP/ OPPS,APPS,TPC,TPH,AF,TSA,TIH,TIC
REAL QHC(30),FREQ(12,30),SQH,AF,HQH(30),MQH(12),QB(30)
INTEGER N
C
DO 10 J = 1,N
C HOURLY HEATING LOAD OF THE BUILDING FOR OCCUPIED AND
C UNOCCUPIED PERIODS FOR JTH TEMP. BIN, kWh.
HQH(J) = (QHC(J)+QB(J))*AF/1000.
10 CONTINUE
C
SQH = 0.0
DO 20 I = 1,12
MQH(I) = 0.0
DO 15 J = 1,N
C MONTHLY HEATING LOAD OF THE BUILDING FOR OCCUPIED AND
C UNOCCUPIED PERIODS, kWh.
MQH(I) = MQH(I) + HQH(J)*FREQ(I,J)
20 CONTINUE
PART I. APPENDIX B. A TYPICAL OUTPUT OF COMPUTER PROGRAM FOR THERMAL ANALYSIS OF BUILDING ENVELOPE
OUTPUT OF
MICRO-COMPUTER PROGRAM FOR THERMAL LOAD
ANALYSIS OF RESIDENCES (THERM)

VARIOUS HOURLY HEAT LOSSES FOR OCCUPIED PERIOD

<table>
<thead>
<tr>
<th>BIN TEMP. °C</th>
<th>WALL kWh</th>
<th>ROOF kWh</th>
<th>INFILTR kWh</th>
<th>VENT kWh</th>
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<tr>
<td>41.7</td>
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HEATING LOAD FOR OCCUPIED PERIOD AGAINST VARIOUS TEMPERATURE BINS

<table>
<thead>
<tr>
<th>BIN TEMP °C</th>
<th>BASEBOARD w/m²</th>
<th>BASEMENT w/m²</th>
<th>HOURLY LOAD kWh</th>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>38.92</td>
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<td>0.00</td>
<td>0.00</td>
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<tr>
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<td>0.00</td>
</tr>
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<td>33.36</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>30.58</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>27.80</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>25.02</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<tr>
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<td>0.26</td>
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<td>72.43</td>
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<tr>
<td>-36.14</td>
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<td>76.33</td>
<td>54.77</td>
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</table>
MONTHLY HEATING LOAD OF THE BUILDING

<table>
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<tr>
<th>MONTH</th>
<th>HEATING LOAD kWh</th>
</tr>
</thead>
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<td>10157.27</td>
</tr>
<tr>
<td>FEB</td>
<td>10668.62</td>
</tr>
<tr>
<td>MARCH</td>
<td>6536.87</td>
</tr>
<tr>
<td>APRIL</td>
<td>3050.07</td>
</tr>
<tr>
<td>MAY</td>
<td>1085.29</td>
</tr>
<tr>
<td>JUNE</td>
<td>186.48</td>
</tr>
<tr>
<td>JULY</td>
<td>14.05</td>
</tr>
<tr>
<td>AUG</td>
<td>79.11</td>
</tr>
<tr>
<td>SEP</td>
<td>939.17</td>
</tr>
<tr>
<td>OCT</td>
<td>2627.06</td>
</tr>
<tr>
<td>NOV</td>
<td>7774.50</td>
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<tr>
<td>DEC</td>
<td>17295.51</td>
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</table>

SEASONAL HEATING LOAD OF BUILDING = 60414.0 kWh

DESIGN HEATING LOAD FOR BUILDING = 37576.57 W

MONTHLY BELOW GRADE BASEMENT PARAMETERS

<table>
<thead>
<tr>
<th>MONTH</th>
<th>AVE TEMP °C</th>
<th>TGW °C</th>
<th>TGF °C</th>
<th>AVE HEAT LOSS WATTS</th>
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<tbody>
<tr>
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<td>2</td>
<td>-0.1</td>
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<td>2361.4</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>-3.2</td>
<td>10.4</td>
<td>1917.3</td>
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</table>

NOTE: TGW & TGF STAND FOR EFFECTIVE GROUND WALL AND GROUND FLOOR TEMPERATURE IN DEGREE C RESPECTIVELY
Infiltration is the uncontrolled flow of air through openings in the building envelope driven by temperature differences (stack effect) and pressure. Air infiltration may be measured directly using the tracer dilution method. The fan pressurization method provides an indirect way to relate the infiltration rate to the leakage area of a structure.

For this study the leakage area of the house was measured using the fan pressurization technique or blower door method, and specific infiltration was predicted using the procedure presented in ASHRAE Handbook (1985).

To reduce the variations in leakage area measurements, both pressurization and depressurization measurements were made. The blower door test was conducted at a wind speed of 1.5 m/s and outside temperature of 14.5 °C. The preferred test conditions are wind speed of 0 to 2 m/s and an outside temperature from 5 to 35 °C (ASTM E779-87).

Table C.1 presents the results of the blower door test. The average measured leakage was plotted against the corresponding pressure differences on a log-log plot to determine the slope $n$ (Figure C.1). The coefficient $C$ was determined using the following least square technique.
Table C.1. Blower Door Test Data

<table>
<thead>
<tr>
<th>Pressure Differential (pa)</th>
<th>Flow Rate During Pressurization (L/s)</th>
<th>Flow Rate During Depressurization (L/s)</th>
<th>Average (L/s)</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>700.0</td>
<td>843.75</td>
<td>771.88</td>
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<td>20</td>
<td>1230.0</td>
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<td>1450.0</td>
<td>1450.00</td>
<td>1450.00</td>
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<tr>
<td>40</td>
<td>1737.5</td>
<td>1693.75</td>
<td>1765.60</td>
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<tr>
<td>50</td>
<td>2012.5</td>
<td>1918.75</td>
<td>1965.60</td>
</tr>
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</table>
Figure C.1. Log of air flow rate vs log of differential pressure for blower door test of McNay Research Center residence

Slope = 0.575
\[ Q = C^* (dp)^n \]  \[ \text{[1]} \]

where

\[ Q = \text{flow rate, L/s} \]
\[ dp = \text{differential pressure, pa} \]

By taking the log of equation 1 on both sides;

\[ \log Q = \log C + n \log dp \]  \[ \text{[2]} \]

By substituting the values of \( dp \) and \( Q \) the coefficient \( C \) was determined as follows:

\[ \log C = \log 1450 - 0.575 \log 30 \]
\[ \log C = 2.312 \]
\[ C = 205.127 \text{ L/s} \]
\[ C = 0.20513 \text{ m}^3/\text{s} \]

The correlation coefficient was calculated as 0.9988 and the flow rate at 4 pa was determined as:

\[ Q = 205.127 \times (4)^{0.575} \]
\[ = 455.205 \text{ L/s} \]
\[ = 0.4552 \text{ m}^3/\text{s} \]

Finally the effective leakage area was calculated from the leakage coefficient \( C \) and the exponent \( n \), at the reference pressure difference of 4 pa, and the air density (1.2 kg/m\(^3\)) at the indoor temperature and pressure as follows:

\[ L = C \times (dp)^{(n-1/2)} \times (\text{den}/2)^{0.5} \]  \[ \text{[3]} \]
\[ = 0.205127 \times (4)^{0.577-0.5} \times (1.2/2)^{0.5} \]
Finally the specific infiltration was estimated by the following correlation (ASHRAE Handbook, 1985, p. 22.16):

\[ \frac{Q}{L} = [(A \times T + B \times V^2)]^{0.5} \quad [4] \]

where

\[ \frac{Q}{L} = \text{specific infiltration, m}^3/\text{h cm}^2 \]

\[ A = \text{stack coefficient, (m}^3/\text{h})^2 (\text{cm})^{-4} (^\circ\text{k})^{-1} \]

\[ T = \text{average indoor-outdoor temperature difference, } ^\circ\text{k} \]

\[ B = \text{wind coefficient, (m}^3/\text{h})^2 (\text{cm})^{-4} (\text{m/s})^{-2} \]

\[ V = \text{average wind speed measured at the local weather station for the time interval of interest, m/s} \]

For two story house having light local shielding; few obstructions, a few trees or small shed (ASHRAE Handbook, 1985, p. 22.17):

\[ A = 0.00376 \]

\[ B = 0.00421 \]

Using average wind speed 3.73 m/s (Nov. 89 to March 1990), the specific infiltration at various temperature bins was computed and tabulated as follows:
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<th>Outside temperature (°C)</th>
<th>Wind Speed (m/s)</th>
<th>Infiltration Rate L/s m²</th>
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PART I. APPENDIX D. LISTING OF COMPUTER PROGRAM BIN
C********************************************
C MICRO-COMPUTER PROGRAM TO CONVERT THE HOURLY
C WEATHER DATA TO VARIOUS TEMPERATURE BINS (BIN)
C
********************************************
C
C DEVELOPED AND PROGRAMMED AT IOWA STATE UNIV.,
C AMES, IOWA.
C
C **************************************************
C
REAL T(750),ABT(30),RH(750),WS(750),MDT(40)
INTEGER FR(30),SFR,NHM,NB,DH
CHARACTER*32 FLNM
WRITE(*,*) 'ENTER FILE NAME ='

DEFINITION OF VARIABLES:

ABT = average bin temperature, degree C
ARH = average relative humidity over the
   period of analysis, %
AT = average temperature over the period of
   analysis, degree C
AWS = average wind speed over the period of
   analysis, m/s
BTEMP = balance point temperature, degree C
DD  = heating degree days, degree C
FR  = number of hours in each temperature bin
NB  = number of temperature bins
NHM = number of hours of the period of analysis
MDT = mean daily temperature, degree C
RH  = hourly relative humidity, %
T   = hourly temperature, degree C
WS  = hourly wind speed, m/s
READ(*,'(A)') FLNM
OPEN(UNIT=8,FILE=FLNM,STATUS='OLD')
READ(8,*) NHM,NB,BTEMP
READ(8,*) (ABT(I), I=1,NB)
C
READ IN HOURLY TEMPERATURE, RELATIVE HUMIDITY, AND WIND SPEED
DO 30 I = 1,NHM
READ (8,20) T(I),RH(I),WS(I)
20 FORMAT(13X,F6.2,4X,F5.2,22X,F5.2)
30 CONTINUE
CLOSE(UNIT=8)
C
INITIALIZE THE VARIABLES
DO 40 1 = 1,NB
FR(I) = 0.0
40 CONTINUE
DO 100 I = 1,NHM
IF(T(I).LE.43.09.AND.T(I).GE.40.32) FR(1)=FR(1)+1
IF(T(I).LE.40.31.AND.T(I).GE.37.54) FR(2)=FR(2)+1
IF(T(I).LE.37.53.AND.T(I).GE.34.76) FR(3)=FR(3)+1
IF(T(I).LE.34.75.AND.T(I).GE.31.98) FR(4)=FR(4)+1
IF(T(I).LE.31.97.AND.T(I).GE.29.20) FR(5)=FR(5)+1
IF(T(I).LE.26.41.AND.T(I).GE.23.64) FR(7)=FR(7)+1
IF(T(I).LE.23.63.AND.T(I).GE.20.86) FR(8)=FR(8)+1
IF(T(I).LE.20.85.AND.T(I).GE.18.08) FR(9)=FR(9)+1
IF(T(I).LE.18.07.AND.T(I).GE.15.30) FR(10)=FR(10)+1
IF(T(I).LE.15.29.AND.T(I).GE.12.52) FR(11)=FR(11)+1
IF(T(I).LE. 9.73.AND.T(I).GE. 6.96) FR(13)=FR(13)+1
IF(T(I).LE. 6.95.AND.T(I).GE. 4.18) FR(14)=FR(14)+1
IF(T(I).LE. 4.17.AND.T(I).GE. 1.40) FR(15)=FR(15)+1
IF(T(I).LE.-1.40.AND.T(I).GE.-4.17) FR(17)=FR(17)+1
IF(T(I).LE.-4.18.AND.T(I).GE.-6.95) FR(18)=FR(18)+1
IF(T(I).LE.-6.96.AND.T(I).GE.-9.73) FR(19)=FR(19)+1
IF(T(I).LE.-9.74.AND.T(I).GE.-12.51) FR(20)=FR(20)+1
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IF(T(I).LE.-15.30.AND.T(I).GE.-18.07) FR(22)=FR(22)+1
IF(T(I).LE.-18.08.AND.T(I).GE.-20.85) FR(23)=FR(23)+1
IF(T(I).LE.-20.86.AND.T(I).GE.-23.63) FR(24)=FR(24)+1
IF(T(I).LE.-23.64.AND.T(I).GE.-26.41) FR(25)=FR(25)+1
IF(T(I).LE.-26.42.AND.T(I).GE.-29.19) FR(26)=FR(26)+1
IF(T(I).LE.-29.20.AND.T(I).GE.-31.97) FR(27)=FR(27)+1
IF(T(I).LE.-31.98.AND.T(I).GE.-34.75) FR(28)=FR(28)+1
IF(T(I).LE.-34.76.AND.T(I).GE.-37.53) FR(29)=FR(29)+1
DO 110 I = 1,NB
SFR = SFR + FR(I)
110 CONTINUE

OPEN (UNIT=9,FILE='A:BIN.RES')
WRITE(9,115)
115 FORMAT(10X,'BIN TEMP.',10X,'FREQ. OF OCCU.')
DO 130 I = 1,NB
WRITE(9,120) ABT(I),FR(I)
120 FORMAT(11X,F7.2,14X,I5)
130 CONTINUE

DO 150 I=1,NHM
ST = ST +T(I)
SRH= SRH+RH(I)
SWS= SWS+WS(I)
150 CONTINUE

AT = ST/NHM
ARH= SRH/NHM
AWS= SWS/NHM
WRITE(9,160) AT,ARH,AWS
160 FORMAT (//5X,'AVERAGE TEMPERATURE, C = ',F6.2/
+ 5X,'AVERAGE RELATIVE HUMIDITY, % = ',F5.2/
+ 5X,'AVERAGE WIND SPEED, M/SEC = ',F5.2)

C COMPUTE MEAN DAILY TEMPERATURE
WRITE(9,162)
162 FORMAT(10X,'DATE',10X,'MEAN TEMP.')
SUM = 0.0
JJ = 1.
DH = 24.
DO 170 I = 1,NHM
SUM = SUM+T(I)
IF (I .EQ. DH) THEN
MDT(JJ) = SUM/24.
WRITE(9,165) JJ,MDT(JJ)
165 FORMAT(10X,I4,10X,F7.2)
SUM = 0.0
DH = DH+24.
JJ = JJ+1
END IF
CONTINUE

COMPUTE HEATING DEGREE DAYS

DD = 0.0

DO 180 KK = 1, JJ
IF (MDT(KK) .LT. BTEMP) THEN
SSS = (MDT(KK) - BTEMP)
DD = DD + ABS(SSS)
END IF

180 CONTINUE

WRITE(9, 190) DD

190 FORMAT(/IOX, 'DEGREE DAYS = ', F10.2)

STOP

END
PART I. APPENDIX E. OCCURRENCE OF THE VARIOUS TEMPERATURE BINS FOR CHARITON AND DES MOINES, IOWA
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</tbody>
</table>
PART I. APPENDIX F. DETERMINITION OF THERMAL PROPERTIES OF THE HOUSE COMPONENTS

1. The thermal transmittance or U-factor is defined as the steady-state, thermal transmission of heat through defined surfaces of a unit of material for an established unit temperature difference on each side of the material. The thermal transmittance includes the added resistance of the boundary air films. The following conditions were assumed in calculating the U-factors:

   a. equilibrium or steady state heat transfer, disregarding effects of heat storage;
   b. surrounding surfaces at ambient air temperature;
   c. exterior wind velocity of 6.7 m/s for winter (surface R = 0.03 m² °c/w);
   d. inside air was assumed still with a thermal resistance, 0.12 m² °c/w;

   U-factors for walls and roof presented in Appendix G were computed from the actual material characteristics of the walls, windows, and roof of the house envelop of McNAY Memorial Research Center using the references (ASHRAE Handbook, 1985; McQuiston and Parker, 1988).

   2. Maximum Solar Heat Gain Factor (MSHGF) for the north, east, south, and west exposures was computed using Table 11 of ASHRAE Handbook (1985) for 41.01° north latitude.
3. The twenty four hour average solar components of cooling load temperature difference for walls and roof were taken from Table 7 (pp.28.13) of ASHRAE Handbook (1985) for north latitude of 41.01° for the months of July and January.

4. The twenty four hour sum of cooling load factor for each exposure in July and January were obtained from Table 8.14a (McQuiston and Parker, 1988) assuming medium weight construction, 50 to 100 mm concrete floor and group E wall.
The following specific data for THERM must be placed in six files on drive A and made accessible to the program at run time.

