THE FEASIBILITY OF A SOLAR POWERED SORPTION DEHUMIDIFICATION SYSTEM APPLIED TO GRAIN DRYING

by

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SYMBOLS

c	specific heat (BTU/lb F)
h	convective heat transfer coefficient (BTU/hr ft**2 F)
hfg	heat of vaporization (BTU/lb)
rh	relative humidity, decimal
t	time, hours
x	bed-depth coordinate, ft
G	dry weight flow rate, lb/hr ft**2
H	humidity ratio, lb/lb
M	local or average moisture content, dry basis (decimal)
MR	moisture ratio, dimensionless
P	pressure, psia
R	gas constant, ft lb/lb
S	cross-sectional bed area, ft**2
T	air temperature, F
Tabs	absolute temperature, R
V	velocity, ft/hr
ρ	dry weight density, lb/ft**3
θ	product temperature, F
ϵ	bed porosity, decimal

as a lower case symbol beside the main variable:

a	air
e	equilibrium
in	inlet
o	at time t=o
p	product

SYMBOLS....CONT.

s	saturated vapor
t	at time t
v	vapor
w	water

INTRODUCTION

During the past five years at Kansas State University, research has been conducted in the Mechanical Engineering Department to model the performance and feasibility of a solar powered sorption dehumidifier. The dehumidifier uses a rotating bed of silica gel. This desiccant removes water from the air stream that is to be dehumidified. Once the desiccant becomes saturated, it is regenerated with the use of solar heated air. As this project progressed, a practical application for the use of the dehumidified air was sought.

The sorption dehumidified air lends itself to a multitude of applications in both industry and agriculture. Dehumidified air has found use in the production of foods, environmental countrol, the chemical and pharmaceutical industries, and the drying of lumber. Recently, the use of solar powered dehumdified air to dry grains has become a topic of interest to the agricultural community concerned with the fossil fuel depletion and subsequent rising conventional fuel costs.

Of the agricultural crops requiring drying, corn uses the most energy, is the largest grain crop in terms of total production, and is normally harvested with more excess moisture than any other grain crop (13). It has been estimated that at least as much energy is used in drying an acre of corn as is used for all the other farm operations necessary to grow and harvest that acre, including operations such as soil preparation, planting, cultivation, and harvesting (16).

The present research applied the numerical model of the solar energy powered sorption dehumidifier to the drying of shelled corn. The objectives of this research were:

1. Decide upon a type of grain dryer that would be most applicable in ease of mathematical modeling, management, and maintenance for research purposes.
2. Once a certain type of dryer was selected, seek out the numerical models available for use.
3. Couple the selected dryer model to the existing sorption model, so that the performance of the complete system can be predicted.
4. With the total sorption grain drying model in hand, model (with the use of various subroutines) three systems for comparison purposes:
    1. Grain dried with the use of ambient air.
    2. Grain dried with solar heated air.
    3. Grain dried with the solar sorption dehumidified air.

THE DEHUMIDIFICATION PROCESS

Solid sorption can be accomplished by absorption of adsorption, depending upon whether there is a chemical change in the desiccant during the process. In the absorption of water vapor on a desiccant, the desiccant undergoes a chemical change to a hydrate state. With the addition of more moisture, absorption will cause the desiccant to dissolve into solution. In adsorption, the desiccant does not react chemically with the condensed water vapor. Sorbent is the term referring to the desiccant, which sorbs moisture from the moist air stream to be dehumidified. The sorbate is the substance sorbed, the water vapor in the air.

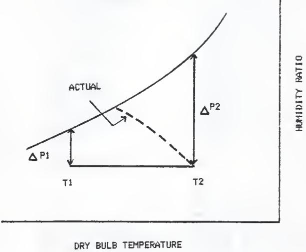
In the sorption process a moisture mass transfer takes place due to a water vapor partial pressure gradient between the desiccant and the air. This process will continue until the vapor pressure of the water in the desiccant reaches equilibrium with the partial pressure of the water vapor in the surrounding air. The result of this action is that the moisture content of the air decreases, and the moisture content of the desiccant increases.

Sorption is an exothermic process, resulting from the heat of condensation of the water vapor plus the heat of wetting. This last term, the heat of wetting, occurrs when the liquid water droplets and the desiccant (silica gel) contact one another. It is greatest when the desiccant has just been reactivated and tapers off as the sorbent reaches saturation. The heat of condensation and the heat of wetting together make up the heat of sorption.

Solid sorbents generally are extremely porous "solid foam", with large internal surface areas. Silica gel, the sorbent used in this study, is

FIGURE 1.1

PSYCHROMETRIC CHART



used to take up moisture at room temperatures from an air stream flowing through it. The process of adsorption by solid desiccants is reversible. Air, when warmed by passing through a solar collector, has an increase in its moisture carrying capacity. Figure 1.1 depicts the reason for this. At a lower temperature, T1, the maximum amount of moisture that can be "picked up" before the air stream reaches saturation, is symbolized by ΔP1 on a psychrometric chart. However, if the air stream is sensibly heated to T2, the maximum amount of moisture that can be held by the air stream, is symbolized by ΔP2. In practice, the maximum Δ P2 will not be reached because some of the energy in the air is lost to the heating of the desiccant. This process is shown as a dotted line on Figure 1.1. Because the higher air stream temperature of the regeneration process causes the air to be further from saturation, equilibrium is sought between the saturated desiccant and the air stream, and water vapor is transferred from the desiccant to the air. Silica gel is especially suited to this application since the temperatures needed to regenerate this desiccant are those attainable by flat plate collectors.

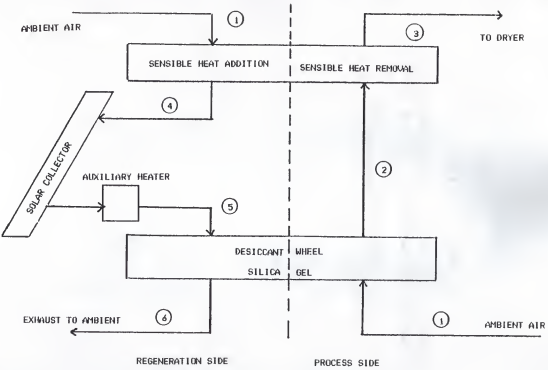
Background

The solar powered sorption dehumidification system in this study was initially developed by Singer (28). It utilizes a desiccant (silica gel) to dehumidify air through adsorption, with solar energy to regenerate the desiccant. Singer's work had three main objectives:

1. To select an optimum solar dehumidification technique by evaluating the numerous dehumidification types and arrangements with regard to their application to the use of solar energy.
2. Develop a computer model simulating this solar dehumidification process.
3. Construct a test apparatus of this system so an evaluation could be made of the computer model.

A schematic of the continuous solar air dehumidification system choosen by Singer is shown in Figure 2.1. To make the system continuous, the desiccant wheel is rotated, allowing the simultaneous dehumidification of air through one half of the bed and desiccant regeneration in the remaining portion of the bed. The flow of air is directed through the system by way of two isolated flow paths: the process flow stream, in which air will be dehumidified, and the regeneration flow stream which is used to regenerate the desiccant.

Silica gel was selected as the desiccant material to be used in the dehumidifier. The reasons for this were threefold. First, silica gel is readily available commercially, and is accepted by the dehumidification industry. Secondly, there is published material available regarding the physical characteristics and equilibrium data of silica gel and water vapor (10) (19) (20). Finally, there have been investigations into the numerical



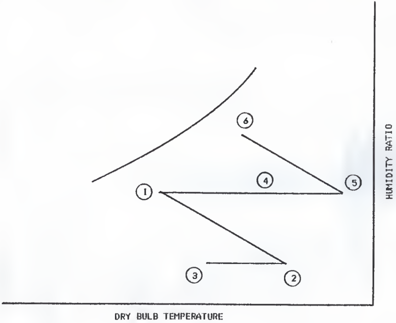
SCHEMATIC OF THE SOLAR POWERED SORPTION DEHUMIDIFICATION SYSTEM
FIGURE 2.1

modeling of the silica gel dehumidification process utilizing fixed and rotating beds (24) (26).