**DESIGN.DAT** hold the following parameters:

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Program Variable Name)</td>
<td>Value</td>
</tr>
<tr>
<td>First read in statement:</td>
<td></td>
</tr>
<tr>
<td>1. Indoor temperature for computing design load (TID), °c</td>
<td>25</td>
</tr>
<tr>
<td>2. total roof area (AR), m²</td>
<td>142.0</td>
</tr>
<tr>
<td>3. Combined heat transfer coefficient for roof and ceiling (URC), w/m² °c</td>
<td>0.364</td>
</tr>
<tr>
<td>4. Outdoor design temperature (ODT), °c</td>
<td>-23.0</td>
</tr>
<tr>
<td>5. total wall area (TAW), m²</td>
<td>216.59</td>
</tr>
<tr>
<td>6. Heat transfer coefficient of walls for design load calculations (UWD), w/m² °c</td>
<td>1.47</td>
</tr>
<tr>
<td>7. Total glass area (TAG), m²</td>
<td>65.39</td>
</tr>
<tr>
<td>8. Heat transfer coefficient of glass for design load calculations (UGD), w/m² °c</td>
<td>2.84</td>
</tr>
<tr>
<td>9. Heat loss coefficient (F2), w/m² °c per meter of perimeter</td>
<td>1.61</td>
</tr>
<tr>
<td>10. Perimeter length, m</td>
<td>59.45</td>
</tr>
<tr>
<td>11. Design volume of outdoor air (infiltration)</td>
<td></td>
</tr>
</tbody>
</table>
12. Humidity ratio of indoor air (WID),
   kg H₂O/kg air 0.008
13. Humidity ratio of outdoor air (WOD),
   kg H₂O/kg air 0.0025
14. Total glass area of above grade basement (TABG), m² 8.15
15. Total wall area of above grade basement (TABWG), m² 42.26

End of DESIGN.DAT

EXPO.DAT holds the following input parameters

First read in statement:
1. Perimeter zone code (PZ) 1.0
2. Interior zone code (IZ) 0.0
3. Occupied period code (POCC) 1.0
4. Unoccupied period code (PUNOC) 0.0
5. Basement code (BS) 1.0
6. Basement walls above grade code (BSWG) 1.0

Second read in statement:
1. Number of different glass exposures (EXP) 4.0
2. Percent possible sunshine in July (JPPS) 0.82
3. Percent possible sunshine in January (APPS) 0.51
4. Mid point of the highest temperature bin occurring at the location (TPC), °c 38.6
5. Mid point of the lowest temperature bin occurring at the location (TPH), °c -33.36
6. Mid point of the temperature bin where the net building loads change from heating to cooling loads (TIH), °c 11.1
7. Lowest temperature bin in which the envelope imposes cooling load on the building (TIC), °c 25.0
8. Building conditioned floor area (AF), m² 118.0
9. Run time for air conditioned system in July (TJ), hrs 24.0
10. Run time for air conditioned system in January (TJA), hrs 24.0
11. Supply air temperature, °c 0.0
12. Inside temperature during occupied period (TIOCC), °c 21.5

Third read in statement:
1. Area of perimeter zone (APZ), m² 118.0
2. Heat factor (HF) (converting unit of load to watts) 1.0
3. Density (DEN), person/100 m² 2.54
4. Sensible heat produced per person (QS), w 74.7
5. Latent heat produced per person (QL), w 74.7
6. Average usage of light in perimeter zone for
   occupied period (AVEL) 0.30
7. Average usage of equipment in perimeter zone for
   occupied period (AVEE) 0.51
8. Sensible light load (WPMSL), w/m² 12.37
9. Equipment load for occupied period
   (WPMSE), w/m² 14.62
10. Ventilation rate for occupied period for perimeter
    zone (VIQCCP), L/s.m² 0.0
11. Amount of infiltration air entering the building
    at TIH (FIH), L/s.m² 1.34
12. Amount of infiltration air entering the building
    at TPH (FPH), L/s.m² 2.15
13. Amount of infiltration air entering the building
    at TIC (FIC), L/s.m² 0.943

IF UNOCCUPIED PERIOD EXISTS THEN FOLLOWING DATA ARE ALSO NEEDED

Fourth read in statement:
1. Inside temperature during unoccupied period (TIUN), °c
2. Average usage of light in perimeter zone for unoccupied
   period (AVELUN)
3. Average usage of equipment in perimeter zone for
   unoccupied period (AVEUN)
4. Lights load for unoccupied period (WPMLUN), w/m²
5. Equipment load for unoccupied period (WPMEUN), w/m²
6. Ventilation rate for unoccupied period for
   perimeter zone (VIUNP), L/s m²

------------------------ End of EXPO.DAT ------------------------

BASE.DAT holds the following input parameters

First read in statement:
1. Depth of basement (D), m 1.57
2. Width of basement (W), m 10.03
3. Length of basement (L), m 10.48
4. Soil Thermal Conductivity (KS), w/m °c 1.59
5. Soil volumetric thermal capacity (ROW), J/m³ °c 2.93E+6
6. Overall R-value of basement walls (RW), m² °c/w 0.565
7. Overall R-value of basement floor (RF), m² °c/w 0.283
8. Annual average temperature (TA), °c 9.4
9. The day number of the year on which the ambient
   temperature curve crosses the mean value (NI) 110.0
10. Basement temperature (TB), °c 21.0
11. Area of basement walls (ABW), m² 64.4
12. Area of basement floor (ABF), m² 105.11

Second read in statement:
1. Array: Days of the months of the year (DM)
Third read in statement:

1. Array: Mean monthly temperature (TMM), °C

Fourth read in statement:

1. Array: Above grade basement glass area for each exposure (ABG), m² 1.46, 1.79, 2.47, 2.45 for exposure N, E, S, W res.

Fifth read in statement:

1. Array: Above grade basement wall area for each exposure (ABWG), m² 11.98, 8.42, 12.11, 9.75 for exposure N, E, S, W res.

---------------------- End of BASE.DAT ----------------------

GLASS.DAT hold following input parameters

First read in statement:


Second read in statement:

1. Array: Maximum solar heat gain factor for each exposure in January (AMSHGF) 60.75, 524.5, 799.5, 524.5 for N, E, S, W res.

Third read in statement:

Array: Glass area for each exposure (AG), m²

16.5, 14.5, 12.05, 22.34 for N, E, S, W res.

Fourth read in statement:

Array: overall heat transmission coefficient for glass (UG), w/m²°C 2.84, 2.84, 2.84, 2.84 for N, E, S, W res.

Fifth read in statement:
Array: shading coefficient of glass for each exposure in July (JSC) 0.85, 0.85, 0.85, 0.85

Sixth read in statement:
Array: shading coefficient for each exposure in January (ASC) 0.85, 0.85, 0.85, 0.85

Seventh read in statement:
Array: twenty-four hour sum of CLF for each exposure (CLFTJ) for July 11.38, 5.49, 6.42, 5.49

Eighth read in statement:
Array: twenty-four hour sum of CLF for each exposure (CLFTA) for January 11.38, 5.49, 6.42, 5.49

Ninth read in statement:
If interior zone exists then following data also needed

1. Area of interior zone (AIZ), m²
2. Roof area of interior zone (ARI), m²
3. Ventilation rate for occupied period for interior zone (VIOCCI), L/s m²
4. Ventilation rate for unoccupied period in interior zone (VIUNI), L/s.m²

--------------- End of GLASS.DAT  ---------------

WALL.DAT holds the following input data

First read in statement:
Array: opaque wall area for each exposure (AW), m²
Second read in statement:
Array: overall heat transfer coefficient for wall (UW), w/m²°C

Third read in statement:
Array: color correction factor (KW)

Fourth read in statement:
Array: twenty-four hour average solar component of CLTD for wall in July (JCLTDW)

Fifth read in statement:
Array: twenty-four hour average solar component of CLTD for wall in January (ACLTDW)

Values in above arrays are given below.

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<tr>
<th>Exposure</th>
<th>AW</th>
<th>UW</th>
<th>KW</th>
<th>JCLTDW</th>
<th>ACLTDW</th>
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<td>42.35</td>
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</table>

Sixth read in statement:
Color correction factor for roof (KR) 0.75

Twenty-four hour sum of CLTD for roof in July (JCLTDR) 11.12

Twenty-four hour sum of CLTD for roof in January (ACLTDR) 1.32

------------------------ End of WALL.DAT ------------------------
BIN.DAT holds the following input data

First read in statement:

Total number of bins (N)

Second read in statement:

Array: Bin temperature (BT), °c (see Appendix E)

Third read in statement:

Array: Frequency of occurrence of each bin temperature for occupied period (FREQOC), hrs (see Appendix E)

If unoccupied period exist then following data are also needed

Fourth read in statement:

Array: frequency of occurrence of each bin temperature for unoccupied period (FREQUN), hrs

------------------------ END OF BIN.DAT ------------------------
PART II. APPENDIX A. LISTING OF SIMULATION PROGRAM FOR PREDICTING THE SEASONAL EFFICIENCY OF BIOFUELED BOILERS
SIMULATION PROGRAM FOR PREDICTING THE SEASONAL
EFFICIENCY OF BIOFUELED BOILERS

*************************************************************************
** DEVELOPED AND PROGRAMMED AT IOWA STATE UNIV., IOWA **
** AMES, IOWA ****
** ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) **
** *AUTHOR: MUNIR AHMAD, 1990 **
** *
** *
** *
** DEFINITION OF REAL INPUT VARIABLES: **

AXDIRT = percent dirt content on as fired basis
AXH20 = percent water content on as fired basis
AHHV = higher heating value of fuel on as fired basis, kJ/kg
AVTD = average temperature difference between outside air temperature & boiler room temperature, degree c
BT = bin temperature, degree c
BRT = boiler room temperature, degree c
CAIR = specific heat of air, kJ/kg degree c
CDIRT = specific heat of dirt in the fuel, kJ/kg degree c
CPW = specific heat of boiler water, kJ/kg degree c
DELT = average temperature drop possible below maximum and minimum boiler temperature setting, degree c
DF = average off cycle draft factor for flue gas flow
FGA = flue gas analysis code, if FGA .eq. 1, analysis given, else not
FREQ = frequency occurrence of each bin temperature, hrs
HHV = higher heating value of fuel on oven dry basis, KJ/kg.
HQH = hourly heating load, kWh
IRWAFl = input rate of wood during on ONE period on as fired basis, Kg/hr
IRWAF2 = input rate of wood during on TWO period on as fired basis, kg/hr
IRWAF3 = input rate of wood during off period on as fired basis, kg/hr
LSOFF = off period sensible losses, %
LSON = on-cycle sensible losses, %
MFOFF = off-period flue gas mass flow rate, kg/sec.
MFON = on cycle flue gas mass flow rate, kg/sec.
MRA = code for mass rate of flue gases, if MRA = eq. 1, mass flow rate of flue gas is given, else not
MPBRT = maximum possible boiler room temperature, °C
MWBT = mass of water in the boiler, kg
N = total number of bins
N1 & N2 = dummy variables.
PEAON1 = percent excess air for on one period, %
PEAON2 = percent excess air for on two period, %
PEAOFF = percent excess air for off period, %
PEFF = part load efficiency, %
PFMOFF = mass flow rate of flue gases at discrete times during the off-period, kg/sec.
PPTOFF = flue gas temperature at discrete times during the off-period, degree C.
PFTON = flue gas temperature at discrete times during the on period, degree C.
PPL = pipe losses, % of total hourly load
PRDL = radiation, and unaccountable losses from boiler, % of input energy
QINON1 = input rate of energy during on one period, kJ/sec
QINON2 = input rate of energy during on two period, kJ/sec
QINOFF = input rate of energy during off period, kJ/sec
QLCP1,2,OF = combustion material losses during on one, on two and off period respectively, %
QLLP1,2,OF = latent heat losses during on one, on two, and off period respectively, %
QLRP1,2,OF = radiation and convection losses during on one, on two, and off periods respectively, %
QLSP1,2,OF = sensible heat losses during on one, on two, and off period respectively, %
RTF = ratio of combustion air to stoichiometric air in the flue.
SPH = specific humidity of combustion air, kg of water per kg of dry air
SSEON1 = steady state efficiency during on one period, %
SSEON2 = steady state efficiency during on two period, %
SSEOFF = steady state efficiency during off period, %
TBMAX = maximum boiler temperature setting, degree c
TBMIN = minimum boiler temperature setting, degree c
TBMIN1 = minimum boiler temperature, below which its
operation is undesirable, degree c
TFOFF3 &
TFOFF4 = off-period flue gas temperature measured at
TIM3 & TIM4 respectively, degree c
TFOFF5 = minimum flue gas temperature during off period,
usually equal to the TFSS3
TFON1 &
TFON2 = on period flue gas temperature measured at TIM1
& TIM2 respectively, degree c
THEFO = the value of temperature difference defined as
(TFSS-TFON) at start up, degree c
TIM1-TIM5 = discrete times at which flue gas temperature
is measured, during ON1 and OFF period, sec
TIMINT = time interval at which temperature of flue gases
are predicted, sec
TIMON = on ONE time per cycle, sec
TIMOFF = off time per cycle, sec
TFSS1 = flue gas steady state temperature during on one
period, degree c
TFSS2 = flue gas temperature during on two period,
degree c
TFSS3 = flue gas temperature during off period, degree c
SAIFO = defined as (TFOFF(TIM3)-TFOFF(tim5))*exp(TIM3/
TAUOFF), degree c
SAIF5 = defined as (TFOFF(TIM5)-TRA), degree c
XASH = percent ash content on oven dry basis of fuel
XC = percent carbon content on bone dry basis of
fuel
XCOF1 = percent carbon CO present in dry flue gases
during on one period, %
XCOF2 = percent carbon CO present in dry flue gases
during on two period, %
XCOF3 = percent carbon CO present in dry flue gases
during off period, %
XCO2F1 = percent CO2 present in dry flue gases during
one period, %
XCO2F2 = percent carbon dioxide present in dry flue
gases during on two period, %
XCO2F3 = percent carbon dioxide present in dry flue
gases during off period, %
c XH2 = percent hydrogen content on oven dry basis of fuel
c XN2 = percent nitrogen content on oven dry basis of fuel
c XN2F1 = percent nitrogen present in dry flue gases during on one period, %
c XN2F2 = percent nitrogen present in dry flue gases during on two period, %
c XN2F3 = percent nitrogen present in dry flue gases during off period, %
c XO2 = percent oxygen on oven dry basis of fuel
c XS = percent sulfur content on oven dry basis of fuel
c XUNBC1 = unburned carbon during ON1 period, % of fuel burned
c XUNBC2 = unburned carbon during ON2 period, % of fuel burned
c XUNBC3 = unburned carbon during off period, % of fuel burned
c PARD = percent argon in the dry product of combustion.
c PCOD = percent CO in the dry product of combustion.
c PCO2D = percent CO2 in the dry product of combustion.
c PH2OD = percent H2O in the dry product of combustion.
c PN2D = percent N2 in the dry product of combustion.
c P02D = percent O2 in the dry product of combustion.

*****************************************************

MAIN PROGRAM

COMMON /FFF/ YCOD,YCO2D,YN2D,YO2D,YARD,YSO2D,MWWFG,
+ MRWFG,PH2OC,PCOC,PCO2C,PN2C,PO2C,PARD,
+ P02D
COMMON /RRR/ IRH20,IRC,IRO2,IRH2,IRN2,IRS,IRDIRT,IRASH,
+ IRUNBC,IRBC,IRCCO,IRCCO2
COMMON /XXX/ XC,XH2,XO2,XN2,XASH,AXDIRT,XS,AXH2O,
+ AXC,AXH2,AXO2,AXN2,AXASH,AXS
COMMON /TANK/TBMAX,TBMIN,TBMIN1,MBW1,CPW,PPL,DELT
COMMON /CONS/ TFSS1,TFON1,TFON2,TFOFF3,TFOFF4,TFOFF5,TIM1,
+ TIM2,TIM3,TIM4,TIM5
COMMON /ROM/ TAUN,TAUOFF,THEFO,SAIFO,CTON,CTOFF
COMMON /STEADY/ RTFON1,AFON1,QINON1,QLSP1,QLLP1,
+ SSEON1,LSOFF,LSON
COMMON /PROF/ PFTON,PFTOFF,TIMINT
COMMON /AIR/ YN2, YO2, YCO2, YAR, YCO, SPH, IRDA

REAL MWWFG, MRWF, IRWAF1, IRWAF2, IRWAF3, IRH2O, IRC, IRO2,
+ IRH2, IRN2, IRS, IRDIRT, IRASH, IRUNBC, IRBC, IRCCO,
+ IRCCO2, MWDFG, MRDFG, MPBRT

REAL BT(30), SSEON1(30), SSEON2(30), QLSP1(30), QLSP2(30),
+ QLLP1(30), QLLP2(30), HQH(30), QLS1(30), QLS2(30),
+ QLL1(30), QLL2(30), INTEG, LSOFF(30), LSON(30),
+ LPS(30), FREQ(30), PFTON(30), PFTOFF(30), IRDA,
+ MWBT, SSEOFF(30), PEFFON(30), PEFF(30), BRT(30),
+ QLSOFF(30), QLLOFF(30), QLSPOF(30), QLLPOF(30),
+ QLCP1(30), QLCP2(30), QLCPOF(30), QLRP1(30), QLRP2(30),
+ QLRPOF(30)

OPEN(UNIT=8, FILE='a:MOD1.DAT')

C INPUT DATA
READ(8,*) XC, XH2, XO2, XN2, XS, XASH, AXDIRT, CDIRT, AKH2O
READ(8,*) IRWAF1, IRWAF2, IRWAF3, XUNBC1, XUNBC2, XUNBC3, HHV
READ(8,*) YN2, YO2, YAR, YCO2, YCO, SPH
READ(8,*) XN2F1, XCOF1, XCO2F1, PRDL, XN2F2, XCOF2,
+ XCO2F2, XN2P3, XCOF3, XCO2F3, PFG
CLOSE(UNIT=8, FILE='a:MOD1.DAT')

C OPEN(UNIT=5, FILE='a:MOD2.DAT')

C READ IN TEMPERATURE OF EACH BIN.
READ(5,*) N, FGA, MRA, CAIR, PEAON1, PEAON2, PEOFF, DF
READ(5,*) (BT(I), I = 1,N)
READ(5,*) (FREQ(I), I = 1,N)
READ(5,*) (HQH(I), I = 1,N)
READ(5,*) (TFSS1, TFSS2, TFSS3, TFON1, TFON2, TFOFF3,
+ TFOFF4, TFOFF5
READ(5,*) (TIM1, TIM2, TIM3, TIM4, TIM5
READ(5,*) (TBMX, TBMN, TBMN1, CPW, PPL, MWBT, AVTD,
+ DELT, MPBRT
READ(5,*) (TIMONT, TIMOFT, TIMINT
CLOSE(UNIT=5, FILE='a:MOD2.DAT')

C CHANGE FLUE GAS EXIT PRESSURE FROM KPA TO MPA
PFG = PFG/1000.

C CONVERT INPUT RATES OF FUEL FROM KG/HR TO KG/SEC
IRWAF1 = IRWAF1/3600.
IRWAF2 = IRWAF2/3600.
IRWAF3 = IRWAF3/3600.
DO 138 I = 1, N
BRT(I) = BT(I) + AVTD
IF (BRT(I) .GT. MPBRT) BRT(I) = MPBRT

CONTINUE

CALL RATE(IRWAF1, HHV, AHHV, XCO2F1, XCOF1, XUNBC1, FGA)

CALL FLUE (PEAON1, IRWAF1, AFON1, RTFON1, FGA, MRA, XN2F1, XCO2F1, XCOF1)

CALL STDEFF (N, IRWAF1, AXH2O, AHHV, SSEON1, QINON1, QLS1, QLL1, QLSF1, QLLF1, BRT, CDIRT, PRDL, TFSS1, QLCPl, QLRPl, PFG)

OPEN (UNIT=9, FILE='a:SIMPSE.RES')

139 FORMAT (/12X, 'NOTE: BRT STANDS FOR BOILER ROOM' / + /12X, ' TEMPERATURE')

WRITE (9, 140)


WRITE (9, 142) XC, AXC, XH2, AXH2, X02, AX02, XN2, AXN2, Xs, AXS, + XASH, AXASH, AXDIRT, AXH2O, HHV, AHHV


WRITE (9, 144)


WRITE (9, 145) PN2C, PN2D, PO2C, PO2D, PCO2C, PCO2D, PCOC, PCOD, + PARC, PARD, PSO2C, PSO2D, PH2OC, PH2OD


WRITE (9, 146) TFSS1

146 FORMAT (/15X, 'FLUE GAS TEMPERATURE, C' = ',', F7.2)

WRITE (9, 147)
266

147 FORMAT(//15X,'VARIOUS HEAT LOSSES DURING ON ONE PERIOD'/)
WRITE(9,148)
148 FORMAT(18X,'BRT',3X,'SENSIBLE',3X,'LATENT',3X,'COMB. MAT.'
+ /24X, ' LOSSES ',3X,' LOSSES',3X,' LOSSES '/
+ 18X, ' C ',3X,' % ',3X,' % ',3X,' % '
)
DO 150 I = 1,N
WRITE(9,149) BRT(I),QLSP1(I),QLLP1(I),QLCPl(I)
150 CONTINUE
WRITE(9,139)
C
CALL RATE (IRWAF2,HHV,AHHV,XCO2F2,XCOF2,XUNBC2,FGA)
CALL FLUE (PEAON2,IRWAF2,AFOFF,RTF0N2,FGA,MRA,XN2F2,
+ XCO2F2,XCOF2)
CALL STDEFF(N,IRWAF2,AXH2O,AHHV,SSEON2,QINON2,QLS2,QLL2,
+ QLSP2,QLLP2,BRT,CDIRT,PRDL,TFSS2,QLCP2,QLRP2,PFG)
C
WRITE(9,151)
151 FORMAT(//15X,'PERCENTAGE OF VARIOUS CONSTITUENTS IN THE'/
+ 15X,'PRODUCT OF COMBUSTION DURING ON TWO PERIOD'/
+ 17X,'CONSTITUENTS',5X,'WET BASIS',5X,'DRY BASIS'/
+ 38X,'%',14X,'%')
WRITE(9,145) PN2C,PN2D,P02C,P02D,PC02C,PC02D,PCOC,PCOD,
+ PARC,PARD,PS02C,PS02D,PH20C,PH20D
WRITE(9,146) TFSS2
WRITE(9,152)
152 FORMAT(//15X,'VARIOUS HEAT LOSSES DURING ON TWO PERIOD')
WRITE(9,148)
DO 153 I = 1,N
WRITE(9,149) BRT(I),QLSP2(I),QLLP2(I),QLCP2(I)
153 CONTINUE
C
C CALL SUBROUTINES RATE, FLUE, AND STDEFF TO PREDICT THE
C STEADY STATE EFFICIENCY DURING OFF PERIOD.
C
CALL RATE (IRWAF3,HHV,AHHV,XCO2F3,XCOF3,XUNBC3,FGA)
CALL FLUE (PEAOFF,IRWAF3,AFOFF,RTFOFF,FGA,MRA,XN2F3,
+ XCO2F3,XCOF3)
CALL STDEFF(N,IRWAF3,AXH2O,AHHV,SSEOFF,QINOFF,QLSOFF,
+ QLLOFF,QLSPOFF,QLLP0F,BRT,CDIRT,PRDL,TFSS3,
+ QLCPOF,QLRP0F,PFG)
C
WRITE(9,154)
154 FORMAT(//15X,'PERCENTAGE OF VARIOUS CONSTITUENTS IN THE '/
+ 15X,'PRODUCT OF COMBUSTION DURING OFF PERIOD'//
+ 17X,'CONSTITUENTS',5X,'WET BASIS',5X,'DRY BASIS'/
+ 38X,'%',14X,'%')
WRITE(9,145) PN2C,PN2D,P02C,P02D,PC02C,PC02D,PCOC,PCOD,
+ PARC,PARD,PS02C,PS02D,PH20C,PH20D
WRITE(9,146) TFSS3
WRITE(9,152)
WRITE(9,145) PN2C,PN2D,PO2C,PO2D,PC2C,PC2D,PCOC,PCOD,
+ PARC,PARD,PSO2C,PSO2D,PH2OC,PH2OD
WRITE(9,146) TFSS3
WRITE(9,155) PEAON1,PEAON2,PEAOFF
155 FORMAT(/15X,'PERCENT EXCESS AIR FOR ON ONE PERIOD =',F7.2
+ //15X,'PERCENT EXCESS AIR FOR ON TWO PERIOD =',F7.2
+ //15X,'PERCENT EXCESS AIR FOR OFF PERIOD =',F7.2)
C WRITE(9,156)
156 FORMAT(/15X,'VARIOUS HEAT LOSSES DURING OFF PERIOD')
WRITE(9,148)
DO 158 I = 1,N
WRITE(9,149) BRT(I),QLSPOF(I),QLLPOF(I),QLCPOF(I)
158 CONTINUE
WRITE(9,160)
160 FORMAT(/20X,' ON & OFF PERIODS AT VARIOUS '/28X,
+ 'LOAD CONDITIONS'//13X,'LOAD',5X,'ON ONE',
+ ' PERIOD',7X,'ON TWO PERIOD',5X,'OFF PERIOD'/
+ 15X,'kWh',8X,' SEC ',16X,'SEC , 14X,'SEC//)
C II = 1
DO 195 I = II,N
TAE = BRT(I)
C CALCULATE THE LOAD (kJ/SEC) FOR ITH TEMPERATURE BIN.
LPS(I) = (HQH(I)*3.6*1000.)/3600.
IF (LPS(I) .LE. 1.05*QINOFF*SSEOFF(I)/100.) THEN
TIMON1 = 0.0
TIMON2 = 0.0
TIMOFF= 0.0
PEFF(I)= 0.0
LSON(I)= 0.0
LSOFF(I)= 0.0
WRITE (9,180) HQH(I),TIMON1,TIM0N2,TIMOFF
GO TO 190
END IF
C CALL SIMBLR(HQH(I),IRWAF1,IRWAF2,IRWAF3,AHV,SSEON1(I),
+ SSEON2(I),SSEOFF(I),TIMOFF,TIMON1,TIMON2)
WRITE(9,180) HQH(I),TIMON1,TIM0N2,TIMOFF
180 FORMAT(12X,F7.2,5X,F7.1,12X,F7.1,9X,F7.1)
C IF (TIMON1 .EQ. 0.0 .AND. TIMOFF .EQ. 0.0) GO TO 185
IF (TIMON2 .EQ. 0.0 .AND. TIMOFF .EQ. 0.0) GO TO 187
IF (TIMON1 .EQ. 0.0 .AND. TIMON2 .EQ. 0.0) GO TO 188
IF (TIMON1 .NE. 0.0 .AND. TIMON2 .NE. 0.0) GO TO 184
IF (TIMON1 .NE. 0.0 .AND. TIMOFF .NE. 0.0) THEN

C CALL TIME(TIMON1,TIMOFF)

C CALL ROMBRG(INTEG,TIMOFF,TAE)

C CALL LOSS(INTEG,TAE,TIMON1,CAIR,DP,AHHV)

C CALCULATE THE PART LOAD EFFICIENCY.
PEFFON(I) = 100. -QLLP1(I)- QLCP1(I)-QLRP1(I)-(LSON(I)+
+LSOFF(I))
PEFF(I) = (PEFFON(I)*TIMON1*QINON1+SSSEFF(I)*TIMOFF*QINOFF)
+/(TIMON1*QINON1+TIMOFF*QINOFF)
END IF
GO TO 190

184 PEFF(I) = (TIMON1*SSSEON1(I)*QINON1+TIMON2*SSSEON2(I)*
+QINON2)/(TIMON1*QINON1+TIMON2*QINON2)
GO TO 190

185 PEFF(I) = SSSEON2(I)
GO TO 190

187 PEFF(I) = SSSEON1(I)
GO TO 190

188 PEFF(I) = SSSEOFF(I)

190 N1 = N1 + 1

195 CONTINUE

C CALCULATE THE SEASONAL EFFICIENCY OF THE SYSTEM

C ( SE, % ).

SSS = 0.0
SUMM= 0.0
DO 200 I = 1, N
IF (PEFF(I) .GT. 0.0) THEN
SUMM = SUMM + PEFF(I)*FREQ(I)
SSS = SSS + FREQ(I)
END IF
200 CONTINUE
IF (SSS .GT. 0.0) THEN
SE = SUMM/SSS
ELSE
SE = 0.0
END IF

C CALCULATE THE TEMPERATURE PROFILE DURING THE TEST
C CONDITIONS.

TIMON1 = TIMONT
TIMOFF= TIMOFF
CALL TIME(TIMON1,TIMOFF)

CALL PROFIL(TIMON1,TIMOFF)

WRITE (9,202)
202 FORMAT(//20X,'SENSIBLE HEAT LOSSES DURING ON & OFF'/ + 20X,'CYCLING AT VARIOUS TEMPERATURE BINS'/ + 23X,'BRT',7X,'LSON1',7X,'LSOFF'/ + 23X,' C ',6X,'% ',6X,'% ')
   DO 204 I = 1,N
      WRITE (9,203) BRT(I), LSON(I),LSOFF(I)
   203 FORMAT(20X,F6.2,6X,F5.2,6X,F5.2)
   204 CONTINUE

WRITE (9,205)
205 FORMAT(//15X,'STEADY STATE & PART LOAD (PEFF)', + ' EFFICIENCY'/25X,'OF WOOD FIRED BOILER'/10X, + 'BIN TEMP.',2X,'FREQ',4X,'HQH',4X,'SSEON1',2X, + 'SSEON2',2X,'SSEOFF',3X,'PEFF'/12X,' C ',6X,'hrs', + 5X,'Kwh',5X,'%',5X,'%',5X,'%',5X,'%'/)
   DO 215 I = 1,N
      WRITE (9,210) BT(I),FREQ(I),HQH(I),SSEON1(I),SSEON2(I), + SSEOFF(I),PEFF(I)
   210 FORMAT(9X,F7.2,1X,F7.1,2X,F7.2,3X,F5.2,3X,F5.2,3X,F5.2,3X,F5.2)
   215 CONTINUE

WRITE(9,220) SE
220 FORMAT(//20X,'SEASONAL EFFICIENCY = ', F5.2,'%')

WRITE(9,225)
225 FORMAT(//15X,'TEMPERATURE PROFILE OF FLUE GASES DURING ON' + 'PERIOD'/27X,'TIME',10X,'TEMPERATURE'/27X,' SEC '/ + 12X,' C '/)
   K1 = TIMINT
   N1 = TIMONT
   N2 = TIMOFT
   KK = 0
   DO 235 I = K1,N1,K1
      KK = KK + 1
      WRITE (9,230) I,PFTON(KK)
   230 FORMAT(25X,I5,12X,F7.2)
   235 CONTINUE

WRITE(9,240)
240 FORMAT(//15X,'TEMPERATURE PROFILE OF FLUE GASES DURING ' + 'OFF PERIOD'/27X,'TIME',10X,'TEMPERATURE'/27X,
DO 250 I = K1,N2,K1
JJ = JJ+1
WRITE(9,230) I,PFTOFF(JJ)
250 CONTINUE
CLOSE(UNIT=9)
STOP
END

SUBROUTINE RATE(IRWAF, HHV, AHHV, XC02DF, XCODF, XUNBC, FGA)
C *****************************************************
C THIS SUBROUTINE CALCULATES THE INPUT RATE OF VARIOUS 
C BIOMASS FUEL ELEMENTS FROM OVEN DRY BASIS TO AS 
C RECEIVED BASIS.
C DEFINITION OF VARIABLES:
==================================================
C AXASH = percent ash content on As Received Basis (ARB) *
C AXC = percent carbon content on ARB *
C AXDIRT = percent dirt content on ARB *
C AXH2 = percent hydrogen content on ARB *
C AXN2 = percent nitrogen content on ARB *
C AXO2 = percent oxygen content on ARB *
C AXS = percent sulfur content on ARB *
C AHHV = higher heating value of fuel on ARB *
C IRASH = input rate of ash, kg/sec *
C IRBC = input rate of burned carbon, kg/sec *
C IRC = input rate of carbon in the fuel, kg/sec *
C IRCO = input rate carbon burned to CO, kg/sec *
C IRCO2 = input rate of carbon burned to CO2, kg/sec *
C IRDIRT = input rate of dirt in the fuel, kg/sec *
C IRH2 = input rate of hydrogen in the fuel, kg/sec *
C IRH2O = input rate of moisture in the fuel, kg/sec *
C IRN2 = input rate of nitrogen in the fuel, kg/sec *
C IRS = input rate of sulfur in the fuel, kg/sec *
C IRUNBC = input rate of unburned carbon, kg/sec *
C *****************************************************
COMMON /XXX/ XC,XH2,XO2,XN2,XASH,AXDIRT,XS,AXH2O,
+ AXC, AXH2, AXO2, AXN2, AXASH, AXS
COMMON /RRR/ IRH2O, IRC, IRO2, IRH2, IRN2, IRS, IRDIRT, IRASH,
+ IRUNBC, IRBC, IRCCO, IRCCO2

REAL XC, XH2, XO2, XN2, XASH, AXDIRT, AXH2O, HHV, IRWAF, IRH2O, IRC,
+ IRO2, IRH2, IRN2, IRS, IRDIRT, IRASH, IRUNBC, IRBC, IRCCO,
+ IRCCO2
C CHANGE ULTIMATE ANALYSIS FROM OVEN DRY BASIS TO AS RECEIVED BASIS.
AXC = XC*{(100.-AXH20-AXDIRT)/100.)
AXH2 = XH2*{(100.-AXH20-AXDIRT)/100.)
AXO2 = XO2*{(100.-AXH20-AXDIRT)/100.)
AXN2 = XN2*{(100.-AXH20-AXDIRT)/100.)
AXASH = XASH*{(100.-AXH20-AXDIRT)/100.)
AXS = XS*{(100.-AXH20-AXDIRT)/100.)
AHHV = HHV*{(100.-AXH20-AXDIRT)/100.)
C INPUT RATE OF VARIOUS FUEL ELEMENTS INTO THE BOILER (kg/sec).
IRH2O = (AXH2O*IRWAF)/100.
IRC = (AXC*IRWAF)/100.
IRO2 = (AXO2*IRWAF)/100.
IRH2 = (AXH2*IRWAF)/100.
IRN2 = (AXN2*IRWAF)/100.
IRS = (AXS*IRWAF)/100.
IRDIRT= (AXDIRT*IRWAF)/100.
IRASH = (AXASH*IRWAF)/100.
C INPUT RATE OF UNBURNED CARBON (IRUNBC, kg/sec)
IRUNBC = (XUNBC*IRC)/100.
C INPUT RATE OF CARBON BURNED (IRBC, kg/sec)
IRBC = IRC - IRUNBC
C IF(FGA .EQ. 1.0) THEN
C INPUT RATE OF CARBON BURNED TO CARBON MONOXIDE (kg/sec).
XCCO = (XCODF/(XCODF+XCO2DF)) *100.0
IRCCO= (XCCO*IRBC)/100.0
C INPUT RATE OF CARBON BURNED TO CARBON DIOXIDE (kg/sec).
XCCO2 = (XCO2DF/(XCODF+XCO2DF)) *100.0
IRCCO2= (XCCO2*IRBC)/100.0
END IF
RETURN
END
C C
SUBROUTINE FLUE( EAP, IRWAF, AF, RTF, FGA, MRA, XN2DF, XCO2DF, +
XCDF)

C **********************************************************************
C
C THIS SUBROUTINE PREDICTS THE FLUE GAS ANALYSIS ON
C WET BASIS.

C DEFINITION OF VARIABLES:

AF = mass ratio of stoichiometric air to fuel
EAP = percentage of excess air used for combustion of fuel
IRDA = rate of actual dry air in to the combustor, kg/sec
MRDFG = mass rate of dry flue gases
MRWFG = mass rate of wet flue gases
MWA = molecular weight of dry air
MWDFG = molecular weight of dry flue gases
MWFG = molecular weight of wet flue gases
RTDA = rate of theoretical dry air required, kg/sec
RTF = ratio of combustion air to stoichiometric air
YARC = mole fraction of argon in the Products Of Combustion (POC)
YCOC = mole fraction of CO in the POC
YCO2C = mole fraction of CO2 in the POC
YH2OC = mole fraction of H2O in the POC
YN2C = mole fraction of N2 in the POC
YO2C = mole fraction of O2 in the POC

C **********************************************************************
C
COMMON /RRR/ IRH20, IRC, IRO2, IRH2, IRN2, IRS, IRDIRT, IRASH,
+ IRUNBC, IRBC, IRCO, IRCO2
COMMON/AIR/ YN2, YO2, YCO2, YAR, YCO, REHC, IRDA
COMMON /FFF/ YC0D, YCO2D, YN2D, YO2D, YARD, YSO2D, MWWFG,
+ MRWFG, PH20C, PCOC, PCO2C, PN2C, PO2C, PARC, PSO2C,
+ MWDFG, MRDFG, PH20D, PCOD, PCO2D, PN2D, PO2D, PARD,
+ PSO2D

REAL IRH20, IRC, IRO2, IRH2, IRN2, IRS, IRDIRT, IRASH, IRUNBC,
+ IRBC, MWA, RTDA, IRDA, EAP, REHC, MWH2, MWH20, MWC, MWN2,
+ MWS, SMRC, YH2OC, YCOC, YCO2C, YN2C, YO2C, YARC, MWDFG, MRWFG,
+ IRCO, IRCO2, MWS02, IRWAF, MWC0, MWC02, MWAR, MWDFG, MRDFG

REAL MRH2F, MRH2OF, MRCF, MRUNBC, MRO2F, MRN2F, MRCOF, MRCO2F,
DATA MWH2, MWH20, MWC, MWCO, MWCO2, MWO2, MWN2, MWAR, MWSO2/
+ 2.016, 18.016, 12.01, 28.01, 44.01, 32.0, 28.016, 32.06,
+ 39.948, 64.06/
C CALCULATE THE MOLECULAR WEIGHT OF DRY AIR.
MWA = YN2*MWN2+Y02*MW02+YAR*MWAR+YC02*MWC02+YC0*MWC0
C CALCULATE THE RATE OF THEORETICAL DRY AIR REQUIRED
C ( RTDA, kg/sec).
RTDA = 11.51*IRC + 34.3*(IRH2-IR02/7.937)+4.335*IRS
C MASS RATIO OF STOICHIOMETRIC AIR TO FUEL.
AF = RTDA/MRAFP
IF (MRA .EQ. 1.) GO TO 50
IF ( FGA .EQ. 1.0) THEN
C CALCULATE THE RATE OF ACTUAL DRY AIR ( IRDA, kg/sec).
IRDA = (((28.02*XN2DF)*((IRC-IRUNBC) + (12.01/32.07)*
+ 1RS))/(12.01*(XC02DF+XC0DF))-IRN2)/0.7685
C
EAP •= ((IRDA-RTDA)/RTDA) *100.
END IF
IF (FGA .EQ. 0.0) THEN
IRDA = RTDA*(1+EAP/100.)
END IF
50 CONTINUE
C RATIO OF COMBUSTION AIR TO STOICHIOMETRIC AIR.
RTF «= IRDA/RTDA
C CONVERT THE VARIOUS CONSTITUENTS OF FUEL TO MOLE
C BASIS.
MRH2F = IRH2/MWH2
MRH2OF= IRH2O/MWH20+MRH2F
MRCF = IRC/MWC
MRUNBC= IRUNBC/MWC
MRO2F = IR02/MWO2
MRN2F = IRN2/MWN2
IF (FGA .EQ. 1.0) THEN
MRCOF = IRCC0/MWC
MRCO2F= IRCC02/MWC
ELSE
MRCOF = 0.0
MRCO2F= MRCF-MRUNBC
END IF
MRARF = 0.0
MRSF = IRS/MWS
C CALCULATE THE MOLE RATE OF CONSTITUENTS IN
COMBUSTION AIR.