Figure 2.2 shows a psychrometric plot of the flow streams at each state during the dehumidificatiion process. Air to be dehumidified (ambient air) enters the process flow stream at state 1 and is adiabatically dehumidified to state 2. The dried air has a higher dry bulb temperature resulting from the heat of sorption being converted to sensible heat in the process airstream. This flow stream then passes through an optional sensible heat exchanger to reduce the final dry bulb temperature to state 3 if desired.

The regeneration flow stream begins with ambient air at state 1. The air is heated to state 4 by passing it through the sensible heat exchanger, adding the heat extracted from the process flow stream. Because this temperature is too low for desiccant bed regeneration, the flow stream is then directed through the flat plate solar collector. If the temperature is still not sufficient for regeneration, an auxiliary heater energizes to increase the temperature to state 5. As the regeneration air stream passes through the desiccant bed, the bed is regenerated and the air stream is humidified to state 6 where it is released to the atmosphere.

The model adopted by Singer to simulate the rotating desiccant bed was developed by Maclaine-Cross and Banks (23). Their solution involved the transformation of mass and energy conservation equations into two potential kinetic wave equations. These equations were linearized and solved numerically to provide exit air stream temperature and humidity. Nelson (24) applied this model to rotating desiccant wheels and published a computer program to apply this method to a rotating bed of silica gel. Singer modified Nelson's program and also included subroutines to model the performance of the solar collector. This constituted a comprehensive



PSYCHROMETRIC PLOT OF THE DEHUMIDIFICATION PROCESS

FIGURE 2.2

system model of a silica gel air dehumidifier with solar energy powered regeneration.

A physical system was built consisting of a desiccant wheel, sensible heat exchanger, air seals, motor drives, dehumidification housing and ducting, solar collector, blowers, auxiliary heaters, and instrumentation. Singer performed numerous tests to compare the predicted results with the experimental results obtained. The computer program was found to be acceptable in predicting the performance of the experimental solar dehumidifier.

Ananth (2) continued the verification of Singer's work by collecting additional data from the experimental apparatus. He studied the performance of the system over a wide range of parameters, varying air flow rates, temperatures, humidity ratios and peripheral leakage rates for the process and regeneration streams. Performance curves were estabilished over all possible ranges for the variables of interest. Ananth also modified the computer program to accept varying inlet conditions within the time frame of the study.

Following Ananth's work, Atkinson (4) began work on incorporating TMY-SOLMET weather data (31) with the dehumidifier model. Since the performance of a solar energy powered system depends on weather conditions, the application of recorded, "averaged" weather data, would allow an hourly estimation of the performance of the dehumidification system. The TMY-SOLMET weather tape provides a typical meteorological year for a particular location. The typical year was determined using statistical methods to select a typical month, for each of the twelve calendar months, from a data bank of 23 year's observation. The tape provides weather data for 26 locations within the United States. Variables such as extraterrestrial, beam, diffuse, and engineering corrected radiation are provided. Other variables on the tape are dry bulb temperature, dew point temperature, atmospheric pressure, and absolute humidity.

Once the performance of the dehumidification process was modified to accept location weather data, Atkinson began work on an economic feasibility study. The method choosen was the P1, P2 method outlined by Duffie and Beckman (12). This method relates present worth factors for the life cycle costs, which is merely the present worth of all costs. This method is applied to both the conventional and solar system to provide a foundation for comparision. The reader is encouraged to consult Atkinson's thesis (4) for further details.

Throughout the course of studying the sorption dehumidifier, the investigators Singer, Ananth, and Atkinson modified the computer model many times, for various reasons. It would be appropriate at this time to summarize the state of this program and it's subroutines when the present investigator began work. The main program served as the basis for reading the location weather data and the calculation of the economic analysis. There were problems with the reading of the weather data, because an algorithm had not been developed which would allow the crossing of month boundaries in reading the tape. The first day of the year was also unattainable. The main program allowed for the input of the economic parameters and functioned as the mechanism for calling the subroutines. There were five subroutines associated with the dehumidifier model: **SYSTEM, COLPER, HUMID, ALFAV, EGV.**

SYSTEM

The subroutine **SYSTEM** read data for the following parameters:

1. The program option, IFLAG, indicated whether the temperture of the regeneration air into the dehumidifier was set to a minimum temperature reached by

the use of an auxiliary heater (#2), or if the entering air temperature was to be set to the outlet temperature of the solar collector (#1).

2. Collector data such as the air volume flow rate (l/s), optimum slope of the collector (see appendix A), latitude and longitude were read.
3. Dehumidifier data including duct temperature drops, the geometrical properties of the silica bed, the revolutions per second of the desiccant wheel, the minimum regeneration temperature (if using option #2, IFLAG), leakage rates, and heat exchanger efficiency were also provided.

SYSTEM called the subroutines **COLPER** and **HUMID**. Output from this subroutine was provided in the form of an echo printing of the dehumidifier operating parameters. An hourly temperature and humidity map of the process side of the dehumidifer, and an hourly temperature and humidity map of the regeneration side was also provided. A total heat balance map of the dehumidifier, heat exchanger, ducting to and from the collector, the collector, the auxiliary heater, and the surplus solar heat available could also be found in this subroutine.

COLPER

The subroutine **COLPER** modeled the performance of the solar collector. It was originally developed by Singer and based on equations in Duffie and Beckman (12). The subroutine determined the useful heat gain in the collector by calculating the amount of radiation striking the collector. It did this by utilizing ambient conditions, collector orientation, time of day, and time of year. Knowing the incident radiation on the surface of the collector, the subroutine proceeded to obtain the collector efficiency given ambient conditions, inlet collector conditions, and loss coefficients. Once the efficiency was calculated, the collector useful heat gain and outlet temperature were determined.

The **COLPER** subroutine also established the amount of heat lost through the ductwork from the collector to the dehumidifier, given estimated temperature drops. If the temperature returning to the dehumidifier was below the required inlet regeneration temperature, the **COLPER** subroutine found the amount of auxiliary heat required to assure proper regeneration temperature. The amount of heat available for storage was also determined. The collector modeled in this section utilized the manufacturer's performance curves for a Solaron Series 3000 collector, but could be modified for other manufactured collectors.

HUMID

THE **HUMID** subroutine analytically modeled the simultaneous heat and mass transfer occuring within the desiccant bed. The model developed by MacLaine-Cross and Banks (23) and computerized by Nelson (24), predicted the performance of a rotating, silica gel, desiccant bed. The subroutine provided process and regeneration outlet temperatures and humidity ratios. Please refer to Singer (28) and Ananth (2) for further details.

ALFAV

ALFAV was a support subroutine for the **HUMID** subprogram. It supplied the equilibrium properties of the moist silica gel and the air water vapor mixture. Nelson's Thesis (24) provides an indepth explanation of the exact function of this subroutine, please consult it for further details.

EGV

EGV (Equilibrium Gamma Values) was also a support subroutine for the **HUMID** subprogram. It determined the incremental steps that would be taken in determining the temperature and humidity ratios during the computational procedure. Consult Nelson (24) or Atkinson (4) for clarification of the purpose of this segment.

All of the subroutines and the main program had to be able to interact with variables of common interest. This was done through the use of large common blocks that allowed the transfer of information from one subprogram to another. Examples included within the common blocks were: the weather data, the inlet and outlet conditions of the major components of the system, counters, and properties of state, location, and geometry.

This thesis completes the next step in the development of the application of this sorption dehumidifier model. The application is directed toward grain drying.

LOAD MODEL

The amount of moisture in grain has an effect on its performance for such processes as harvesting, storage, and germinating. If the grain is too "wet" it will provide an environment in which molds and insects will thrive. If the grain is "over-dried", it's ability to germinate can be adversely effected. In practice, grain will not be harvested at moisture contents greater than 35% and grain drying will not usually continue for moisture contents below 10% (wet basis) (21).

The grain moisture contents in Table 3.A are those recommended for the safe storage of grain. The length of time that crops can be stored varies with the moisture content and type of crop. To store a crop for 5 years the moisture content should be approximately 2% below the moisture content that is considered safe for a 1 year storage (8).

Table 3.A
Moisture Content During Harvest and for Safe Storage, Percent, w.b.

Cereal	Maximum During Harvest	Optimum at Harvest for Minimum Loss	Usual when Harvested	Required for Safe Storage for 1 yr	for 5 yr
Barley	30	18-20	10-18	13	11
Corn	35	28-32	14-30	13	10-11
Oats	32	15-20	10-18	14	11
Rice	30	25-27	16-25	12-14	10-12
Rye	25	16-20	12-18	13	11
Sorghum	35	30-35	10-20	12-13	10-11
Wheat	38	18-20	9-17	13-14	11-12

From **Drying Cereal Grains**, Brooker, BakKer-Arkema, and Hall, 1982.
Sources: C. W. Hall (1957); D. W. Hall (1970); Matz (1969); Sinha (1973).

The objective in grain drying is to reduce the moisture content so that spoilage will not occur before the grain can be used. Drying a high-moisture grain at an original moisture content, (Mo), to a final moisture content, (Mf), can be carried out over a long period of time if a low drying air temperature is used; less time is required when a higher air temperature is used.

Temperature is not the only parameter that influences the time required to reduce the moisture content of a grain. Air relative humidity, airflow, initial moisture content and final moisture content all dictate the amount of time that will be required to reach the desired condition of the grain. The usual ranges of airflow and temperature are listed in Table 3.B (B).

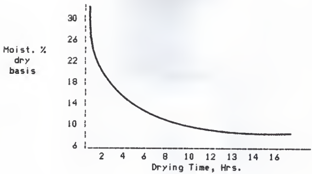
Table 3.B
Usual Range of Airflows for Drying Systems, CFM/BU

Aeration	1/50 - 1
Natural Air (unheated)	2 - 5
Layer Drying	2 - 10
Heated Air (130 - 500 F)	30 - 100

A typical drying curve is shown in Figure 3.1. The reader will notice the characteristic rapid rate of drying initially, and the slower rate, as the total time of the drying increases (21). As the moisture content gets closer to equilibrium conditions with the air, the drying becomes so slow that is can hardly be detected. This description applies to the drying of grain of any kind that is fully exposed to an atmosphere of constant temperature and humidity. Generally, the rate of drying is faster if the initial moisture content was higher. High drying temperatures and low air absolute humidity will also result in faster drying rates.

Figure 3.1

Typical Drying Curve



At this point, some important concepts in the understanding of grain drying will be defined; Equilibrium Moisture Content (EMC), Moisture Ratio (MR), and the reporting of moisture content on a wet or dry basis (w.b. and d.b., repectively).

Equilibrium Moisture Content

The equilibrium moisture content determines the minimum moisture content to which grain can be dried under a given set of drying conditions. It is defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time. EMC depends upon the humidity and temperature conditions of the surroundings as well as the maturity and type of grain (8).

Moisture Ratio

The moisture ratio is a quantity often referred to in grain drying nomenclature. It is defined as:

$MR = (M - Me) / (Mo - Me)$

where -

MR = moisture ratio.

M = current moisture content of the grain.

Me = desired moisture content of the grain at the end of drying.

Mo = moisture of the grain at the start of drying.

Moisture Content on a Wet Basis

The moisture content of a grain is used as a measure of maturity and quality. The elevators, or market place, are usually interested in the moisture content on a wet basis. This is because the denominator, the wet weight, is the quantity obtained when the truck loaded with the grain is weighed. The definition of a wet basis moisture content is (8):

$$M_w \text{ wet basis} = \frac{w - d}{w}(100)$$

where: w = wet weight   d = dry weight

Mw = moisture content on a wet, percent basis

Moisture Content on a Dry Basis

The moisture content of a grain on a dry basis is used in many engineering calculations. Definition:

$$M_d \text{ dry basis} = \frac{w - d}{d}(100)$$

where: Md = moisture content on dry basis, percentage

For example, if we are told that grain has a moisture content of 25%, we might expect this to mean that 100 lb. of grain contains 25 lb. of water; this is correct if the moisture content is expressed in per cent wet basis. On the other hand, it is just as reasonable to assume that the 25% moisture content is expressed on a dry basis; in this case 100 lb. of grain contains 20 lb. of water and 80 lb. of dry matter since 20 is 25% of 80. Accordingly, when the moisture content is reported as percentage it is necessary to have an understanding as to which basis is used. One is neither more correct nor more logical than the other (21).

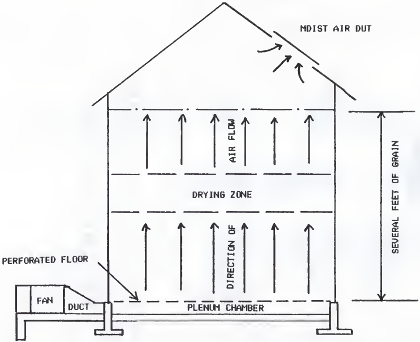
In selecting a grain drying mathematical model to be coupled with the solar sorption dehumidifier model, a dryer system had to first be selected. There are several types of dryer designs that were considered. They basically fell into two broad categories: those that dry grain in batches, and those that dry grain as it flows continuously through the equipment.

Batch Drying

Fixed Bed Drying

This type of system can use a bin with diameter from a few feet, to many feet. It is usually deep (up to 16 feet) and has a perforated floor through which a relatively low airflow rate is provided. The inlet air can be ambient or heated. The grain can just "set there" or it can be stirred. Characteristic of fixed bed drying is the phenomenon of "drying zones". Figure 3.2 is a schematic of a fixed bed dryer. As drying air moves upward, there is an exchange of moisture, from grain to air, in a finite depth or zone of grain. At the start of the drying process the zone is located at the bottom of the dryer. As the drying continues the zone moves upward, and the grain has been dried to EMC when the zone reaches the top of the bed.

There are several different types of batch systems that will not be discussed further because they are too difficult to apply as a mathematical model and they require careful management in use. Brooker, et al., (8) provide a thorough discussion on the subject in the chapter titled "Grain Drying Systems".



SCHEMATIC OF A FIXED BED DRYER

FIGURE 3.2

Continuous Flow Dryers

Crossflow Dryers

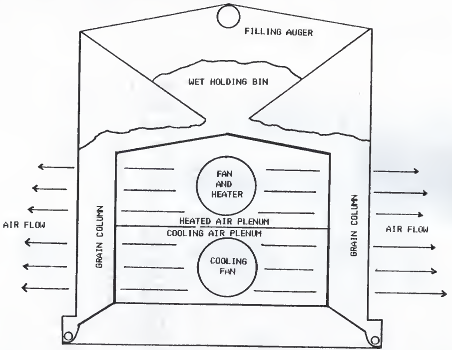
Figure 3.3 is a sketch of a typical crossflow dryer, in which grain flows from a wet-grain holding bin at the top, down the columns, and is discharged at the bottom. The upper portions of the columns are drying sections and the lower portions are cooling sections. A metering device and temperature sensor are used to regulate the flow rate of the grain. The name "Crossflow" comes from the fact that the flow of heated air is perpendicular to the flow of the grain (8).