MRARA = IRDA*YAR/MWA
MRCOA = IRDA*YCO/MWA
MRCO2A = IRDA*YCO2/MWA
MRN2A = IRDA*YN2/MWA
MRO2A = IRDA*YO2/MWA
MRH20A = (IRDA*REHC)/MWA

CALCULATE THE MOLE RATE OF CONSTITUENTS IN PRODUCTS OF COMBUSTION

MRARC = MRARF + MRARA
MRCOC = MRCOF + MRCOA
MRCO2C = MRCO2F + MRCO2A
MRN2C = MRN2F + MRN2A
MRH2OC = MRH2OF + MRH2OA
MRO2C = MRO2F + MRO2A - (MRCOF/2.0 + MRCO2F + MRH2F/2.0 + MRSF)
MRS02C = MRSF

CALCULATE THE MOLE FRACTION OF WET FLUE GASES

SMRC = MRH20C+MRCOC+MRCO2C+MRN2C+MRO2C+MRARC+MRS02C
YH20C = MRH20C/SMRC
YCOC = MRCOC/SMRC
YC02C = MRCO2C/SMRC
YN2C = MRN2C/SMRC
YO2C = MRO2C/SMRC
YARC = MRARC/SMRC
YS02C = MRS02C/SMRC

CALCULATE THE PERCENT OF VARIOUS ELEMENTS IN WET FLUE GASES

PH20C = YH20C*100.
PCOC = YCOC*100.
PC02C = YC02C*100.
PN2C = YN2C*100.
P02C = YO2C*100.
PARC = YARC*100.
PS02C = YS02C*100.

CALCULATE MOLECULAR WEIGHT AND MASS RATE OF WET FLUE GASES.

MWWFG = YARC*MWAR+YCOC*MWCO+YCO2C*MWCO2+YH20C*MWH2O+
        + YN2C*MWN2+YO2C*MWO2+YS02C*MWSO2
MRWFG = SMRC*MWWFG

CALCULATE THE MOLE FRACTION OF THE DRY PRODUCT OF COMBUSTION

SMRD = SMRC-MRH20C
YCOD = MRCOC/SMRD
YCO2D = MRCO2C/SMRD
YN2D = MRN2C/SMRD
YO2D  = MR02C/SMRD
YARD  = MRARC/SMRD
YS02D = MRS02C/SMRD

C CALCULATE THE PERCENTAGE OF VARIOUS CONSTITUENTS IN THE
C DRY FLUE GASES
PH2OD = 0.0
PCOD  = YCOD*100.
PCO2D = YCO2D*100.
PN2D  = YN2D*100.
PO2D  = YO2D*100.
PARD  = YARD*100.
PS02D = YS02D*100.

C CALCULATE THE MOLECULAR WEIGHT AND MASS RATE OF DRY FLUE
C GASES
MWDFG = YARD*MWAR+YC0D*MWC0+YCO2D*MWC02+YN2D*MWN2+
+ YO2D*MW02+YS02D*MWS02
MRDFG = SMRD*MWDFG
RETURN
END

C

SUBROUTINE STDEFF(N,IRWAF,AHX20,AHHV,ESS,QIN,QLS,QLL,
+ QLSP,QLLP,BRT,CDIRT,PRDL,TFSS,QLCP,QLRP,PFG)
Q**************************************************************
C *
C THIS SUBROUTINE PREDICTS THE STEADY STATE EFFICIENCY *
C OF BIOMASS FUELED BOILERS AT VARIOUS TEMPERATURE BINS *
C *
C DEFINITION OF VARIABLES:
C **************************************************************
C QLDFG = rate of heat loss due to heat in dry flue gases, kJ/sec
C QLMF = rate of heat loss due to moisture in fuel, kJ/sec
C QLHF = rate of heat loss due to hydrogen in the fuel, kJ/sec
C QLMA = rate of heat loss due to moisture in the combustion air, kJ/sec
C QLUNC = rate of heat loss due to unburned carbon in total dry refuse, kJ/sec
C QLCO = rate of heat loss due to formation of carbon monoxide, kJ/sec
C QLD = rate of heat loss due to sensible heat in flue dirt, kJ/sec
QLBW = rate of heat loss due to bringing the bound water to the energy level of free water, kJ/sec
IRBW = input rate of bound water, kJ/sec
QIN = rate of input energy to the boiler, kJ/sec
QLRAD = rate of radiation & unaccountable losses, kJ/sec
QLS = sum of all the sensible heat losses, kJ/sec
QLL = sum of all the latent heat losses, kJ/sec
QLOSS = sum of all the heat losses, kJ/sec

******************************************************************************

COMMON /RRR/ IRH20,IRC,IRO2,IRH2,IRN2,IRS,IRDIRT,IRASH,
+ IRUNBC,IRBC,IRCCO,IRCCO2
COMMON /FFF/ YCOD,YC02D,YN2D,YO2D,YARD,YSO2D,MWWFG,
+ MWWFG,PH2OC,PCOC,PC02C,PN2C,PO2C,PARC,PSO2C,
+ MWWFG,MRDFG,PH2OD,PCOD,PCO2D,PN2D,PO2D,FARD,
+ PSO2D
COMMON /AIR/ YN2,YO2,YCOD,Y02D,YARD,YC02,YAR,YC0,SPH,IRDA

REAL IRH20,IRC,IR02,IRH2,IRN2,IRS,IRDIRT,IRASH,
+ IRBC,IRCCO, YCOD,YC02D,YN2D,YARD,MWWFG,MRDFG,
+ MC,IRDA,IRWAF,IRBW,MWWFG,MRDFG
REAL BRT(30),TFUEL(30),TAE(30),ESS(30),QLS(30),
+ QLL(30),QLSP(30),QLLP(30),QLCP(30),QLRP(30),
+ QLC(30),QLR(30)

C INITIALIZE THE VARIABLES
DO 10 I = 1,N
QLS(I) = 0.0
QLL(I) = 0.0
QLC(I) = 0.0
QLR(I) = 0.0
QLSP(I) = 0.0
QLLP(I) = 0.0
QLCP(I) = 0.0
QLRP(I) = 0.0
ESS(I) = 0.0
10 CONTINUE

C ASSIGN THE VALUES TO THE TEMPERATURE OF FUEL & AIR
C ENTERING THE Boiler Furnace.
DO 20 I = 1,N
TFUEL(I) = BRT(I)
TAE (I) = BRT(I)
20 CONTINUE

C DO 40 I = 1,N
C

HGA = HGAS(TFSS, TAE(I), YCOD, YCO2D, YN2D, YO2D, YARD, YSO2D, +
MWDFG)
QLDFG = MRDFG*HGA
C

HVFG = HSUPV(TFSS, PFG)
HSLF = HSLIQ(TFUEL(I))
QLMF = IRH2O*(HVFG-HSLF)
C

QLHF = 8.936*IRH2*(HVFG-HSLF)
C

HVAE = HVAP(TAE(I))
QLMA = IRDA*SPH*(HVFG-HVAE)
C

QLUNC = 33694.25*IRUNBC
C

QLCO = 10178.194*IRCCO
C

QLD = IRDIRT*CDIRT*(TFSS-TAE(I))
C

RATE OF HEAT LOSS DUE TO BRINGING THE BOUND WATER
C
TO THE ENERGY LEVEL OF FREE WATER (KJ/sec).
IF (AXH2O .GE. 23.08) THEN
MC = 23.08
ELSE
MC = AXH2O
ENDIF
C

INPUT RATE OF BOUND WATER (kg/sec).
IRBW = MC*IRWAF/100.
HBW = (1./MC)*(4.679415E2*MC-3.2314115E1*(MC**2.)+
+ 1.04078667*(MC**3.)+4.680145E-2*(MC**4.)-
+ 6.588278E-3*(MC**5.)+2.569851667E-4*(MC**6)-
+ 3.48937E-6*(MC**7.))*1.055
C

QLBW = IRBW*HBW
C

QIN = IRWAF*AHHV
C

QLRAD = (PRDL/100.)*QIN
QLS(I) = QLDFG+QLD
QLL(I) = QLHF+QLMF+QLMA+QLBW
QLC(I) = QLUNC+QLCO
QLR(I) = QLRAD
C

SENSIBLE AND LATENT LOSSES ON PERCENT BASIS.
QLSP (I) = (QLS(I)/QIN)*100.
QLLP (I) = (QLL(I)/QIN)*100.
QLCP(I) = (QLC(I)/QIN)*100.
QLRF(I) = (QLR(I)/QIN)*100.

C SUM OF ALL THE HEAT LOSSES ,kJ/sec
QLOSS = QLS(I)+QLL(I)+QLC(I)+QLR(I)

C STEADY STATE EFFICIENCY OF THE WOOD FIRED BOILER.
ESS(I) = ((QIN-QLOSS)/QIN)*100.

C
40 CONTINUE
RETURN
END

C
FUNCTION HSUPV (T,P)
***************************************************************
C THIS FUNCTION COMPUTES THE ENTHALPY OF A SUPERHEATED
C VAPOR AT FLUE GAS TEMPERATURE AND PRESSURE. THE EQUATIONS*
C FOR ENTHALPY ARE FROM "STEAM AND GAS TABLES WITH COMPUTER*
C EQUATIONS", BY T. F. IRVINE AND P. E. LILEY, P. 51. *
C
C***************************************************************
REAL M,KT,P
DATA AA,BB,CC,A1,B1,C1/0.426776E2,-0.389270E4,-0.948654E1,-0.387592E3,-0.125875E5,-0.152578E2/
+ 0.426776E2,-0.389270E4,-0.948654E1,-0.387592E3,-0.125875E5,-0.152578E2/
DATA B11,B12,B13/2.04121E3,-4.040021E1,-4.8095E-1/
DATA B21,B22,B23/1.610693,5.472051E-2,7.517537E-4/
DATA B31,B32,B33/3.383117E-4,-1.975736E-5,-2.87409E-7/
DATA B41,B42,B43,B44,B45/1.70782E3,-1.699419E1,6.2746295E-2,-1.0284259E-4,6.4561298E-8/
+ 6.2746295E-2,-1.0284259E-4,6.4561298E-8/
DATA M/4.5E1/
C COMPUTE SATURATION TEMPERATURE
IF (P .GE. 0.000611 .AND. P .LE. 12.33) THEN
TSA = AA+BB/(LOG(P)+CC)
END IF
IF ( P .GE. 12.33 .AND. P .LE. 22.1) THEN
TSA = A1+B1/(LOG(P)+C1)
END IF
KT = T+273.15
A1 = B11 +B12*P+B13*P**2
A2 = B21+B22*P+B23*P**2
A3 = B31+B32*P+B33*P**2
A4 = B41+B42*TSA+B43*TSA**2+B44*TSA**3+B45*TSA**4
HSUPV = A1+A2*KT+A3*KT**2-A4*EXP((TSA-KT)/M))
END
FUNCTION HVAP (T)
C *****************************************************
C * THIS FUNCTION CALCULATES THE ENTHALPY OF A VAPOR AS A *
C * FUNCTION OF TEMPERATURE. THE EQUATIONS FOR ENTHALPY ARE *
C * FROM "STEAM AND GAS TABLES WITH COMPUTER EQUATIONS", *
C * T. F. IRVINE AND P. E. LILEY, PP. 22, 23. *
C *****************************************************
C
REAL T, KT, KTC, TC, E(10)
KT = (T+273.15)
DATA A, B, C, D, HGCR, KTC/1.0, 4.57874342E-1, 5.08441288,
+ -1.48513244, 2.0993E3, 647.3/
DATA (E(I), I = 1, 7) /-4.81351884, 2.69411792, -7.39064542,
+ 1.04961689E1, -5.46840036, 0.0, 0.0/
C
TC = (KTC-KT)/KTC
YS1 = A+B*TC**(1./3.)+C*TC**(5./6.)+D*TC**(7./8.)
YS2 = 0.0
DO 20 N = 1, 7
YS2 = YS2+E(N)*TC**N
20 CONTINUE
YS = YS1+YS2
HVAP = YS*HGCR
END
C
C
FUNCTION HSULIQT(T)
C *****************************************************
C * THIS FUNCTION CALCULATES THE ENTHALPY OF A SATURATED *
C * LIQUID AT TEMPERATURE OF FUEL ENTERING THE BOILER. THE *
C * EQUATIONS FOR ENTHALPY ARE FROM "STEAM AND GAS TABLES *
C * WITH COMPUTER EQUATIONS", T. F. IRVINE AND P. E. LILEY, *
C *****************************************************
C
REAL T, KT, KTC, TC, E(10), EE(10), EEE(10)
KT = T + 273.15
C
DATA A, B, C, D /0.0, 0.0, 0.0, 0.0, 0.0/
DATA (E(I), I = 1, 7) /6.24698837E2, -2.34385369E3,
+ -9.50812101E3, 7.16287928E4, -1.63535221E5,
+ 1.66531093E5, -6.47854585E4/
DATA AA,BB,CC,DD /8.839230108E-1,0.0,0.0,0.0/
DATA EE(J), J = 1,7)/-2.67172935,6.22640035,
+ -1.3178973E1,-1.91322436,6.87937653E1,
+ -1.24819906E2,7.21435404E1/
DATA AAA,BBB,CCC,DDD /1.0,-4.41057805E-1,-5.522555517,
+ 6.43994847/
DATA EEE(I), I = 1,7)/-1.64578795,-1.30574143,0.0,0.0,
+ 0.0,0.0,0.0/
DATA HFCR,KTC/2.0993E3,647.3/
C
TC = (KTC-KT)/KTC
IF (K.T. LT. 300.0) THEN
YS1 = A+B*TC**(1./3.)+C*TC**(5./6.)+D*TC** + (7./8.)
C
YS2 = 0.0
DO 20 N = 1,7
YS2 = YS2+E(N)*TC**N
20 CONTINUE
YS = YS1+YS2
END IF
C
IF(KT .GE. 300. .AND. KT .LT. 600.) THEN
YS1 = AA+BB*TC**(1./3.)+CC*TC**(5./6.)+D*TC** + (7./8.)
C
YS2 = 0.0
DO 40 N = 1,7
YS2 = YS2+EE(N)*TC**N
40 CONTINUE
YS = YS1+YS2
END IF
C
IF(KT .GE. 600. .AND. KT .LT. 647.3) THEN
YS1 = AAA+BBB*TC**(1./3.)+CCC*TC**(5./6.)+D*TC** + (7./8.)
C
YS2 = 0.0
DO 60 N = 1,7
YS2 = YS2+EEE(N)*TC**N
60 CONTINUE
YS = YS1+YS2
END IF
HSLIQ = YS*HFCR
END
FUNCTION HGAS(TFG, TAE, YCO, YCO2, YN2, YO2, YAR, YSO2, MW)

**THIS FUNCTION CALCULATES THE ENTHALPY OF A GAS AS A FUNCTION OF TEMPERATURE AND MOLE FRACTIONS. THE EQUATIONS FOR SPECIFIC HEAT AT CONSTANT PRESSURE (CP) ARE FROM "FUNDAMENTALS OF CLASSICAL THERMODYNAMICS", G. J. VAN WYLEN AND R. E. SONNTAG, P. 688. CP FOR ARGON IS ASSUMED TO BE CONSTANT: 20.7849 kJ/kg mole K. THE MAXIMUM ERROR FOR AIR IS AROUND 0.5%**

REAL TFG, TAE, KTFG, KTAE, MW

KTFG = (TFG + 273.15) / 100.
KTAE = (TAE + 273.15) / 100.

DATA A1, A2, A3, A4 / 39.06, 512.79, 1072.7, 820.4 /
DATA B1, B2, B3, B4 / 37.432, 0.020102, 178.57, 236.88 /
DATA C1, C2, C3, C4 / 3.7357, 30.529, 4.1034, 0.024198 /
DATA D1, D2, D3, D4, D5, D6, D7 / 69.145, 0.70463, 200.77, 176.76 /
DATA F1, F2, F3, F4, F5, F6, F7 / 4.32805E-1, 5.9994156E-4, + 4.593367E-7, -1.433024E-9, 1.0409341E-12, + -2.5313735E-16, 0.0 /
DATA G1, G2, G3, G4, G5, G6, G7 / 0.52034, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 /

HN2 = ((A1*KTFG + (A2/0.5)*KTFG**(-0.5) - A3*KTFG**(-1.0) + (A4/2.0)*KTFG**(-2.0)) - (A1*KTAE + (A2/0.5)*KTAE**(-0.5) - A3*KTAE**(-1.0) + (A4/2.0)*KTAE**(-2.0))) * 100.0

H02 = ((B1*KTFG + (B2/2.5)*KTFG**2.5 + (B3/0.5)*KTFG**(-0.5) + 1.5 - (C3/2.0)*KTAE**2.0 + (C4/3.0)*KTAE**3.0)) * 100.0

HC02 = ((-C1*KTFG + (C2/1.5)*KTFG**1.5 - (C3/2.0)*KTFG**2.0 + (C4/3.0)*KTFG**3.0) - (-C1*KTAE + (C2/1.5)*KTAE**1.5 + 1.5 - (C3/2.0)*KTAE**2.0 + (C4/3.0)*KTAE**3.0)) * 100.0

HCO = ((E1*KTFG - (E2/1.75)*KTFG**1.75 - (E3/0.5)*KTFG**0.5) + 0.5 + (E4/0.25)*KTFG**0.25 - (E1*KTAE - (E2/1.75)* + KTAE**1.75 - (E3/0.5)*KTAE**0.5 + (E4/0.25)*KTAE**0.25)) * 100.0
HSO2 = ((F1*KTFG + (F2/2.0)*KTFG**2.0 + (F3/3.0)*KTFG**3.0
+ (F4/4.0)*KTFG**4.0 + (F5/5.0)*KTFG**5.0 + (F6/6.0)*
+ KTFG**6.0 + (F7/7.0)*KTFG**7.0) - (F1*KTAE+(F2/2.0)
+ *KTAE**2.0 + (F3/3.0)*KTAE**3.0 + (F4/4.0)*KTAE**4.0
+ (F5/5.0)*KTAE**5.0 + (F6/6.0)*KTAE**6.0 + (F7/7.0)*
+ KTAE**7.0)) * 100. * 64.063

HAR = ((G1*KTFG + (G2/2.0)*KTFG**2.0 + (G3/3.0)*KTFG**3.0
+ (G4/4.0)*KTFG**4.0 + (G5/5.0)*KTFG**5.0 + (G6/6.0)*
+ KTFG**6.0 + (G7/7.0)*KTFG**7.0) - (G1*KTAE+(G2/2.0)
+ *KTAE**2.0 + (G3/3.0)*KTAE**3.0 + (G4/4.0)*KTAE**4.0
+ (G5/5.0)*KTAE**5.0 + (G6/6.0)*KTAE**6.0 + (G7/7.0)*
+ KTAE**7.0)) * 100. * 39.948

ENTHALPY OF GAS.