Concurrent Dryers

In concurrent dryers the air flows in the same direction as the grain. Figure 3.4 is a schematic of such a dryer. There are no large central plenums used in this dryer as are used in the crossflow dryer. The characteristics of a concurrent dryer are a series of small ducts used to introduce the air and to also provide for the escape of the air. Heated air is forced into the upper row of ducts, and cool air is forced into the lower ducts. Both the heated and cool air exhaust through a duct that extends across the dryer. Wet grain is preheated as it moves downward along the ducts carrying heated air with it. After the grain passes the lower edge of the ducts, the air and the grain move in the same direction. The hottest air enters the wettest grain and is quickly cooled. The grain temperature is lower than the air temperature at this point in the flow, because a high rate of evaporation is taking place. As the grain continues to move downward, its temperature increases and then decreases along with that of the drying air (8).

Counterflow Dryers

In counterflow dryers the air flows in the opposite direction of the



SCHEMATIC OF A CROSSFLOW DRYER

FIGURE 3.3

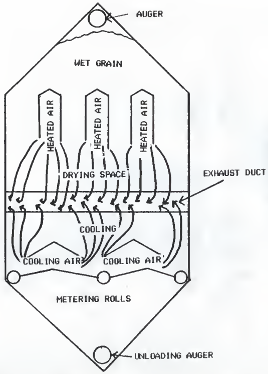


FIGURE 3.4 - SCHEMATIC OF A CONCURRENT FLOW DRYER

movement of the grain. This method can be visualized by considering a bin which holds a group of thin layers of grain. The drying air blows upward through the layers. At each time interval, a new layer is placed on the top of the stack and a layer removed from the bottom. See Figure 3.5 for an example counterflow dryer (28) (8).

One of the biggest drawbacks of a continuous flow dryer for research purposes is the extra equipment needed for material handling, and the problems that could arise in the maintenance and management of the necessary moving mechanical parts. Usually, there is associated with the continuous flow systems a considerable amount of expensive handling equipment (augers, metering devices, temperature sensors). In fact, the capacity of such a system may actually be limited by the capacity of the auger system. Maintenance of all mechanical equipment would also have to be considered.

Another problem that arises when considering the use of a continuous flow system is the higher temperatures needed (200-500F). Since there is less contact time during the process between the drying air and the grain, the higher air temperatures are needed to obtain the same results as in a batch dryer. This results in a inefficent use of the energy in the hot air because a good portion of that energy is used in heating the grain. The application of a solar collector to heat the air entering a continuous flow system would present several problems. Costs of collector systems to provide high temperatures are considerably greater than for lower temperature systems. Collection efficiencies are reduced in high-temperature collectors unless expensive measures are taken to limit heat losses (13).

On the other hand, a batch-type, fixed bed dryer has the following advantages:

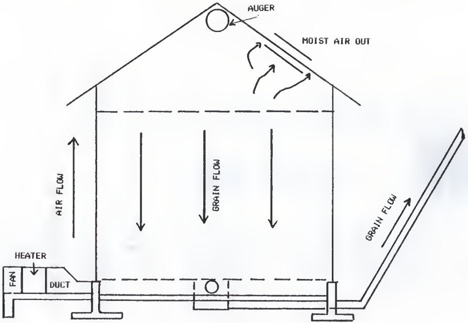


FIGURE 3.5 - SCHEMATIC OF A COUNTER FLOW DRYER

1. The grain can be harvested at any rate desired.
2. Simple management.
3. Minimum grain handling.
4. The energy in the drying air is efficiently used.
5. The grain is not over-dried.
6. The low-temperature air causes a minimum of cracking.
7. The temperatures needed for batch drying are obtainable with flat plate collectors.

Although a batch dryer may not dry as quickly as a continuous flow dryer, it can provide an excellent basis for comparisons of feasibility and performance when varying the drying air temperature and humidity. Therefore, the dryer choosen for this study was a fixbed bed, batch dryer. Once the dryer type was selected, a mathematical model for the fixed bed dryer was investigated.

Review of Grain Drying Models

Research was done to determine what types of drying models were available for use. Hukill (21) in 1954 proposed a model that expressed analytically the moisture of the grain as a function of bed height and time. More recently, Thompson, et al, (27) developed mathematical grain drying models for concurrent flow, crossflow, and counterflow grain dryers. These models were empirical in nature and apply only to corn drying. Grain drying models based on laws of heat and mass transfer lead to complicated systems of equations that can only be solved with the use of large computers (but can more generally be applied to other biological products). Bloome and Shove (7), and Barre, et al, (6), made a number of assumptions in their analyses to simplify the solution of the the heat and mass transfer drying equations. Their assumptions have been claimed only partially valid by colleagues (8). The most general application of the fundamental laws of heat and mass transfer to drying biological products was made by Bakker-Arkema, et al, (5).

The grain drying model developed by Bakker-Arkema, et al, at Michigan State University was the model choosen in this study. The reasons for this were:

1. The equations of mass and heat transfer are general in nature, and therefore could be applied to other biological products when an appropriate thin-layer equation could be determined.
2. Fully documented computer listings for the modeling of fixed bed, crossflow, concurrent, and counterflow driers are included (5). If the type of dryer was later changed in some further study, the models would be available.

3. The grain drying models could be considered a black box which only required certain input information in order to furnish the desired output.
4. The models developed at MSU are capable of predicting the performance of fixed bed, crossflow, concurrent, and counterflow driers to within 10% of experimental drying rates and temperatures (25).

The fixed-bed model is based on ideas of Schumann (1929), Van Arsdel (1955), Klapp (1961), and Bakker-Arkema, et al (1967). The highlights of the model as described in **Drying Cereal Grains** (B) will be detailed in the following pages.

Initially an elemental bed volume is drawn as shown in Figure 4.1. Energy and mass balances are written on a differential volume (Sdx). The four unknowns in this system of equations are: M, the average grain kernel moisture content; H, the humidity ratio of the air; T, the air temperature; and θ, the kernel temperature. Four equations must be derived to solve for the four unknowns.

The four equations required to solve this model follow:

1.) Enthalpy of the Air

Energy out = energy in - energy transferred by convection

$$(Gaca + GacvH)*(T + (\partial T/\partial x)dx)Sdt=(Gaca + GacvH)STdt - haSdx(T-\theta)dt$$

2.) Enthalpy of the Product

energy transferred = change in internal product energy - energy for evaporation

$$haSdx(T-\theta)dt =$$

$$(\rho pcp + \rho pcwM)Sdx(\partial \theta/\partial t)dt$$

$$-[hfg + cv(T - \theta)]Ga(\partial H/\partial x)dxSdt$$

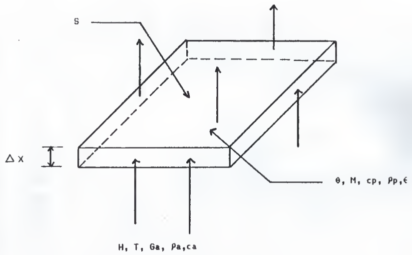


FIGURE 4.1 - ELEMENTAL BED VOLUME

3.) Humidity of the Air

moisture transferred = moisture in - moisture out

$$\rho pSdx(\partial M/\partial t)dt = GaSHdt - GaS(H + (\partial H/\partial x)dx)dt$$

4.) Moisture Content

$$(\partial M/\partial t) = \text{ an appropriate thin layer equation.}$$

These equations constitute the simulation model for the fixed bed grain dryer. Since an analytical solution to the system of equations is impossible, the differential equations are solved by finite difference techniques.

The initial and boundary conditions of the corn and the drying air must be known in order to solve the equations. The known values must include:

1. The initial temperature and moisture content of the grain.
2. The initial temperature and humidity of the drying air.

The specific boundary conditions for the fixed bed dryer are:

$$T(o,t) = T(\text{inlet})$$

$$\theta(x,o) = \theta(\text{initial})$$

$$H(o,t) = H(\text{inlet})$$

$$M(x,o) = M(\text{initial})$$

Where T = temperature of the air, θ = temperature of the grain, H = humidity ratio of the air, M = moisture content of the grain.