HGAS = (YN2*HN2 + YO2*HO2 + YC02*HCO2 + YCO*HCO
+ + YAR*HAR + YSO2*HSO2) / MW
END

SUBROUTINE SIMBLR (HQH, IRWAFl, IRWAFl2, IRWAFl3, AHHV, SSEON1,
+ SSEON2, SSEOFF, TIMOFF, TIMON1, TIMON2)

C**                        ****************************************************

C** THIS SUBROUTINE PREDICTS THE BOILER OPERATING TIME AT
C** VARIOUS MODES OF OPERATION.
C**                        ****************************************************

C COMMON/TANK/TBMAX, TBMN, TBMIN1, MWBT, CPW, PPL, DELT
C
C REAL TBMAX, TBMN, TBMIN1, MWBT, CPW, L, IRWAFl, IRWAFl2, IRWAFl3
C
C QINON1 = IRWAFl*AHHV
QINON2 = IRWAFl2*AHHV
QINOFF = IRWAFl3*AHHV
L = ((HQH+(PPL/100.)*HQH)*3.6*1000.)/3600.
SON1 = SSEON1/100.
SON2 = SSEON2/100.
SOFF = SSEOFF/100.

C

TIMON1 = 0.0
TIMON2 = 0.0
TIMOFF = 0.0
IF (L .GT. 0.95*QINON1*SON1 .AND. L .LT. 1.05*
+ QINON1*SON1) GO TO 90
IF (L .LT. 0.95*QINON1*SON1 .AND. L .GT. 1.05*QINOFF*SOFF) GO TO 20
IF (L .GT. 1.05*QINON1*SON1 .AND. L .LT. 0.95*QINON2*SON2) GO TO 50
IF (L .GT. 0.95*QINON2*SON2) GO TO 80

C

20 Q = QINOFF
TS = TBMAX
EFC = SOFF
COFF = 0.0
DO 40 I = 15, 14000, 15
DELTIM = 15.0
TS = TS + (DELTIM/(MWBT*CPW))*EFC*Q-L
IF (TS .LE. TBMAX-DELT) THEN
IF (COFF .EQ. 1.0) GO TO 30
COFF = 1.
TIMOFF = I
Q = QINON1
EFC = SON1
30 CONTINUE
END IF
IF (TS .LE. TBMIN1) THEN
TIMOFF = 0.0
TIMON1 = 14000.
GO TO 100
END IF
IF (TS .GE. TBMAX) THEN
TIMON1 = I-TIMOFF-DELTIM
GO TO 100
END IF
40 CONTINUE
C

50 TS = TBMIN
EFC = SON1
Q = QINON1
CON1 = 0.0
DO 60 I = 15, 14000, 15
DELTIM = 15.0
TS = TS + (DELTIM/(MWBT*CPW))*EFC*Q-L
IF (TS .LE. TBMIN-DELT) THEN
IF (CON1 .EQ. 1.0) GO TO 55
CON1 = 1.
TIMON1 = I
55 CONTINUE
END IF
IF (CON1 .EQ. 1.0) THEN
EFC = SON2
Q = QINON2
END IF
IF (TS .GE. TBMIN) THEN
TIMON2 = I-TIMON1-DELTIM
GO TO 100
END IF
IF (TS .LE. TBMIN1) THEN
TIMON1 = 0.0
TIMON2 = 14000.
GO TO 100
END IF
60 CONTINUE
GO TO 100
80 TIMON2 = 14000.
GO TO 100
90 TIMON1 = 14000.
100 CONTINUE
RETURN
END

C
C
SUBROUTINE TIME(TIMON,TIMOFF)

C*******************************************************************************
C
C SUBROUTINE TIME COMPUTES THE TIME CONSTANT FOR ON &
C OFF PERIOD, AND CORRECTION FACTORS FOR THE RELATIVE
C LENGTH OF THE ON AND OFF PERIODS.

C*******************************************************************************
C
C DEFINITION OF VARIABLES:
C
C CTON &
C CTOFF = correction factors for the relative length of
C on & off periods
C
C SAIFO = defined as (TFOFF(TIM3)-TFOFF(TIM5)) EXP( TIM3/TAUOFF), degree C
C
C TAUON = time constant determined during warm up, sec
C
C TAUOFF = time constant determined during cool down, sec
C
C THEOF = the value of temperature difference defined as
C (TFSS-TFON) at start up, degree C

C*******************************************************************************
C
C
COMMON /CONS/ TFSS1,TFON1,TFON2,TFOFF3,TFOFF4,TFOFF5,TIM1,
    + TIM2,TIM3,TIM4,TIM5
COMMON /ROM/ TAUON,TAUOFF,THEFO,SAIFO,CTON,CTOFF
C
TAUON = (TIM2-TIM1)/LOG((TFSS1-TFON1)/(TFSS1-TFON2))
C
TAUOFF = (TIM4-TIM3)/LOG((TFOFF3-TFOFF5)/
    + (TFOFF4-TFOFF5))
C
THEFO = (TFSS1-TFON1)*EXP(TIM1/TAUON)
C
SAIFO = (TFOFF3-TFOFF5)*EXP(TIM3/TAUOFF)
C
CTON = (1.0 - (SAIFO/(TFSS1-TOFF5))*EXP(-TIMOFF/TAUOFF))/
    + (1.0 -((THEFO*SAIFO)/(TFSS1-TFOFF5)**2.0)*EXP(-(TIMON/
    + TAUON + TIMOFF/TAUOFF)))
C
CTOFF = (1.0 - (THEFO/(TFSS1-TOFF5))*EXP(-TIMON/TAUON))/
    + (1.0 -((THEFO*SAIFO)/(TFSS1-TFOFF5)**2.0)*EXP(-(TIMON/
    + TAUON + TIMOFF/TAUOFF)))
C
RETURN
END
C
SUBROUTINE ROMBREG(INTEG,TIMOFF,TAE)
C******************************************************************************
C    THIS SUBROUTINE EVALUATES THE INTEGRAL OF F(t) dt
C    USING THE ROMBUREG APPROACH.
C******************************************************************************
C
COMMON /CONS/ TFSS1,TFON1,TFON2,TFOFF3,TFOFF4,TFOFF5,TIM1,
    + TIM2,TIM3,TIM4,TIM5
COMMON /ROM/ TAUON,TAUOFF,THEFO,SAIFO,CTON,CTOFF
C
REAL INTEG,T(100,100),TOL,ERR
C
CALCULATE FUNCTION AT VARIOUS TEMPERATURE STEPS.
F(TFOFF) = ((TOFF-TAE)**0.56)*(TOFF-TFOFF5)/
    + ((TOFF+273.15)**1.19)
C
INITIALIZE THE VARIABLES.
INTEG = 0.0
TOL = 0.01
M = 1
J = 1
T(M,J) = 0.0

C ASSIGN THE VALUES TO THE LIMITS OF THE INTEGRAL.
A = 0.0
B = TIMOFF

C
TFA = SAIFO*CTOFF*EXP(-A/TAUOFF)+TFOFF5
TFB = SAIFO*CTOFF*EXP(-B/TAUOFF)+TFOFF5
AA = F(TFA)
BB = F(TFB)
IF( AA .LE. 0.0 ) AA = 0.0
IF( BB .LE. 0.0 ) BB = 0.0
T(M,J) = ((B-A)/2.0)*(AA+BB)

C
DO 100 M = 2,100
N = 2**(M-1)
H = (B-A)/N
SUM = 0.0
DO 60 K = 1,N-1,2
E = A+K*H
TFOFF = SAIFO*CTOFF*EXP(-E/TAUOFF)+TFOFF5
SUM1 = F(TFOFF)
IF(SUM1 .LE. 0.0) SUM1 = 0.0
SUM = SUM + SUM1
CONTINUE

C
T(M,J) = ((1.0/2.0)*T(M-1,J)+H*SUM)

C
DO 70 I = 2,M
T(M,I) = T(M,I-1)+(T(M,I-1)-T(M-1,I-1))/(4**(I-1)-1)
ERR = (T(M,I-1)-T(M-1,I-1))
IF (ABS(ERR) .LE. TOL) GO TO 110
IF (H .GE. 8000.) GO TO 105
CONTINUE

C
105 WRITE(*,106)
106 FORMAT(5X,'CONVERGENCE WAS NOT ACHieved')
110 INTEG = T(M,I)

C
RETURN
END
SUBROUTINE LOSS(INTEG,I,TAE,TIMON1,CAIR,DF,AHHV)

*********************************************************************************
C THIS SUBROUTINE PREDICTS THE ON & OFF PERIOD LOSSES
C
DEFINITION OF VARIABLES:
---------------------------------------------
LSON = sensible heat losses for the on period at each bin temperature, %
LSOFF = sensible heat losses for the off period at each bin temperature, %
MFON = mass flow rate of flue gases during on period

*********************************************************************************
C
COMMON /CONS/ TFSS1,TFON1,TFON2,TFOFF3,TFOFF4,TFOFF5,TIM1,
TIM2,TIM3,TIM4,TIM5
C
COMMON /POM/ TAUON,TAUOFF,THEFO,SAIFO,CTON,CTOFF
COMMON /STEADY/ RTFON1,AFON1,QINON1,QLSP1,QLLP1,
+ SSEON1,LSOFF,LSON
C
REAL INTEG,QLSP1(30),QLLP1(30),SSEON1(30),LSOFF(30),
+ LSON(30),MFON1
C
LSON(I) = QLSP1(I) - (CAIR*100.0*THEFO*CTON*(1.0 +
+ RTFON1*AFON1)*(1.0-EXP(-TIMON1/TAUON))) /
+ (AHHV*(TIMON1/TAUON))
C
MFON1 = (QINON1/AHHV)*(1.0+RTFON1*AFON1)
C
LSOFF(I) = ((100.0*CAIR*DF*MFON1)/(QINON1*TIMON1)) *
+ (((TFSS1+273.15)**1.19)/((TFSS1-TAE)**0.56))
+ *INTEG
C
RETURN
END
SUBROUTINE PROFIL (TIMON1,TIMOFF)
C ***************************************************************
C THIS SUBROUTINE PREDICTS THE TEMPERATURE PROFILE DURING * 
C ON & OFF PERIOD, AND MASS FLOW RATE OF FLUE GASES ANY * 
C TIME DURING OFF PERIOD . *
C ***************************************************************
C
COMMON /CONS/ TFSS1,TFON1,TFON2,TFOFF3,TFOFF4,TFOFF5,TIM1, 
+ TIM2,TIM3,TIM4,TIM5
COMMON /ROM/ TAUON,TAUOFF,THEFO,SAIFO,CTON,CTOFF
COMMON /PROF/ PFTON,PFTOFF,TIMINT
C
REAL PFTON(30), PFTOFF(30)
C
C CALCULATE THE FLUE GAS TEMPERATURE AT VARIOUS TIME 
C INTERVALS DURING ON PERIOD.
TIM = TIMINT
DO 10 I = 1,50
IF (TIM .GT. TIMON1) GO TO 20
PFTON(I) = TFSS1- THEFO*CTON*EXP(-TIM/TAUON)
TIM = TIM + TIMINT
10 CONTINUE
C
C CALCULATE THE FLUE GAS TEMPERATURE AT VARIOUS TIME 
C INTERVALS DURING OFF-PERIOD.
20 TIM = TIMINT
DO 30 I = 1,50
IF (TIM .GT. TIMOFF) GO TO 40
PFTOFF(I) = SAIFO*CTOFF*EXP(-TIM/TAUOFF)+TFOFF5
TIM = TIM+TIMINT
30 CONTINUE
CONTINUE
CONTINUE
40 RETURN
END
C
C***************************************************************
PART II. APPENDIX B. A TYPICAL OUTPUT OF SIMULATION PROGRAM FOR PREDICTING THE SEASONAL EFFICIENCY OF BIOFUELED BOILERS
### COMPOSITION OF FUEL ON OVEN DRY AND AS RECEIVED BASIS

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<tr>
<th>Constituent</th>
<th>Oven Dry Basis</th>
<th>As Received Basis</th>
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<td>Hydrogen</td>
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</tr>
<tr>
<td>Oxygen</td>
<td>41.7%</td>
<td>23.0%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Ash</td>
<td>1.4%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Dirt</td>
<td>0.0%</td>
<td>0.0%</td>
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<td>45.0%</td>
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<td>HHV, kJ/kg</td>
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### PERCENTAGE OF VARIOUS CONSTITUENTS IN THE PRODUCTS OF COMBUSTION DURING ONE PERIOD

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<tr>
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<td>15.26%</td>
<td>16.53%</td>
</tr>
<tr>
<td>CO2</td>
<td>3.96%</td>
<td>4.29%</td>
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<tr>
<td>CO</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>AR</td>
<td>0.85%</td>
<td>0.92%</td>
</tr>
<tr>
<td>SO2</td>
<td>0.00%</td>
<td>0.00%</td>
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<tr>
<td>H2O</td>
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<td>0.00%</td>
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Flue Gas Temperature, C = 260.00
VARIABLE HEAT LOSSES DURING ONE PERIOD

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<tr>
<th>BRT TEMP (°C)</th>
<th>SENSIBLE LOSSES (%)</th>
<th>LATENT LOSSES (%)</th>
<th>COMB. MAT. LOSSES (%)</th>
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<tbody>
<tr>
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<td>32.67</td>
<td>20.17</td>
<td>3.89</td>
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NOTE: BRT STANDS FOR BOILER ROOM TEMPERATURE
PERCENTAGE OF VARIOUS CONSTITUENTS IN THE PRODUCT OF COMBUSTION DURING ON TWO PERIOD

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<th>CONSTITUENTS</th>
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<td>0.01</td>
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<tr>
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<td>0.93</td>
</tr>
<tr>
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<td>0.00</td>
</tr>
<tr>
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FLUE GAS TEMPERATURE, C = 371.10

VARIABLES HEAT LOSSES DURING ON TWO PERIOD

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<tr>
<th>BRT</th>
<th>SENSIBLE LOSSES</th>
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<th>COMB. MAT. LOSSES</th>
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<td>%</td>
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PERCENTAGE OF VARIOUS CONSTITUENTS IN THE PRODUCT OF COMBUSTION DURING OFF PERIOD

<table>
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<th>DRY BASIS</th>
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<tbody>
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<td>SO2</td>
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<td>H2O</td>
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</tbody>
</table>

FLUE GAS TEMPERATURE, C = 204.00

PERCENT EXCESS AIR FOR ON ONE PERIOD = 350.93

PERCENT EXCESS AIR FOR ON TWO PERIOD = 39.35

PERCENT EXCESS AIR FOR OFF PERIOD = 624.64
<table>
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<th>C (°C)</th>
<th>BRT LOSSES</th>
<th>SENSIBLE LOSSES</th>
<th>LATENT LOSSES</th>
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### ON & OFF PERIODS AT VARIOUS LOAD CONDITIONS

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<th>OFF PERIOD SEC</th>
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STANDE STATE & PART LOAD (PEFF) EFFICIENCY  
OF WOOD FIRED BOILER

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SEASONAL EFFICIENCY = 34.39 %
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PART II. APPENDIX C. INPUT PARAMETERS AND OPERATING DETAILS OF SIMULATION PROGRAM FOR PREDICTING THE SEASONAL EFFICIENCY OF BIOFUELED BOILERS

The following specific data for Simulation Program for Predicting the Seasonal Efficiency of Biofueled boilers (SIMPSE) must be placed in two files on drive A and made accessible to the program at run time.

MOD1.DAT hold the following input parameters:

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<th>Parameter Description</th>
<th>Parameter</th>
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<td>(Program Variable Name)</td>
<td>Value</td>
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First read in statement:

(Note that all the data are in free format)

1. Percent carbon content on dry basis of fuel (XC) 50.64
2. Percent hydrogen content on dry basis of fuel (XH2) 6.02
3. Percent oxygen content on dry basis of fuel (OX2) 41.74
4. Percent nitrogen content on dry basis of fuel (XN2) 0.25
5. Percent sulphur content on dry basis of fuel (XS) 0.00
6. Percent ash content on dry basis of fuel (XASH) 1.35
7. Percent dirt content on as fired basis (AXDIRT) 0.0
8. Specific heat of dirt (CDIRT), kJ/kg °C 1.00
9. Percent moisture content of fuel on as fired basis (AXH2O) 45.00

Second read in statement:
1. Input rate of wood fuel during ON1 period on as-fired basis (IRWAF1), kg/hr 25.0
2. Input rate of wood fuel during ON2 period on as-fired basis (IRWAF2), kg/hr 40.0
3. Input rate of fuel during OFF period on as-fired basis (IRWAF3), kg/hr 13.0
4. Unburned carbon during ON1 period (XUNBC1), % of carbon in the fuel 4.5
5. Unburned carbon during ON2 period (XUNBC2), % of carbon in the fuel 3.0
6. Unburned carbon during OFF period (XUNBC3), % of carbon in the fuel 6.0
7. Higher heating value of wood fuel on dry basis (HHV), kJ/kg 19752.0

Third read in statement:
1. Nitrogen in combustion air on fractional basis (YN2) 0.7809
2. Oxygen in combustion air on fractional basis (Y02) 0.2095
3. Argon in combustion air on fractional basis (YAR) 0.0092
4. CO2 in combustion air on fractional basis (YCO2) 0.0003
5. CO in combustion air on fractional basis (YCO) 0.0001
6. Specific humidity of combustion air (SPH), kg H2O/kg of air 0.0038

Fourth read in statement:
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------------  End of MOD1.DAT  --------------

MOD2.DAT hold the following input parameters
First read in statement:

1. Number of temperature bins (N) 25

2. Code for flue gas analysis (FGA), IF (FGA .EQ. 1)
   flue gas analysis is given else not 1

3. Code for mass rate of flue gas analysis (MRA),
   IF (MRA .EQ. 1) mass rate is give else not 0.0

4. Specific heat of combustion air (CAIR), kJ/kg °C 1.0

5. Percent excess air during ON1 period (PEAON1) 0.0
   (Note when excess air is equal to zero, this mean program
   will compute it using dry flue gas analysis)

6. Percent excess air during ON2 period (PEAON2) 0.0

7. Percent excess air during OFF period (PEAOFF) 0.0

8. Average off period draft factor for flue gas flow 0.85

Second read in statement:

1. Bin temperature array (BT), °C (see Appendix B)

Third read in statement:

1. Number of hours in each temperature bin array (FREQ),
   (see PART I. Appendix E)

Fourth read in statement:

1. Hourly heating load array at various bin
   temperatures (HQH), kwh (see Appendix B)

Fifth read in statement:

1. Flue gas temperature during ON1 period (TFSS1), °C 260.0
2. Flue gas temperature during ON2 period (TFSS2), °C 371.1
3. Flue gas temperature during OFF period (TFSS3), °C 204.0
4. ON1 period flue gas temperature measured at TIM1 (TFON1), °C 225.0
5. ON1 period flue gas temperature measured at TIM2 (TFON2), °C 253.0
6. OFF period flue gas temperature measured at TIM3 (TFOFF3), °C 248.7
7. OFF period flue gas temperature measured at TIM4 (TFOFF4), °C 225.8
8. Minimum flue gas temperature during OFF period (TFOFF5), °C (Note this is usually equal to TFSS3) 204.0

Sixth read in statement:
1. Discrete time at which TFON1 was measured (TIM1), s 60.0
2. Discrete time at which TFON2 was measured (TIM2), s 300.0
3. Discrete time at which TFOFF3 was measured (TIM3), s 120.0
4. Discrete time at which TFOFF4 was measured (TIM4), s 720.0
5. Discrete time at which TFOFF5 was measured (TIM5), s 1020.0

Seventh read in statement:
1. Maximum boiler temperature setting (TBMAX), °C 87.8
2. Minimum boiler temperature setting (TBMIN), °C 82.2
3. Minimum boiler temperature below which its operation
   is undesirable, °C 68.0
4. Specific heat of boiler water, kJ/kg °C 3.7
5. Pipe losses (PPL), % of building load 1.0
6. Mass of water in the boiler tank (MWBT), kg 556.0
7. Average difference of boiler room temperature from
   the outside air temperature (AVDT), °C 22.22
8. Average temperature drop below maximum and minimum
   setting of boiler temperature at which control on
   the I.D. fan and open the primary air damper
   respectively, °C 5.0
9. Maximum possible boiler room temperature (MPBRT), °C 32.2

Eighth read in statement:
1. Time for which the temperature of flue gases was
   predicted during OFF to ON1 mode (TIMONT), s 1200.0
2. Time for which the temperature of flue gases was
   predicted during ON1 to OFF mode (TIMOFT), s 1800.0
3. Time interval at which temperature of flue gases are predicted, s 60.0

---------------------- End of MOD2.DAT ----------------------
PART III. APPENDIX A. LISTING OF COMPUTER PROGRAM FOR LIFE CYCLE COST ANALYSIS OF BIOFUELED ENERGY SYSTEM
DEFINITION OF REAL INPUT VARIABLES:

**HHW** = higher heating value of wood on oven dry basis (kJ/kg).

**CC** = carrying cost, $/ton

**DISR** = market discount rate (%).

**DPC** = down payment for competing system.

**DPW** = down payment for wood fired system.

**DR** = declining rate for depreciation calculations.

**HHVC** = higher heating value of competing fuel (kJ/L).

**IFCF1** = inflation rate for competing fuel cost (%) for the first period of economic life of system (NCF1 years).

**IFCF2** = IFCF for the second period (NCF2 years).

**IFCF3** = IFCF for the third period (NCF3 years).

**IFMOR** = inflation rate on mortgage (%), usually equal to zero.

**IFOP** = inflation rate for operation & maintenance cost (%).

**IFPI** = inflation rate for property taxes and insurance cost (%).

**IFWF1** = inflation rate for wood fuel cost (%) for the first period of economic life of the system (NWF1 years).

**IFWF2** = IFWF for the second period (NWF2 years).
IFWF3 = IFWF for the third period (NWF3 years).

IMOR = interest rate on mortgage amount (%).

INCR = income tax credit rate (%).

INVC = initial investment of competing system.

INVW = initial investment of wood fired system.

ITXR = state and federal income tax rates (%).

MCWF = moisture content of wood fuel, % wet basis.

PC = price of competing fuel ($/L).

PFINC = percent financed (competing system).

PFINW = percent financed (wood energy system).

POMC = first year operation & maintenance cost of competing system (% of INVC).

POMW = first year operation & maintenance cost of wood fired system (% of INVW).

PTIC = first year property tax and insurance cost of competing system (% of initial investment).

PTIW = first year property tax and insurance cost of wood fired system (% of initial investment).

PW = price of wood fuel ($/ton).

SEC = seasonal efficiency of competing system (%).

SEW = seasonal efficiency of wood energy system.

SFCON = seasonal fuel consumption, metric ton

SL = seasonal load (kJ).

SVC = salvage value of competing system at the end of the period of analysis.

SVW = salvage value of wood fired system at the end of period of analysis.

UCF = unit conversion factor, from tons to kilograms

INPUT VARIABLES FOR HARVESTING SYSTEM

PBUL = purchase price of bulldozer.

PCS = purchase price of chain saw.

PCV = purchase price of chip vans.

PFB = purchase price of feller bunchers.

PGS = purchase price of rubber tired grapple skidder.

PPUT = purchase price of pickup truck.

PTR1 = purchase price of tractor one.

PTR2 = purchase price of tractor two.

PWTC = purchase price of whole tree chipper.

PCON = purchase price of conveyor.

simlarly;

AWTC = annual use of whole tree chiper (hrs).

EWTC = economic life of whole tree chiper (years).

GWTC/DWTC = gasoline/diesel consumption of whole tree chipper (liter/hr).
NWTC = number of whole tree chipper in the harvesting system.
RWTC = repair & maintenance cost of whole tree chipper.
SWTC = salvage value of whole tree chipper (US$).
FWTC = fractional use of whole tree chipper for chipping operation.
IRS = interest rate on the system investment (%).
PGASO = price of gasoline ($/L).
PDIE = price of diesel ($/L).

INTEGER INPUT VARIABLES

CSYS = code for competing system (CSYS=0 always).
INCRC = income tax credit code.
INCRP = income tax credit period (years).
ITXC = income tax code.
MORCC = mortgage code for competing system.
MORCW = mortgage code for wood energy system.
NC = economic life of competing system (years).
NDD = no. of years for which double declining method was used for depreciation calculation, for income tax purposes.
NE = no. of years for which economic analysis is desired.
NFINC = no. of years for which competing system is financed.
NFINW = no. of years for which wood energy system is financed.
NW = economic life of wood energy system (year).
PWG = price code for wood fuel.
WSYS = code for wood energy system (WSYS=1 always).

REAL OUTPUT VARIABLES

AFC = annual fuel cost of competing system.
AFW = annual fuel cost of wood energy system.
AMPC = annual mortgage payment cost of competing system.
AMPW = annual mortgage payment cost of wood energy system.
AOMC = annual operation & maintenance cost of competing system.
AOMW = annual operation & maintenance cost of wood energy system.
APTIC = annual property tax and insurance cost of competing system.
APTIW = annual property tax and insurance cost of wood energy system.
CFZ = cash flow for zero years.
DCFS = discounted cumulative fuel savings, $.
LCCC = life cycle cost for competing system.
LCCW = life cycle cost for wood fired system.
LCS = life cycle savings for the wood fired system before income tax deduction.
LCSA = life cycle savings after taxes.
PYCF = present worth of yearly cash flow.
PYCFA = present worth of after tax yearly cash flow.
PYFS = present worth of yearly fuel savings.
SCFS = simple cumulative fuel savings.
SIR = saving to investment ratio.
YCF = yearly cash flow before income tax deductions over investment period.
YCFA = after tax yearly cash flow.
YFS = yearly fuel savings, $.
YTA = yearly taxable amount (US$).
YTAX = yearly tax liability.
YTCC = yearly total cost for competing system.
YTCW = yearly total cost for wood fired system.

**MAIN PROGRAMME**

COMMON/HAR/PWTC, FGS, FFB, PTR1, PTR2, PCV, FBUL, PPAT, PCS, PCON,
+ NWTC, NGS, NFB, NTR1, NTR2, NCV, NBUL, NPAT, NCS, NCON,
+ SWTTC, SGS, SFB, STR1, STR2, SCV, SBUL, SPAT, SCS, SCON,
+ EWTC, EGS, EFB, ETR1, ETR2, ECV, EBUL, EPAT, ECS, ECON,
+ AWTC, AGS, AFB, ATR1, ATR2, ACV, ABUL, APAT, ACS, ACON,
+ GWTC, GGS, GFB, GTR1, GTR2, GCV, GBUL, GPAT, GCS, GCON,
+ DWTC, DGS, DFB, DTR1, DTR2, DCV, DBUL, DPAT, DCS, DCN,
+ RWTC, RGS, RF, RTR1, RTR2, RCV, RBUL, RPUT, RCS, RCON,
+ FWTC, FGS, FFB, FTR1, FTR2, FCV, FBUL, FPUT, FCS, FCON

COMMON /WWW/ INVW, INVC, APTIW, APTIC, AFW, AFC, AOMW, AOMC, AMPW,
+ AMPC, NE, PWF, LCCW, LCCC, LCS, YCF, PYCF, YTCW,
+ YTCC, MORC, DP, DFC, CFZ, DIS, MORCC, SVC, YFS,
+ PYFS, SCFS, DCFS
COMMON /AWWW/ SVW, NDD, IMOR, YCFA, NFINW, LCSA, ITXR, PFINW, 
+ DEPRE, YTA, YTAX, PYCFA, INCRR, INCRP, INCRC, DR 
C
REAL APTIW(50), AFW(50), AOMW(50), AMPW(50), APTIC(50), AFC(50) 
+ AOMC(50), AMPC(50), YCF(50), YCFA(50), YTCW(50), YTCC(50), 
+ PWF(50), PYCF(50), DEPRE(50), YTA(50), YTAX(50), 
+ PYCFA(50), YFS(50), PYFS(50)
REAL INVW, IFPI, IMOR, IFMOR, INVC, IRS, NWTC, NGS, NFBD, NIR1, NCV,
+ NBUL, NPUT, NCS, IFOP, INCRR, ITXR, LCCW, LCCC, LCSW, LCSA,
+ IFWF1, IFWF2, IFWF3, IFCF1, IFCF2, IFCF3, MCWF, NTR2, NCON 
C
OPEN (UNIT=8, FILE= 'A:WEC01.DAT') 
C READ IN THE INPUT VARIABLES FOR ECONOMIC ANALYSIS OF WOOD 
C FIRED SYSTEM (WFS).
READ(8,*) INVW, SVW, PTIW, POMW, NW, NE, WSYS, CSYS 
READ(8,*) IFPI, IFOP, IMOR, IFMOR, DISR, DR, UCF 
READ(8,*) IFWF1, IFWF2, IFWF3, NWF1, NWF2, NWF3 
READ(8,*) MORCW, PFINW, NFINW, SL, SEW, HHVW, MCWF, PWG 
READ(8,*) ITXC, ITXR, INCRC, INCRR, INCRP, NDD 
C INPUT DATA FOR COMPETING SYSTEM.
READ (8,*) INVC, SVC, PTIC, POMC, PC, NC
READ (8,*) IFCF1, IFCF2, IFCF3, NCF1, NCF2, NCF3 
READ (8,*) MORCC, PFINC, NFINC, SEC, HHVC 
IF (PWG .EQ. 1.0) THEN
READ(8,*) PW 
END IF
CLOSE (UNIT=8, FILE= 'A:WEC01.DAT')
C
IF (PWG .EQ. 0.0) THEN
OPEN (UNIT=8, FILE= 'A:WEC02.DAT')
C INPUT DATA FOR HARVESTING SYSTEM.
READ (8,*) PWTC, PGs, PFB, PTR1, PTR2, PCV, PBUL, PPUT, PCS, PCON, 
+ NWTC, NGS, NFBD, NIR1, NIR2, NCV, NWUL, NPUT, NCS, NCON, 
+ SWTC, SGS, SFB, STR1, STR2, SCV, SBUL, SPUT, SCS, SCON, 
+ EWTC, EGS, EFB, ET1, ET2, ECV, EBUL, EPUT, ECS, ECON, 
+ AWTC, AGS, AFB, AT1, AT2, ACV, ABUL, APUT, ACS, ACON, 
+ GWTC, GGS, GFB, GTR1, GTR2, GCV, GBUL, GPUT, GCS, GCON, 
+ DWTC, DGS, DBF, DTR1, DTR2, DCV, DBUL, DPUT, DCs, DCON, 
+ RWTC, RGS, RFB, RAT1, RAT2, RCV, RBUL, RPUT, RCS, RCON, 
+ FWTC, FGS, FFB, FTR1, FTR2, FCV, FBUL, FPUT, FCS, FCON 
READ (8,*) IRS, PGASO, PDIE, YLBR, YPHS, CC 
CLOSE (UNIT=8, FILE= 'A:WEC02.DAT') 
END IF
C
CONVERT THE FOLLOWING VARIABLES FROM % TO DECIMALS.
IFPI = IFPI/100.
IFWF1 = IFWF1/100.
IFWF2 = IFWF2/100.
IFWF3 = IFWF3/100.
IFOP = IFOP/100.
SEW = SEW/100.
IFCF1 = IFCF1/100.
IFCF2 = IFCF2/100.
IFCF3 = IFCF3/100.
SEC = SEC/100.

C HIGHER HEATING VALUE OF WOOD FUEL ON AS RECEIVED BASIS, 
C kJ/kg .
AHHV = HHVW*(1.-MCWF/100.)

C CALL SUBROUTINE CHIP TO PREDICT THE COST OF WOODCHIPS 
C ($/TON) FOR THE WHOLE TREE CHIP HARVESTING SYSTEM.
IF (PWG .EQ. 0.0) THEN
CALL CHIP (PW, YLBR, IRS, PGASO, PDIE, YPHS, CC)
END IF

C CALL SUBROUTINE TAX TO CALCULATE THE PROPERTY TAX AND 
C INSURANCE COST FOR THE ITH YEAR OF WFS.
CALL TAX (PTIW, SVW, INVW, NW, APTIW, IFPI, NE)

C CALL SUBROUTINE FUEL TO PREDICT THE ANNUAL FUEL COST 
C FOR WFS.
CALL FUEL (SL, SEW, AHHV, PW, AFW, IFWF1, IFWF2, IFWF3, IFW1, 
NWF2, NWF3, NE, WSYS, UCF)

C CALL SUBROUTINE OPMAIN TO PREDICT THE OPERATION AND 
C MAINTENANCE COST FOR THE ITH YEAR OF THE WFS.
CALL OPMAIN (AOMW, IFOP, POMW, INVW, NE)

IF (MORCW .EQ. 1) THEN
C CALL SUBROUTINE MORTGA TO PREDICT THE ANNUALIZED EXTRA 
C MORTGAGE PAYMENT.
CALL MORTGA (DPW, INVW, PFINW, NFINW, IMOR, IFMOR, AMPW, NE)
END IF

C CALL AGAIN SUBROUTINES TAX, FUEL, OPMAIN, AND MORTGA TO WORK 
C OUT THE ANNUAL COST OF TAX & INSURANCE, FUEL, OPERATION & 
C MAINTENANCE AND EXTRA MORTGAGE PAYMENTS FOR THE COMPETING 
C SYSTEM.
CALL TAX (PTIC, SVC, INVC, NC, APTIC, IFPI, NE)
CALL FUEL (SL, SEC, HHVC, PC, AFC, IFCF1, IFCF2, IFCF3, NCF1, 
NCF2, NCF3, NE, CSYS, UCF)
CALL OPMAIN (AOMC, IFOP, POMC, INVC, NE)
IF (MORCC .EQ. 1) THEN
CALL MORTGA (DPC, INVC, PFINC, NFINC, IMOR, IFMOR, AMPC, NE)
END IF

C
CALL WORTH (SVW,SIR)

C
IF (ITXC .EQ. 1) THEN
CALL AWORTH (INVW,NW,AMPW,MORCW,DISR,YCF,CFZ)
END IF
C
CALL PBACK TO WORKOUT SIMPLE PAYBACK PERIOD .
CALL PBACK (INVW,YCF,YCFA,SPBT,SPAT,NE,ITXC,INVC)
C
CALL PBACK TO WORKOUT DISCOUNTED PAYBACK PERIOD .
CALL PBACK (INVW,PYCFA,DPBT,DPAT,NE,ITXC,INVC)
C
OPEN (UNIT=9,FILE='A:WEC0.RES')
WRITE (9,258)
258 FORMAT(15X,'ECONOMIC ANALYSIS OF BIOMASS ENERGY SYSTEM')
IF (MORCW .NE. 1 .AND. MORCC .NE. 1) THEN
YCZW = INVW
YCZC = INVC
WRITE (9,260)
260 FORMAT(//10X,'BIOMASS ENERGY SYSTEM COSTS($) FOR EXPECTED'
+ 'LIFETIME')
WRITE (9,270)
270 FORMAT(//31X,'OPERATION',5X,'PROPERTY TAX'/34X,'AND',12X,
+ 'AND',1X,'YEAR',3X,'INVESTMENT',2X,'+',2X,'FUEL',
+ '+',2X,'MAINTENANCE',2X,'+',2X,'INSURANCE','=',2X,
+ 'TOTAL COST')
WRITE (9,280) INVW,YCZW
280 FORMAT(//3X,'0',4X,F9.1,40X,F9.1)
DO 300 I = 1,NE
WRITE (9,290) I,AFW(I),AOMW(I),APTIW(I),YTCW(I)
290 FORMAT(2X,12,16X,F9.1,4X,F8.1,4X,F6.1,6X,F9.1)
300 CONTINUE
WRITE (9,310)
310 FORMAT(//44X,'OPER.',5X,'PRO. TAX'/22X,'MORT.','18X,'AND',
C
WRITE(9,340) DPW,YCZW
340 FORMAT(//5X,'0',4X,F9.1,44X,F9.1)
DO 360 I = 1,NE
WRITE(9,350) I,AMPW(I),AFW(I),AOMW(I),APTIW(I),YTCW(I)
350 FORMAT(4X,12,14X,F9.1,2X,F9.1,2X,F8.1,2X,F8.1,3X,F9.1)
360 CONTINUE
WRITE(9,310)
WRITE(9,330)
WRITE(9,340) DPC,YCZC
DO 370 I = 1,NE
WRITE(9,350) I,AMPC(I),AFC(I),AOMC(I),APTIC(I),YTCC(I)
370 CONTINUE
END IF
IF(MORCW .EQ. 1 .AND. MORCC .NE. 1) THEN
YCZW = DPW
YCZC = INVC
WRITE(9,260)
WRITE(9,330)
WRITE(9,340) DPW,YCZW
DO 380 I = 1,NE
WRITE(9,350) I,AMPW(I),AFW(I),AOMW(I),APTIW(I),YTCW(I)
380 CONTINUE
WRITE(9,310)
WRITE(9,270)
WRITE(9,280) INVC,YCZC
DO 390 I = 1,NE
WRITE(9,290) I,AFC(I),AOMC(I),APTIC(I),YTCC(I)
390 CONTINUE
END IF
IF(MORCW .NE. 1 .AND. MORCC .EQ. 1) THEN
YCZW = INVW
YCZC = DPC
WRITE(9,260)
WRITE(9,270)
WRITE(9,280) INVW,YCZW
DO 400 I = 1,NE
WRITE(9,290) I,AFW(I),AOMW(I),APTIW(I),YTCW(I)
400 CONTINUE
WRITE(9,310)
WRITE(9,330)
WRITE(9,340) DPC,YCZC
DO 410 I = 1,NE
WRITE (9, 350) I, AMPC(I), AFC(I), AOMC(I), APTIC(I), YTCC(I)