The program uses the following sequence in solving the differential equations:

1.) input data
2.) initialize arrays
3.) evaluate constants used
4.) solve the differential equations
5.) ouput when appropriate

To solve the model equations, the values of T, H, θ, and M must be specified at each position within the bed before the dryer is started. Bakker-Arkema, et al, found the following method to be the most stable and reliable:

$$T(x,o) = T(inlet)$$

$$\theta(x,o) = \theta(initial)$$

$$H(x,o) = H(inlet)$$

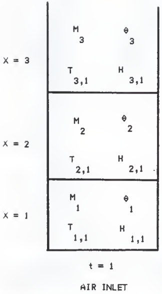
$$M(x,o) = M(initial)$$

The conditions above are physically incorrect because they assume the first blast of drying air displaces all air within the dryer without heat or mass transfer. The bed is initialized this way strictly for stability. Also covered in this initialization process is the grain temperature next to the air inlet. This temperature is set equal to the average of the inlet air and the initial grain temperature:

$$\theta(o,o) = (T(inlet) + \theta(initial))/2$$

The third initialization step is to solve for all values of the absolute humidity, moisture content, air temperature, and grain temperature for each position in the bed for the first time through the calculations. Figure 4.2 shows the indexing scheme for the pertinent values in this study.

The portion of the computer program that models the fixed bed dryer is made up of a main program **FIXBED** and three subroutines; **LAYEQ2**, **READYT**, **ZEROIN**. There are also functions called upon in the calculations such as **EMC**, and all the functions included in the **SYCHART PACKAGE**. Common properties such as the heat capacity of air and water, atmospheric pressure, and the bulk density of the grain were made available to all the subroutines and functions through the use of a **BLOCKDATA FORTRAN** option.



SUBSCRIPTS x,t where x = depth in bed
t = time

FIGURE 4.2 - INDEXING SCHEME

FIXBED

This is the main program for the numerical modeling of the fixed bed grain dryer. It is within this segment that all the initialization takes place and the actual depth calculations occur. All constants needed are calculated, and all output for the dryer originates here. It also serves as the basis for calling needed subroutines and functions.

Function EMC

EMC is a function subroutine that computes the Equilibrium Moisture Content of corn from a given relative humidity and temperature. The equations used are:

For temperatures less than 235F the DeBoer equation -(see appendix B).

For temperatures greater than 235F the Thompson equation -(see appendix C).

LAYEQ2

The subroutine **LAYEQ2** is the thin layer drying equation that calculates the moisture content of the grain as it varies with time. There are thin layer equations that apply to different grain temperature ranges. The equations used in this study were the Subbah equation (see appendix D) for grain temperatures below 80F, and the Troeger equation (see appendix E) for grain temperatures between 80F and 160F. The question arose; could the Troeger equation be used as a less accurate, but relatively reliable predictor of moisture contents for temperatures less than 80F? The benefits of using one thin layer equation would allow the temperature boundary of 80F to be crossed in a study time frame. This would eliminate the need for complicated checks within the bed to determine which equation to use. If the Troeger equation was found to be unsatisfactory in predicting moisture contents for grain temperatures below 80F, how was the situation to be handled if both equations were required at different positions within the bed? To answer this question, a trial run was made.

Ambient air for Omaha, NE was used as the dryer inlet air for the day of October 20. The simulation had the air enter a fixed bed dryer of five feet in height and one square foot in cross sectional area. The CFM was set at 120, and the grain temperature was initially set at 60F. The initial corn moisture content was 33% dry basis. There were 15 increments per foot in the calculations. In the first simulation the Troeger equation was used; in the second the Subbah. The results can be found in Table 4.A and Graph #1. The Troeger equation was found to be unacceptable in predicting moisture content in grain below 80F. Therefore , if the study crossed the boundary of 80F, different thin layer equations would have to be employed.

READYT

This subroutine is a support program for LAYEQ2 , it makes preliminary checks and calculations for the thin layer equation and calculates the moisture ratio.

SYCHART PACKAGE

The **SYCHART** group of 19 function subprograms and one subroutine are a numerical modeling of the psychrometric chart. Lerew (22) programmed this collection of theoretical and empirical psychrometric equations as a set of interconnected FORTRAN subprograms. Dry-bulb, wet-bulb and dew-point temperature, humidity ratio, relative humidity, vapor pressure, enthalpy and specific volume equations are included in the model. If any two independent properties of moist air are known, it is possible to find the remaining properties.

ZEROIN

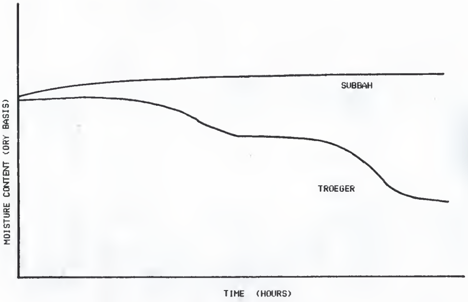
ZEROIN is a root finding technique. It is based upon an algorithm which is a mixture of linear interpolation, extrapolation and bisection. ZEROIN will issue a warning when there are no roots or multiple roots between the initial guesses. If this error message appears, it normally

TABLE 4.A

VALUES OF MOISTURE CONTENT SIMULATED USING THE TROEGER AND SUBBAH EQUATIONS

input conditions: product temperature 60F
moisture content 33%
120 CFM
ambient air is the drying air

HOUR	MOISTURE CONTENTS AT THE SECOND FOOT IN THE BED TROEGER	SUBBAH
1	.3269	.3333
3	.3269	.3333
5	.3270	.3333
7	.3283	.3340
9	.3305	.3347
11	.3292	.3347
13	.3254	.3347
15	.3173	.3347
17	.3080	.3347
19	.3019	.3347
21	.3003	.3347
23	.2996	.3347
25	.2985	.3347
27	.2977	.3347
29	.2970	.3347
31	.2958	.3347
33	.2932	.3347
35	.2862	.3347
37	.2755	.3347
39	.2660	.3347
41	.2591	.3347
43	.2545	.3347
45	.2502	.3347
47	.2468	.3347



GRAPH #1 - MOISTURE CONTENT (DRY BASIS) VS. TIME (HOURS) indicates instability requiring a larger value for the number of layers calculated per foot.

MODIFICATIONS TO THE FIXBED PROGRAM

In order to apply this model to the existing solar sorption dehumidifier, the program had to be modified to accept varying inlet conditions of air absolute humidity and temperature. Problems also arose in the repetition of some variable names used in both the fixed bed program and the existing sorption dehumidifier program. The programs together, had to be interfaced with the use of large common blocks. The grain temperature boundary of 80F could not be reasonably crossed, due to the checks that would have to be made at each node to determine which thin layer equation to use during transition periods.

To allow for variations in the entering air properties, the ENTRY FORTRAN option was used to allow the calculations to begin inside the depth loop after the initialization process had taken place. Each hour, the air exiting from the dehumidifier had a different temperature and humidity. To compensate for this variation, at each hour the bottom nodes of the bed were set to the exit conditions of the dehumidifier. (or the ambient air, or collector exit conditions, depending upon the study.) The numerical analysis then continued in the same manner, taking into account the change in the bottom node. These changes eventually were noticed at nodes higher up in the bed as the process continued. The reader will notice when consulting Appendix I, that the relative humidity was not reset to allow for varying inlet conditions. This was because to do so, would require excessive calculation and this quantity was not of primary concern to the writer.

Also considered in the modification of the fixed bed program were the constants involved in the calculations, and how they would be affected by

Table 4.8

THE EFFECTS OF CHANGES IN THE ENTERING ABSOLUTE HUMIDITY ON THE FIXBED FORTRAN PROGRAM

	ABS HUMIDITY			
Name	.0001	.0020	.0060	.0100
CON1	64.69458	64.49754	64.08662	63.68097
CON2	120.29984	119.93344	119.16934	118.41502
CON3	60.51686	60.42650	60.23761	60.05043
CON4	10.37428	10.37428	10.37428	10.37428
CON5	38.71001	37.71001	37.71001	37.71001
CON6	121.03372	120.85300	120.47522	120.10086
CON7	1941.19702	1942.12183	1944.04980	1945.95410
SCON1	86.54869	86.24405	85.60966	84.98454
SCON2	0.44726	0.44884	0.45217	0.45549
SCON3	39.18451	39.10738	38.94649	38.78748
DELT	0.02158	0.02157	0.02155	0.02153

The change in value of all constants is less than 2% when the entering absolute humidity varies from 0.0001 to 0.0100.

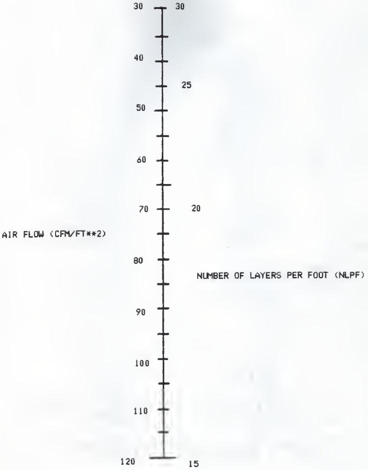


FIGURE 4.3 - APPROXIMATE VALUES OF AIR FLOW RATE VS. NUMBER OF LAYERS PER FOOT

changes in the entering air properties. There are many terms which do not change in a particular drying problem. The reader should consult Grain Dryer Simulation (5) for further details concerning these constants. They are, briefly, intermediate values that are calculated using constant values such as air flow rate, specific heats, and densities. It was determined that all constants changed in value less than 2%, when the entering absolute humidity varied from 0.0001 to 0.0100. Only one constant, cons7, was found to alter noticeably with changes in air temperature. This was because cons7 contains a ΔT term, and consequently varied considerably with changing air temperatures. Consequently, all the constants except cons7, were calculated only once. They were calculated at the air conditions of the first hour of the study, and remained constant throughout. Cons7, however, was placed inside the depth loop, and calculated each hour to compensate for changes in entering air temperatures. (see Table 4.B).

The size of the increments for depth and time are extremely critical in the fixed bed program. If too large, the equations will diverge or oscillate from the true solution. If too small, the solution requires excessive, and expensive computer time. Figure 4.3 contains approximate values of air flow rate verses number of layers per foot necessary for stability. If the program fails with good data, there are two options available to the user; raise the value of the number of layers per foot, or lower the safety factor in the time increment equation.

The fixed bed program will terminate and return control to the main program when one of two things happen; 1.) The specified drying time has been met. 2.) The average moisture content in the bed falls below the specified value. A sample output of the fixed bed program as well as the modified listing can be found in Appendices I and G, respectively.

DESCRIPTION OF SYSTEMS STUDIED

Six different systems were considered in the application of solar powered sorption dehumidified air to dry shelled corn. A brief outline of each system follows in the next few pages. Included in the descriptions are schematics of the processes detailed.

SYSTEM 1 AND 1A

The systems 1 and 1A are made up of a fixed bed dryer, that will dry the commoditiy, shelled corn. A fan is used to blow air into the plenum chamber located at the bottom of the dryer. The air passes through a perforated floor, then upward through the grain, removing moisture, and exiting in a saturated state at the top of the dryer. The only difference between the two systems is the use of an auxiliary heater in system 1A to preheat the inlet ambient air, to a set value of 100 F. Modeling these two systems will accomplish two things. First, the rate at which the location ambient air will dry the grain can be determined. Secondly, a comparison can be made between the two systems on how much faster the auxiliary heater will dry the same bin of grain, and how much the user would have to pay in the way of auxiliary energy for that faster drying time. The auxiliary heat is supplied in this study by liquefied petroleum gas. The cost of this fossil fuel was set at $10.00/10**6 BTU. Figures 5.1 and 5.2 are schemtics of systems 1 and 1A, respectively.

The numerical modeling of the systems 1 and 1A required the following information and subroutines to be calculated:

1. The TMY-SOLMET weather data for the particular location studied. (Omaha, Nebraska)
2. The fixed bed dryer simulation. This includes the calculation of air temperature, product temperature, moisture content,

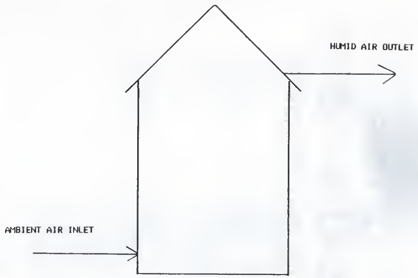


FIGURE 5.1 - FIXED BED DRYER (AMBIENT DRYING AIR - SYSTEM 1)

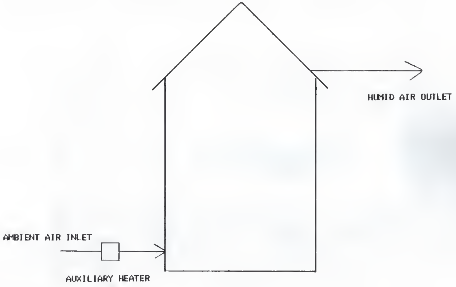


FIGURE 5.2 - FIXED BED DRYER (HEATED AMBIENT DRYING AIR - SYSTEM 1A)

and absolute humidity to be calculation for each position in the bed.

3. In the case of system 1A, the calculation of the auxiliary energy required to maintain the inlet dryer air at 100 F dry bulb temperature.

SYSTEM 2 AND 2A

Systems 2 and 2A are represented in figures 5.3 and 5.4, respectively. Ambient air enters a flat plate collector and is warmed to a temperature dictated by the ambient conditions and collector variables. The warmed air is then used to dry the shelled corn. Once again, the difference between the two systems is that system 2A uses an auxiliary heater to heat the air to a set minimum inlet temperature of 100F. There will be times when the collector will warm the air to a temperature which is greater than 100F. If this situation occurs, the extra energy was not allowed to be used. The inlet air temperature remained constant at 100F. This allowed the amount of auxiliary energy needed to produce the same drying air as the auxiliary heated ambient air, to be quantified. However, this is definately a variable that needs to be studied, as suggested in in the section RECOMMENDATIONS FOR FURTHER STUDY.

The numerical modeling of these two systems required the use of the following subroutines:

1. The TMY-SOLMET weather data for the particular location studied. (Omaha, NE)
2. The fixed bed dryer simulation.
3. The collector performance subroutine, COLPER.
4. The calculation of the auxiliary energy used by system 2A to maintain the inlet dryer air at 100F.
5. An economic analysis to determine the life cycle costs of

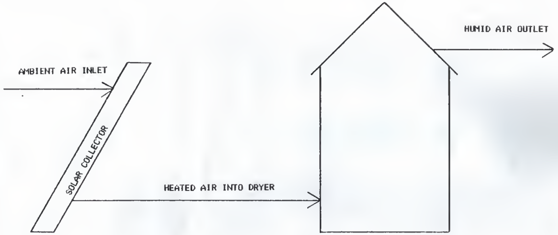


FIGURE 5.3 - FIXED BED DRYER (SOLAR HEATED DRYING AIR - SYSTEM 2)

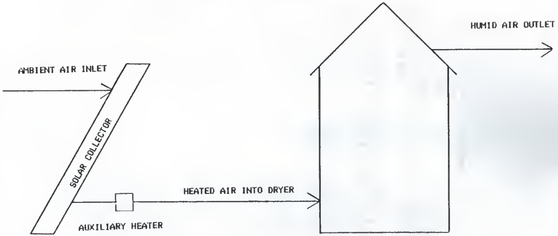


FIGURE 5.4 - FIXED BED DRYER (SOLAR AND AUXILIARY HEATED DRYINT AIR - SYSTEM 2A)