CONTINUE
END IF
WRITE (9, 420)

FORMAT (///15X, 'CASH FLOW ANALYSIS BEFORE INCOME TAXES'//
+ 15X, 'YEAR', 5X, 'YEARLY CASH', 5X, 'PRE. WORTH OF'//
+ 26X, 'FLOW', 11X, 'YCF'//)
WRITE (9, 430) CFIZ, CFZ

FORMAT (14X, ' 0 ', 7X, F9.1, 8X, F9.1)

DO 450 I = 1, NE
WRITE (9, 440) I, YCF(I), PYCF(I)

CONTINUE
WRITE (9, 460) LCCW, LCCC, LCSW

FORMAT (///15X, 'PRESENT WORTH OF LIFE CYCLE COST'/
+ 15X, 'FOR BIOMASS ENERGY SYSTEM = ', F12.1
+ ///15X, 'PRESENT WORTH OF LIFE CYCLE COST'/
+ 15X, 'FOR COMPETING SYSTEM = ', F12.1
+ ///15X, 'PRESENT WORTH OF LIFE CYCLE SAVINGS= ', F12.1
WRITE (9, 461)

FORMAT (///24X, 'FUEL SAVINGS ANALYSIS'//
+ 15X, 'YEAR', 7X, 'YEARLY FUEL', 5X, 'PRE. WORTH OF'//
+ 27X, 'SAVINGS', 10X, 'YFS'//)

DO 462 I = 1, NE
WRITE (9, 440) I, YFS(I), PYFS(I)

CONTINUE
WRITE (9, 464) SCFS, DCFS, SIR

FORMAT (///15X, 'SIMPLE CUMULATIVE FUEL SAVINGS = ', F12.1
+ F12.1/15X, 'DISCOUNTED CUMULATIVE FUEL SAVINGS = ', F12.1
+ F12.2)

IF (ITXC .EQ. 1) THEN
WRITE (9, 465)

FORMAT (///15X, 'TAXABLE AMOUNT & NET INCOME IN TAXES')
WRITE (9, 470)

FORMAT (///6X, 'YEAR', 5X, 'DIFF IN COST', 4X, 'DEPRE.', 6X,
+ 'TAXABLE', 7X, 'NET INCOME'//46X, 'AMOUNT', 6X, 'IN TAX'//)

DO 490 I = 1, NE
WRITE (9, 480) I, YCF(I), DEPRE(I), YTA(I), YTAX(I)

CONTINUE
WRITE (9, 500)

FORMAT (///15X, 'CASH FLOW ANALYSIS AFTER TAXES')
WRITE (9, 510)
510 FORMAT(//10X,'YEAR',5X,'CASH FLOW',5X,'CASH FLOW',5X,
  + 'P.WORTH OF'/34X,'AFTER TAXES',5X,'CFAT')
  WRITE(9,520) CFZ,CFZ,CFZ
520 FORMAT(//12X,'0',6X,F9.1,2(5X,F9.1))
  DO 540 I = 1,NE
      WRITE(9,530) I, YCF(I),YCFA(I),PYCFA(I)
  530 FORMAT(11X,I2,6X,F9.1,2(5X,F9.1))
  CONTINUE
  WRITE(9,545) LCSA
  545 FORMAT(///10X,'PRESENT WORTH OF LIFE CYCLE SAVINGS'/
       + 10X,'AFTER TAXES'=:F12.1)
      END IF
      IF (SPBT .EQ. 0.0) THEN
          WRITE(9,547)
  547 FORMAT(/10X,'NO SIMPLE PAYBACK PERIOD BEFORE INCOME' +
       ' TAKES')
          WRITE(9,550) SPBT
      ELSE
  550 FORMAT(/10X,'SIMPLE PAYBACK PERIOD BEFORE INCOME TAXES' +
       '=','F4.1',' YEARS')
          END IF
          IF (DPBT .EQ. 0.0) THEN
              WRITE(9,552)
552 FORMAT(/10X,'NO DISCOUNTED PAYBACK PERIOD BEFORE INCOME' +
       ' TAKES')
          ELSE
  554 FORMAT(/10X,'DISCOUNTED PAYBACK PERIOD BEFORE INCOME' +
       ' TAKES = ','F4.1',' YEARS')
          END IF
C
      IF (ITXC .NE. 1) GO TO 565
      IF (SPAT .EQ. 0.0) THEN
          WRITE(9,556)
556 FORMAT(/10X,'NO SIMPLE PAYBACK PERIOD AFTER INCOME TAXES')
          ELSE
  558 FORMAT(/10X,'SIMPLE PAYBACK PERIOD AFTER INCOME TAXES' +
       '=','F4.1',' YEARS')
          END IF
          IF (DPAT .EQ. 0.0) THEN
              WRITE(9,560)
560 FORMAT(/10X,'NO DISCOUNTED PAYBACK PERIOD AFTER INCOME' +
       ' TAKES')
          ELSE

WRITE(9,562) DPAT
562 FORMAT(/10X,'DISCOUNTED PAYBACK PERIOD AFTER INCOME' + ' TAXES = ',F4.1,' YEARS')
END IF
565 CONTINUE
WRITE(9,567) PW,PC
567 FORMAT(/10X,'PRICE OF WOOD FUEL = ',F6.2,' $/TON', + /10X,'PRICE OF COMPETING FUEL = ',F6.2,' $/L')
C
C COMPUTE SEASONAL FUEL CONSUMPTION, METRIC TON
SFCON = SL/(AHHV*SEW*1000.)
C CONVERT SEASONAL LOAD FROM KJ TO kWh
SL = SL/3600.
SEW = SEW*100.
WRITE(9,570) SL,SEW,SFCON
570 FORMAT(/10X,'TOTAL SEASONAL HEATING LOAD = ',F12.2, + ' kWh/10X,'SEASONAL EFFICIENCY = ',F6.1, + '/10X,'SEASONAL FUEL CONSUMPTION = ',F12.2, + ' Metric ton')
STOP
END
C
SUBROUTINE CHIP (PW,YLBR,IRS,PGASO,PDIE,YPHS,CC)
Q
**************************************************************
c * THIS SUBROUTINE PREDICTS THE COST OF WOODCHIPS ($/TON) * c FOR THE WHOLE TREE HARVESTING SYSTEM . * c * c DEFINITION OF VARIABLES: * c **************************************************************
C YDEP = yearly depreciation cost of harvesting system, $ * C YFC = yearly fixed cost of harvesting system (HS), $ * C YGC = yearly gasoline cost of harvesting system, $ * C YINT = yearly amount of interest on the investment of * C harvesting system, $ * C YTIH = yearly taxes,insurance & housing cost of the * C system, $ * C YLUBC= yearly lubrication cost of the system, $ * C YRC = yearly repair & maintenance cost, $ * C YVC = yearly total variable cost, $/hr * C PW = cost of wood chips, $/ton * C YTC = yearly total operating cost, $/hr * C **************************************************************
C
COMM/HAR/PWTC,PGS,PFB,PTR1,PTR2,PCV,PBUL,PPUT,PCS,PCON,
+ NWTC,NGS,NFB,NTR1,NTR2,NCV,NBUL,NPUT,NCS,NCON,
+ SWTC,SGS,SEB,STR1,STR2,SCV,SBUL,SPUT,SCS,SCON,
+ EWT,C,EGS,EFB,ETR1,ETR2,ECV,EBUL,EPUT,ECOS,ECON,
+ AWT,C,AGS,AFB,ATR1,ATR2,ACV,ABUL,APUT,ACS,ACON,
+ GTW,C,GGS,GBE,GTR1,GTR2,GCV,GBUL,GPUT,GCOS,GCON,
+ DWT,C,DGS,DFB,DTR1,DTR2,DCV,DBUL,DPUT,DCS,DCON,
+ RWT,C,RGB,RFB,RTR1,RTR2,RCV,RBUL,RPUT,RCOS,RCON,
+ FWT,C,FGS,FFB,FTR1,FTR2,FCV,FBUL,FPUT,FCOS,FCON
REAL IRS,NWTC,NGS,NFB,NTR1,NTR2,NCV,NBUL,NPUT,NCS,NCON
YDEP = NWTC*FWTC*((PWTC-SWTC)/EWTC) +
+ NGS*FGS*((PGS-SGS)/EGS) +
+ NFB*FFB*((PFEB+FFB)/EFB) +
+ NTR1*FTR1*((PTR1+STR1)/ETR1) +
+ NTR2*FTR2*((PTR2+STR2)/ETR2) +
+ NCV*FCV*((PCV+SCV)/ECV) +
+ NBUL*FBUL*((PBUL+SBUL)/EBUL) +
+ NPUT*FPUT*((PPUT+SPUT)/EPUT) +
+ NCS*FCS*((PCS+SCS)/ECS) +
+ NCON*FCON*((PCON+SCON)/ECON)

C
YINT = (NWTC*FWTC*SWTC)/2. +
+ NGS*FGS*(PGS+SGS)/2. +
+ NFB*FFB*(PFEB+FFB)/2. +
+ NTR1*FTR1*(PTR1+STR1)/2. +
+ NTR2*FTR2*(PTR2+STR2)/2. +
+ NCV*FCV*(PCV+SCV)/2. +
+ NBUL*FBUL*(PBUL+SBUL)/2. +
+ NPUT*FPUT*(PPUT+SPUT)/2. +
+ NCS*FCS*(PCS+SCS)/2. +
+ NCON*FCON*(PCON+SCON)/2.) * IRS/100.

C
YTHI = 0.01*(NWTC*FWTC*PWTC+NGS*FGS*PGS+NFB*FFB+PFBB+
+ NTR1*FTR1*FTR1+STR1+FTR2*PTR2+NCV*FCV+FCV+
+ NBUL*FBUL*PBUL+NPUT*FPUT*PPUT+NCS*FCS+NCS+
+ NCON+FCON*FCON)
YFC = YDEP + YINT + YTHI
YGC = (NWTC*GWC*AWTC*FWTC + NGS*GS+GAC*FGS +
+ NFB*GB*AFB*FFB + NTR1*ATR1*GTR1*FTR1 +
+ NCV*GC+AFB*FFB + NBUL*GBUL*ABUL*FBUL +
+ NPUT*GPUT*APUT*PUT + NCS*GCS*ACOS*FCV +
+ NTR2+GTR2*ATR2*FTR2 + NCON*GCON*ACON*FCON)*PGASO
YDC = (NWTC*GWTC*FWTC + NGS*GDS*GDS+GFS +
+ NFB*DFB*AFB*FFB + NTR1*DTR1*ATR1*FTR1 +
+ NCV*DCV*ACV*FCV + NBUL*DBUL*ABUL*FBUL +
+ NPUT*DPUT*APUT*FPUT + NCS*DCS*ACS*FCS +
+ NTR2*DTR2*ATR2*FTR2 + NCON*DCON*ACON*FCON)*PDIE

YLUBC = 0.15*(YGC+YDC)

C

YRC = ((RWTC/100.)*NWTC*PWTC*AWTC*FWTC +
+ (RGS/100.)*NGS*PGS*AGS*FGS +
+ (RFB/100.)*NFB*PFB*AFB*FFB +
+ (RTR1/100.)*NTR1*PTR1*ATR1*FTR1 +
+ (RTR2/100.)*NTR2*PTR2*ATR2*FTR2 +
+ (RCV/100.)*NCV*PCV*ACV*FCV +
+ (RBUL/100.)*NBUL*PBUL*ABUL*FBUL +
+ (RPUT/100.)*NPUT*PPUT*APUT*FPUI +
+ (RCS/100.)*NCS*PCS*ACS*FCS +
+ (RCON/100.)*NCON*PCON*ACON*FCON)/100.

C

YVC = YGC+YLUBC+YRC +YLBR
YTC = YFC + YVC
PW = YTC/YPHS + CC

C

RETURN
END

C

SUBROUTINE TAX (PTI,SV,INV,N,APTI,IFPI,NE)
C
C DEFINITION OF VARIABLES:
C
C APTI = annual property tax & insurance cost of the ith
C year
C DEP = depreciation of the system using straight line
C method
C IPTI = property tax and insurance rate for the ith year
C
C REAL APTI(50),PTI,SV,INV,PRIN,IPTI(50),IFPI
C
C DEP = (INV-SV)/N
C TO CALCULATE THE PROPERTY TAX & INSURANCE RATE (PTI) FOR
C INFLATION.
C
DO 10 I = 1,NE
IPTI(I) = PTI*(1.+IFPI)**(I-1)
CONTINUE
I = 1
APTI(I) = INV*IPTI(I)/100.
PRIN = INV
DO 20 I = 2,NE
PRIN = PRIN-DEP
APTI(I) = PRIN*IPTI(I)/100.
20 CONTINUE
RETURN
END

SUBROUTINE FUEL (SL, SE, HHV, PFUEL, AF, IFF1, IFF2, IFF3, 
+ NF1, NF2, NF3, NE, SYS, UCF)

C ***************************************************************
C * THIS SUBROUTINE PREDICTS THE ANNUAL FUEL COST OF THE * 
C * ENERGY SYSTEMS * 
C ***************************************************************
C
REAL AF(50), SL, SE, HHV, PFUEL, IFF1, IFF2, IFF3, IFFI(50)

C TO CALCULATE THE FIRST YEAR FUEL COST.
C
IF (SYS .EQ. 1.0) THEN
FYFC = ((SL*PFUEL)/(SE*HHV*UCF))
ELSE
FYFC = ((SL*PFUEL)/(SE*HHV))
END IF

C
DO 5 I = 1,NF1
IFFI(I) = (1.+IFF1)**(I-1)
5 CONTINUE
IF (NF2 .EQ. 0.0) GO TO 20
DO 10 I = 1,NF2
N = NF1+I
IFFI(N) = IFFI(NF1)*(1.+IFF2)**I
10 CONTINUE
IF (NF3 .EQ. 0.0) GO TO 20
N = NF1+NF2
DO 15 I = 1,NF3
NN = N+I
IFFI(NN) = IFFI(N)*(1.+IFF3)**I
15 CONTINUE
DO 25 I = 1, NE
AF(I) = FYFC * IFFI(I)
25 CONTINUE
C
RETURN
END
C
C
SUBROUTINE OPMAIN (AOM, IFOP, POM, INV, N)
C*****************************************************************************
C            THIS SUBROUTINE PREDICTS THE OPERATION & MAINTENANCE           *
C            COST FOR THE ITH YEAR OF THE ENERGY SYSTEMS                  *
C*****************************************************************************
C
REAL AOM(50), IFOP, POM, INV
C
TO CALCULATE THE FIRST YEAR OPERATION & MAINTENANCE COST.
FY0M = POM*INV/100.
C
TO CALCULATE THE OPERATION & MAINTENANCE COST FOR THE ITH
YEAR.
DO 20 I = 1, N
AOM(I) = FY0M*(1. + IFOP)**(I-1)
20 CONTINUE
C
RETURN
END
C
C
SUBROUTINE MORTGA (DP, INV, PFN, NFIN, IMOR, IFMOR, AMP, N)
C*****************************************************************************
C            THIS SUBROUTINE PREDICTS THE ANNULIZED EXTRA MORTGAGE          *
C            PAYMENTS                                                      *
C*****************************************************************************
C
C DEFINITION OF VARIABLES:
C*****************************************************************************
C             AMP = annual payment on the mortgage, $
C             DP = down payment, $
C             MORTA= mortgage amount, $
C*****************************************************************************
REAL AMP(50), INV, IMOR, IFMOR, MORTA
C
TO CALCULATE THE DOWN PAYMENT.
DP = INV-(PFIN*INV)/100.
C
TO CALCULATE THE MORTGAGE AMOUNT.
MORTA = (PFIN*INV)/100.
C
TO CALCULATE ANNUAL PAYMENT ON THE MORTGAGE.
PWF = WFAC(NFIN, IMOR, IFMOR)
DO 20 I = 1,N
IF (I .GT. NFIN) THEN
AMP(I) = 0.0
ELSE
AMP(I) = MORTA/PWF
ENDIF
20 CONTINUE
RETURN
END
C
C
SUBROUTINE WORTH (SVW, SIR)
C ***********************************************************************
C * THIS SUBROUTINE PREDICTS THE CASH FLOW ANALYSIS BEFORE INCOME TAXES *
C * AND THE TOTAL PRESENT WORTH OF THE LIFE CYCLE SAVINGS FOR BIOMASS ENERGY SYSTEM *
C ***********************************************************************
C
COMMON/WWW/ INVW, INVC, APTIW, APTIC, AFW, AFC, AOMW, AOMC, AMPW,
+ AMPC, NE, PWF, LCCW, LCCC, LCSW, YCF, PYCF, YTCC,
+ YTCW, MORCW, DPW, DPC, CFZ, DISR, MORCC, SVC, YFS,
+ PYFS, SCFS, DCFS
C
REAL INVW, INVC, APTIW(50), APTIC(50), AFW(50), AFC(50),
+ AOMW(50), AOMC(50), DISR, YCF(50), LCCW, LCCC, LCSW,
+ PWF(50), AMPW(50), AMPC(50), YTCW(50), YTCC(50), PYCF(50),
+ YFS(50), PYFS(50)
C
TO CALCULATE THE PRESENT WORTH OF LIFE CYCLE COST FOR BIOMASS ENERGY SYSTEM.
SAPT = 0.0
SAF = 0.0
SAOM = 0.0
SAMP = 0.0
DO 20 I = 1,NE
PWF(I) = PAC(I,DISR)
SAPT = SAPT + APTW(I)*PWF(I)
SAF = SAF + AFW(I)*PWF(I)
SAOM = SAOM + AOMW(I)*PWF(I)
IF (MORCW .EQ. 1) THEN
SAMP = SAMP + AMPW(I)*PWF(I)
END IF
20 CONTINUE
C BEGINNING OF BLOCK OF CODE TO CALCULATE THE PRESENT WORTH OF THE SALVAGE VALUE OF THE WOOD ENERGY SYSTEM.
PSVW = ((SVW/100.)*INVW)*PWF(NE)
IF (MORCW .EQ. 1) THEN
LCCW = DPW+SAMP+SAPT+SAF+SAOM-PSVW
ELSE
LCCW = INVW+SAPT+SAF+SAOM-PSVW
END IF
C TO CALCULATE THE PRESENT WORTH OF LIFE CYCLE COST FOR COMPETING SYSTEM.
SSAPT = 0.0
SSAF = 0.0
SSAOM = 0.0
DO 40 I = 1,NE
SSAPT = SSAPT + APTIC(I)*PWF(I)
SSAF = SSAF + AFC(I)*PWF(I)
SSAOM = SSAOM + AOMC(I)*PWF(I)
IF (MORCC .EQ. 1) THEN
SSAMP = SSAMP + AMPC(I)*PWF(I)
END IF
40 CONTINUE
C BEGINNING OF BLOCK OF CODE TO CALCULATE THE PRESENT WORTH OF THE SALVAGE VALUE OF THE COMPETING SYSTEM.
PSVC = ((SVC/100.)*INVC)*PWF(NE)
IF (MORCC .EQ. 1) THEN
LCCC = DPC+SSAMP+SSAPT+SSAF+SSAOM-PSVC
ELSE
LCCC = INVC+SSAPT+SSAF+SSAOM-PSVC
END IF
C TO CALCULATE THE CASH FLOW FOR ZERO YEAR.
IF (MORCW .EQ. 1 .AND. MORCC .EQ. 1) THEN
CFZ = DPC-DPW
END IF
IF (MORCW .NE. 1 .AND. MORCC .NE. 1) THEN
CFZ = INVC-INVW
END IF
IF (MORCW .EQ. 1 .AND. MORCC .NE. 1) THEN
  CFZ = INVC-DPW
END IF
IF (MORCW .NE. 1 .AND. MORCC .EQ. 1) THEN
  CFZ = DPC-INVW
END IF