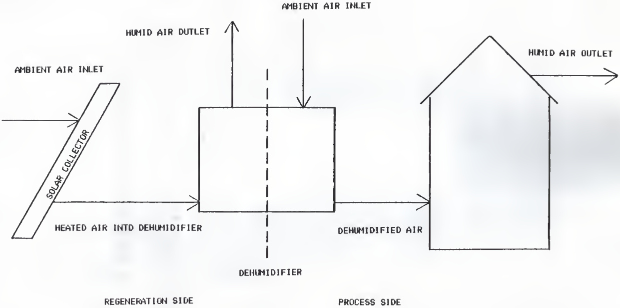


FIGURE 5.5 - FIXED BED DRYER (SORPTION DEHUMIDIFIED DRYING AIR - SYSTEM 3)

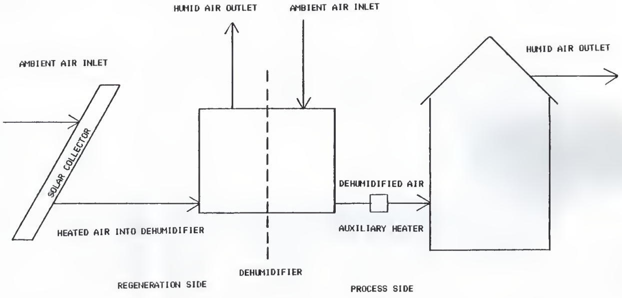


FIGURE 5.6-FIXED BED DRYER (SORPTION DEHUMIDIFIED & HEATED DRYING AIR-SYSTEM 3A)

a flat plate collector.

SYSTEM 3 AND 3A

The final set of systems studied employed the solar powered sorption dehumidifier. Figures 5.5 and 5.6 represent the systems 3 and 3A, respectively. The difference between the two systems lies only in the use of an auxiliary heater in system 3A to insure the dryer inlet air is at least 100F when entering the dryer. Auxiliary heat was also used in this set of systems to maintain a regeneration temperature of 176F. In system 3 the value calculated for the use of auxiliary heat is that amount used to regenerate the silica gel only. In the case of system 3A, the auxiliary heat costs were broken down into two parts; the regeneration auxiliary heat, and the dryer inlet auxiliary heat. Once again, the inlet air in system 3A was fixed at 100F, and was not allowed to go above that value. This reduced the number of variables to be considered in the study.

The modeling of systems 3 and 3A used the following subroutines:

1. The TMY-SOLMET weather data for the particular location studied.
2. The fixed bed dryer simulation.
3. The collector performance subroutine.
4. An economic analysis of the life cycle costs of a solar powered sorption dehumidifier compared to a conventional dehumidfier.
5. The simulation of a silica gel rotating bed.
6. The calculation of the auxiliary energy costs needed for the regeneration of the desiccant, and to maintain a dryer inlet temperature of 100F.

RESULTS AND DISCUSSION

To summarize, the six grain drying systems studied used the following types of drying air:

1. ambient air
1A. auxiliary heated ambient air
2. solar heated air
2A. solar and auxiliary heated air
3. sorption dehumidified air
3A. sorption dehumidified and auxiliary heated air

Difficulties arose in the modeling of system 2, the solar heated drying air. This was due to the fact that the temperature of the grain crossed the temperature boundary of 80F twice within the study. As was discussed in the section **REVIEW OF GRAIN DRYING MODELS**, different thinlayer equations would have to be used to correctly model the dryer. This would lead to complicated checks at each time increment and at each node within the bed to specify which equation to use. Therefore, system 2, the solar heated air system, could not reasonably be modeled using the present dryer simulation.

The other five systems were modeled and favorable weather conditions were sought in October for Omaha, Nebraska. The TMY-SOLMET tape was read for the month of October for Omaha. The data was reviewed to find a time span of about one week which had an average clearness index. The clearness index is defined as the ratio of the average radiation on a horizontal surface to the extraterrestrial radiation. The days selected for this study were October the 20th through the 23rd. The parameters of the systems were set at the following values:

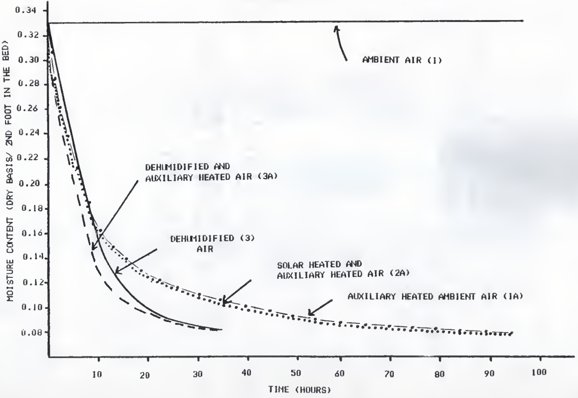
1.	regeneration and process air flow rates	120 CFM/FT**2
2.	density of the air stream	0.075 lb/FT**3
3.	rotating speed of desiccant wheel	600 sec/rev
4.	bed thickness	0.112 FT
5.	frontal area	0.6092 FT**2
6.	void fraction	0.750
7.	pressure drop, process & regeneration side	4.216 in. water
8.	peripheral leakage rates	0.0
9.	collector area	60.3532 FT**2
10.	slope of collector	10.49 degree
11.	latitude	41.37 degree
12.	longitude	96.00 degeee
13.	duct temp drop to collector	0.0 F
14.	duct temp drop to dehumidifier	1.8 F
15.	minimum temperature for regeneration	176.0 F
16.	heat exchanger efficiency	0.0
17.	income producing property	
18.	initial product temperature	80.0 F
19.	bed depth	5.0 FT
20.	cross-sectional area of bed	1.0 FT**2
21.	initial moisture content of grain (d.b.)	33.0 %
22.	number of layers per foot	15.0
23.	total time of study	96.0 hours
24.	final moisture content (d.b.)	8.0 %
25.	grain	shelled corn
26.	auxiliary energy	LPG
27.	cost of auxiliary energy	$10.00/10**6 BTU
28.	market discount rate	12.0%

29.	term of mortgage	5 years
30.	dowpayment	10.0%
31.	mortgage interest rate	12.0%
32.	term of depreciation	5 years
33.	property tax	$0.0
34.	assessed valuation	$0.0
35.	resale value	$0.0
36.	miscellaneous costs	2.0%
37.	fixed equipment costs - solar	$1000.00
38.	fixed equipment costs - conventional	$2000.00
39.	cost of auxiliary heater	$250.00
40.	cost per collector area	$300.00
41.	federal tax credit	55.0%
42.	fuel inflation rate	13.0%
43.	general inflation rate	6.0%
44.	federal tax rate	30.0%
45.	state tax rate	5.0%
46.	term of economic analysis	15 years
47.	accelerated cost recovery depreciation	

The drying rates of the different systems can be found in Graph #2. The ambient air conditions for October, as recorded on the TMY-SOLMET weather tape, will not dry the corn. This will not be true for every October in Omaha, Nebraska. However, for the conditions presented on the tape, the ambient air will not dry the shelled corn. In fact, the moisture content of the grain actually increased slightly because the EMC of the air was greater than the initial moisture content of the corn. The other four systems dried at the rates shown in Graph #2. The reader will notice that the dehumidified/auxiliary heated air dried the fastest. The auxiliary

GRAPH #2

MOISTURE CONTENT VS. TIME



heated ambient air (1A) and the solar/auxiliary heated air (2A) dried at the slowest rates. These two systems dried at the same rates because the air entering the dryer was set at 100F. From this data the savings in auxiliary energy due to the use of the solar collector can be calculated. A conclusion can also be made that the ambient air heated to 100F can not dry as quickly as ambient air that is dehumidified. Therefore, there is a definite advantage to using dehumidified air over heated air when considering drying rates. The time to dry the four bushels of corn (1 bushel = 1.25 cu. ft.) to 8% moisture content (d.b.) was much shorter for the dehumidified air. Both of the systems that used dehumidified air, (3) and (3A), dried at about the same rate; The dehumidified and auxiliary heated air (3A), finishing about one hour before the dehumidified only air (3). It should be noted that an initial moisture content of 33% d.b. and a drying air flow rate of 120 CFM is an extreme drying condition. Certainly, when applying this model to predict the performance of real dryers, more realistic parameters should be used.