TO CALCULATE THE YEARLY CASH FLOW BEFORE INCOME TAXES.
DO 50 I = 1,NE
IF (MORCW .EQ. 1 .AND. MORCC .EQ. 1) THEN
  YTCW(I) = AMPW(I)+APTIW(I)+AFW(I)+AOMW(I)
  YTCC(I) = AMPC(I)+APTIC(I)+AFC(I)+AOMC(I)
END IF
IF (MORCW .NE, 1 .AND. MORCC .NE. 1) THEN
  YTCW(I) = APTIW(I) + AFW(I) + AOMW(I)
  YTCC(I) = APTIC(I) + AFC(I) + AOMC(I)
END IF
IF (MORCW .EQ. 1 .AND. MORCC .NE. 1) THEN
  YTCW(I) = AMPW(I) + APTIW(I) + AFW(I) + AOMW(I)
  YTCC(I) = APTIC(I) + AFC(I) + AOMC(I)
END IF
IF (MORCW .NE. 1 .AND. MORCC .EQ. 1) THEN
  YTCW(I) = APTIW(I) + AFW(I) + AOMW(I)
  YTCC(I) = AMPC(I) + APTIC(I)+ AFC(I)+AOMC(I)
END IF
IF (I .EQ. NE) THEN
  YCF(I) = YTCC(I)-(SVC/100.)*INVC - (YTCW(I)-(SVW/100.)*INVC
  ELSE
    YCF(I) = YTCC(I) - YTCW(I)
  END IF

YEARLY FUEL SAVINGS .
YFS(I) = AFC(I) - AFW(I)
CONTINUE

TO CALCULATE THE PRESENT WORTH OF LIFE CYCLE SAVINGS FOR
WOOD FIRED SYSTEM.
LCSW = LCCC-LCCW
TO CALCULATE THE PRESENT WORTH OF YEARLY CASH FLOW & FUEL
SAVINGS .
SCFS = 0.0
DCFS = 0.0
DO 60 I = 1,NE
  PYCF(I) = YCF(I)*PWF(I)
  PYFS(I) = YFS(I)*PWF(I)
  SCFS = SCFS + YFS(I)
  DCFS = DCFS + PYFS(I)
PRESENT WORTH OF INCREMENTAL OPERATION & MAINTENANCE COST.
PIOM = SAOM-SSAOM

PRESENT WORTH OF INCREMENTAL SALVAGE VALUE.
PISV = PSVW-PSVC

SAVING TO INVESTMENT RATIO.
SIR = (DCFS-PIOM)/((INVW-INVC)-PISV)
RETURN
END

SUBROUTINE A Worth (INVW,NW,AMPW,MORCW,DISR,YCF,CFZ)

THIS SUBROUTINE PREDICTS THE AFTER TAX LIFE CYCLE SAVINGS AND YEARLY CASH FLOW FOR BIOMASS ENERGY SYSTEM

DEFINITION OF VARIABLES:
INVW = AMOUNT OF INVESTMENT FOR WHICH STRAIGHT LINE METHOD IS APPLICABLE, $
NSS = NUMBER OF YEARS FOR WHICH STRAIGHT LINE METHOD IS APPLICABLE
YINT = YEARLY INTEREST PAYMENT, $
YTA = YEARLY TAXABLE AMOUNT, $

TO CALCULATE THE YEARLY DEPRECIATION USING THE DOUBLE DECLINING METHOD.

COMMON/AWWW/ SVW,NDD,IMOR,YCFA,NFINW,LCSA,ITXR,PFINW, + DEPRE,YTA,YTAX,PYCFA,INCRR,INCRP,INCRC,DR

REAL DEPRE(50),INVW,YCF(50),MORTA,AMPW(50),PYCFA(50),INVSS, + YINT(50),YTA(50),YCFA(50),YTAX(50),IMOR,PWF(50),ITXR, + INCRR,LCSA

TO CALCULATE THE YEARLY DEPRECIATION USING THE DOUBLE DECLINING METHOD.
SDD = 0.0
DO 10 I = 1,NDD
VN = INVW*(1.-DR/NW)**I
VNP1 = INVW*(1.-DR/NW)**(I+1)
IF (I .EQ. 1) THEN
DEPRE(I) = INVW - VN
ELSE

DEPRE(I) = VN - VNP1
END IF
SDD = SDD + DEPRE(I)
10 CONTINUE
C
NSS = NW - NDD
INVSS = INVW - SDD
II = NDD + 1
DO 20 I = II,NW
DEPRE(I) = (INVSS - SVW)/NSS
20 CONTINUE
C
IF (MORCW .EQ. 1) THEN
C TO CALCULATE THE YEARLY INTEREST PAYMENT.
MORTA = (PFINW*INVW)/100.
PBAL = MORTA
DO 25 I = 1,NFINW
YINT(I) = (IMOR*PBAL)/100.
PPAY = AMPW(I) - YINT(I)
PBAL = PBAL-PPAY
25 CONTINUE
END IF
LCSA = 0.0
DO 40 I = 1,NW
IF (YCF(I) .LE. 0.0) THEN
YTA(I) = 0.0
YTAX(I) = 0.0
GO TO 35
END IF
C TO CALCULATE THE YEARLY TAXABLE AMOUNT.
IF (MORCW .EQ. 1) THEN
YTA(I) = YCF(I) - DEPRE(I) - YINT(I)
ELSE
YTA(I) = YCF(I) - DEPRE(I)
END IF
IF (YTA(I) .LE. 0.0) YTA(I) = 0.0
C TO CALCULATE THE INCREASE IN TAX LIABILITY.
IF (INCRC .EQ. 1) THEN
IF ( I .GT. INCRP) GO TO 30
YTAX(I) = (ITXR/100.)*YTA(I) - ((INCRR/100.)*INVW)
GO TO 35
END IF
30 YTAX(I) = (ITXR/100.)*YTA(I)
35 CONTINUE
IF( YTAX(I) .LE. 0.0) YTAX(I) = 0.0
TO CALCULATE THE AFTER TAX YEARLY CASH FLOW.

\[ YCFA(I) = YCF(I) - YTAX(I) \]

TO CALCULATE THE PRESENT WORTH OF AFTER TAX YEARLY CASH FLOW.

\[ PWF(I) = PAC(I, DISR) \]

\[ PYCFA(I) = YCFA(I) \times PWF(I) \]

\[ LCSA = LCSA + PYCFA(I) \]

CONTINUE

LIFE CYCLE SAVINGS AFTER TAXES.

\[ LCSA = LCSA + CFZ \]

RETURN

END

SUBROUTINE PBACK (INVW,YCF,YCFA,NPBT,NPAT,NE,ITXC,INVC)

THIS SUBROUTINE PREDICTS THE PAYBACK PERIOD (SIMPLE & DISCOUNTED) BEFORE AND AFTER TAX PAYMENTS.

REAL INVW,YCF(50),YCFA(50),NPBT,NPAT,NE,ITXC,INVC

TO CALCULATE THE PAYBACK PERIOD BEFORE TAX PAYMENTS.

\[ AC = 0.0 \]

\[ DIC = INVW - INVC \]

\[ DO 20 I = 1, NE \]

IF (YCF(I) .LE. 0.0) GO TO 20

\[ AC = AC + YCF(I) \]

IF (AC .GE. DIC) GO TO 30

20 CONTINUE

\[ NPBT = 0.0 \]

GO TO 35

30 NPBT = I - (AC-DIC)/YCF(I)

CONTINUE

TO CALCULATE THE PAYBACK PERIOD AFTER TAX PAYMENT.

IF (ITXC .EQ. 1) THEN

\[ AAC = 0.0 \]

\[ DO 40 I = 1, NE \]

IF(YCFA(I) .LE. 0.0) GO TO 40

\[ AAC = AAC + YCFA(I) \]

IF (AAC .GE. DIC) GO TO 50

40 CONTINUE

\[ NPAT = 0.0 \]

GO TO 55
NPAT = I - (AAC - DIC)/YCFA(I)
CONTINUE
END IF
RETURN
END

FUNCTION WFAC (NFIN,IMOR,IFMOR)
C****************************************************************
c *
THIS FUNCTION CALCULATES THE PRESENT WORTH FACTOR *
C *
C****************************************************************
REAL IMOR,IFMOR,INMOR,INFMOR
INMOR = IMOR/100.
INFMOR= IFMOR/100.
TO CALCULATE THE PRESENT WORTH FACTOR.
WFAC = 1./(INMOR-INFMOR)*(1. -((1. + INFMOR)/(1. +INMOR))**NFIN)
RETURN
END

FUNCTION PAC (I,DYISR)
C *****************************************************************
C THIS FUNCTION CALCULATES THE PRESENT WORTH OF THE ITH YEAR OF CASH FLOW
C *****************************************************************
C TO CALCULATE THE PRESENT WORTH FOR THE ITH YEAR.
D = DISR/100.
PAC = 1./((1+D)**I
RETURN
END
PART III. APPENDIX B. A TYPICAL OUTPUT OF COMPUTER PROGRAM FOR LIFE CYCLE COST ANALYSIS OF BIOFUELED ENERGY SYSTEM
ECONOMIC ANALYSIS OF BIOMASS ENERGY SYSTEM

BIOMASS ENERGY SYSTEM COSTS ($) FOR EXPECTED LIFETIME

<table>
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<tr>
<th>YEAR</th>
<th>INVESTMENT + FUEL + MAINTENANCE</th>
<th>PROPERTY TAX AND INSURANCE</th>
<th>TOTAL COST</th>
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### COMPETING SYSTEM COSTS ($) FOR EXPECTED LIFETIME OPERATION

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### CASH FLOW ANALYSIS BEFORE INCOME TAXES

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PRESENT WORTH OF LIFE CYCLE COST
FOR BIOMASS ENERGY SYSTEM = 92340.1

PRESENT WORTH OF LIFE CYCLE COST
FOR COMPETING SYSTEM = 98062.9

PRESENT WORTH OF LIFE CYCLE SAVINGS = 5722.9
## FUEL SAVINGS ANALYSIS

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<td>25</td>
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</tbody>
</table>

SIMPLE CUMULATIVE FUEL SAVINGS = 154642.3

DISCOUNTED CUMULATIVE FUEL SAVINGS = 56696.0

SAVING TO INVESTMENT RATIO = 1.23

SIMPLE PAYBACK PERIOD BEFORE INCOME TAXES = 10.4 YEARS

DISCOUNTED PAYBACK PERIOD BEFORE INCOME TAXES = 18.5 YEARS

PRICE OF WOOD FUEL = 20.00 $/TON
PRICE OF COMPETING FUEL = 0.21 $/L
TOTAL SEASONAL HEATING LOAD = 123055.60 kWh
SEASONAL EFFICIENCY = 40.0%
SEASONAL FUEL CONSUMPTION = 101.95 Metric ton
### PART III. APPENDIX C. INPUT PARAMETERS FOR LIFE CYCLE COST ANALYSIS OF McNAY BIOMASS ENERGY SYSTEM

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Real variables:</strong></td>
<td></td>
</tr>
<tr>
<td>1. carrying cost of biofuel (CC), $/ton</td>
<td>10.0&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2. market discount rate per year (DISR), %</td>
<td>8.0</td>
</tr>
<tr>
<td>3. declining rate for depreciation calculations (DR), %</td>
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</tr>
<tr>
<td>4. higher heating value of wood fuel on oven dry basis (HHVW), kJ/kg</td>
<td>19752.0</td>
</tr>
<tr>
<td>5. higher heating value of competing fuel (HHVC), kJ/L</td>
<td>25000.0&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>6. inflation rate for competing fuel cost for the first period (25 years) of economic life (NCF1) of system, %</td>
<td>4.0</td>
</tr>
<tr>
<td>7. IFCF for the second period (IFCF2), %</td>
<td>0.0</td>
</tr>
<tr>
<td>8. IFCF for the third period (IFCF3), %</td>
<td>0.0</td>
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<tr>
<td>9. inflation rate on mortgage (IFMOR), %</td>
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</tr>
<tr>
<td>10. inflation rate for operation &amp; maintenance cost (IFOP), %</td>
<td>4.0</td>
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</tbody>
</table>

<sup>a</sup>Consultation with Dr. Joe P. Colletti

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>11.</td>
<td>inflation rate for property tax &amp; insurance cost (IFPI), %</td>
<td>4.0</td>
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<tr>
<td>12.</td>
<td>inflation rate for wood fuel cost for the first period of economic life (25 years) of the system (IFWF1), %</td>
<td>4.0</td>
</tr>
<tr>
<td>13.</td>
<td>IFWF for the second period (IFWF2), %</td>
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</tr>
<tr>
<td>14.</td>
<td>IFWF for the third period (IFWF3), %</td>
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<tr>
<td>15.</td>
<td>interest rate on the mortgage amount (IMOR), %</td>
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<tr>
<td>16.</td>
<td>income tax credit rate (INCRR), %</td>
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<td>17.</td>
<td>initial investment of competing system (INVC), $</td>
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<tr>
<td>18.</td>
<td>initial investment of wood fired system (INVW), $</td>
<td>35000.0</td>
</tr>
<tr>
<td>19.</td>
<td>state &amp; federal income tax rates (ITXR), %</td>
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<tr>
<td>20.</td>
<td>price of competing fuel (PC), $/L</td>
<td>0.21</td>
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<tr>
<td>21.</td>
<td>moisture content of wood fuel (MCWF), %</td>
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<tr>
<td>22.</td>
<td>percent financed competing system (PFINC)</td>
<td>0.0</td>
</tr>
<tr>
<td>23.</td>
<td>percent financed wood energy system (PFINW)</td>
<td>0.0</td>
</tr>
<tr>
<td>24.</td>
<td>first year operation &amp; maintenance cost of competing system (POMC), % of INVC</td>
<td>0.25</td>
</tr>
<tr>
<td>25.</td>
<td>first year operation &amp; maintenance cost of wood fired system (POMW), % of INV</td>
<td>5.00</td>
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</table>
26. first year property tax & insurance cost of competing system (PTIC), % of INVC 0.0
27. first year property tax & insurance cost of wood fired system (PTIW), % of INVW 0.0
28. seasonal efficiency of competing system (SEC), % 65.0
29. seasonal efficiency of wood energy system (SEW), % 40.0
30. seasonal load (SL), kJ 4.43E+8°
31. salvage value of competing system at the end of period of analysis (SVC), % of INVC 10.0
32. salvage value of wood fired system at the end of period of analysis (SVW), % of INVW 10.0
33. real interest rate on the investment of harvesting system (IRS), % 7.0
34. yearly production of harvesting system, tons (YPHS), tons 100.0
35. yearly labor cost (YLBH), $/100 tons 3800.0
36. price of gasoline (PGASO), $/L 0.28
37. Price of diesel fuel (PDIE), $/L 0.32
38. Capacity of both systems, million kJ/hr 0.52

Integer Input Variables:

1. code for competing system (CSYS) 0 (always)
2. income tax credit code (INCRC) 0
3. income tax credit period, years (INCRP) 0
4. income tax code (ITXC) 0
5. mortgage code for competing system (MORCC) 0
6. mortgage code for wood energy system (MORCW) 0
7. economic life of competing system (NC) 25
8. no. of years for which double declining method were used for depreciation calculations for income tax purposes (NDD) 0
9. number of years for which economic analysis is desired (NE) 25
10. number of years for which the wood energy system is financed (NFINW) 0
11. number of years for which the competing system is financed (NFINC) 0
12. economic life of wood energy system (NW) 25
13. price code for wood fuel (PWG) 1 (0)
14. code for wood energy system (WSYS) 1 (always)