A summary of the auxiliary energy usage can be found in Figures 6.1, 6.2, 6.3, and 6.4. The figures represent the daily costs for October 20, 21, 22, and 23. Values for the cost per bushel are also presented. On the first day, October 20, the auxiliary energy costs are represented in Figure 6.1. The dehumidified/auxiliary heated drying air required the most auxiliary energy ($3.70 or $0.93/bu.). The reader will notice that most of that energy was used to regenerate the silica gel. Only a small portion of the energy was used to heat the dryer inlet air. Generally, it can be said that regenerating the desiccant requires a lot of auxiliary energy because the solar collector does not reach a temperature high enough for sufficient regeneration. This is particularly true for the time of year considered, October, which is the usual standard corn harvesting time. Because the

FIGURE 6.1
AUXILIARY ENERGY COSTS FOR OCTOBER 20
OMAHA, NEBRASKA

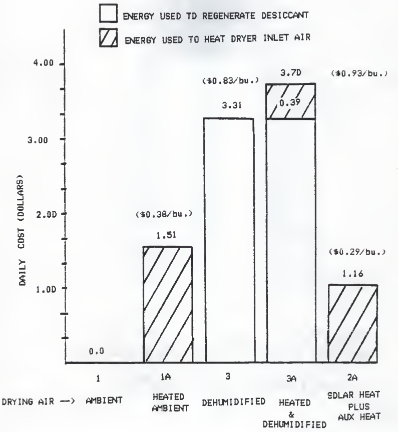


FIGURE 6.2
AUXILIARY ENERGY COSTS FOR OCTOBER 21
OMAHA, NEBRASKA

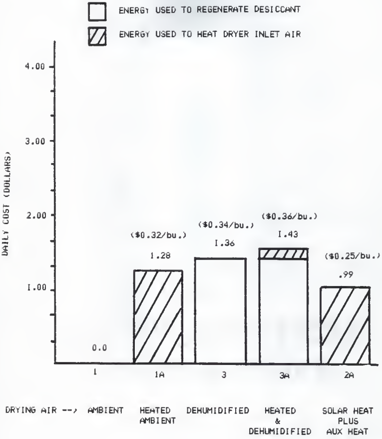


FIGURE 6.3

AUXILIARY ENERGY COSTS FOR OCTOBER 22

OMAHA, NEBRASKA

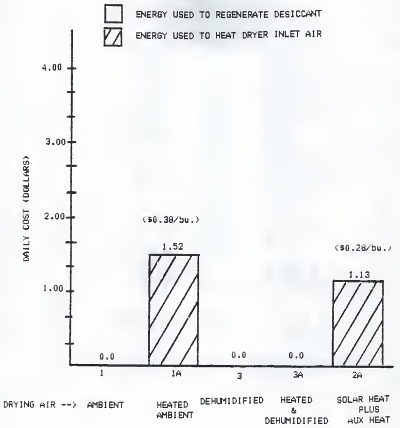


FIGURE 6.4

AUXILIARY ENERGY COSTS FOR OCTOBER 23
OMAHA, NEBRASKA

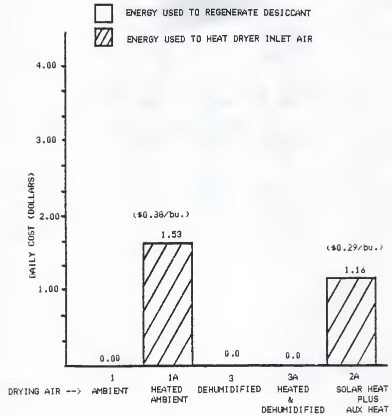
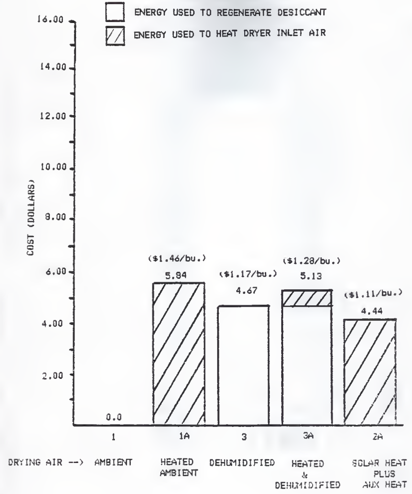


FIGURE 6.5

TOTAL COST OF AUXILIARY ENERGY FOR THE STUDY
OCTOBER 20,21,22,23
OMAHA, NEBRASKA



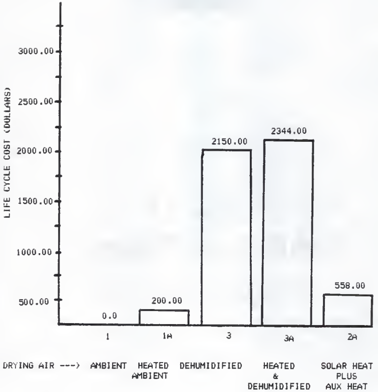
regeneration process requires a lot of energy, the dehumidified drying air system required the second highest amount of LPG ($3.31 or ($0.83/bu.). The solar/auxiliary heated drying air required less auxiliary energy ($1.16 or $0.29/bu.) than the heated ambient air ($1.51 or $0.38/bu.). This is expected because the solar collector contributes a portion of the energy needed. The ambient drying air did not require an outside energy source, but as was found in Graph #2, has negligible drying capacity.

In Figure 6.2 the reader will notice that the costs for the dehumidified air systems, (3) and (3A), dropped off dramatically. This is because the four bushels of corn being dried in these two systems reached their desired ending moisture content of 8% (d.b.) about eight hours into the second day. As a result, auxiliary energy was not required by these two systems, (3) and (3A), for the remaining 16 hours of that day. The solar/auxiliary heated air and the heated ambient air, drying at the same rate, continued to use auxiliary energy. The values vary slightly from the previous day due to different weather conditions as supplied on the TMY-SOLMET tape.

By the third day, Figure 6.3, the dehumidified/auxiliary heated system (3A) and the dehumidified system (3) did not require any further auxiliary energy. Thus, the values for these two systems are shown as 0.0. Again, the solar/auxiliary heated air and the heated ambient air continue to dry, using about the same amount of energy as was required in the previous days. The slight variations are due only to changing weather conditions. Figure 6.4 presents the auxiliary energy usage for the final day, October 23. The same results are obtained here as in Figure 6.3.

The total costs of energy for the study can be found in Figure 6.5. The cost of drying per bushel is also shown. Because the dehumidified air systems, (3) and (3A), finished drying shortly after the second day began,

FIGURE 6.6
LIFE CYCLE COSTS



the total amount of auxiliary heat used by the two systems was actually less overall than the conventionally heated ambient drying air. It should be noted that the pressure drops in the fixed bed dryer were not considered in this study. The addition of this factor would produce even more favorable results for the sorption dehumidifier. Looking at Figure 6.5, the ambient drying did not use any auxiliary energy, but did not have the capacity to dry the grain. It is interesting to note that the solar/auxiliary heated drying air used the least amount of auxiliary energy of the four systems that used it. There is a different of about 10 cents per bushel to dry the corn using the dehumidified/heated air versus the dehumidified only air. This differece represents the cost to heat the drying air. The rest, which is about 91% of the cost, is due to the auxiliary heat needed to regenerate the silica gel. If this number could somehow be lowered, this method of drying grain would become more attractive.

When comparing drying rates and their costs, it is apparent that the fastest drying rate is obtained with the dehumidified/auxiliary heated air. In Graph #2, the reader will notice that the dehumidified/auxiliary heated and the dehumidifed drying air reach the desired ending moisture content of 8% d.b. at about the same time. There was infact, only a difference of one hour between the two drying times. The dehumidified air dries at a faster rate and is also less expensive than the conventionally heated ambient air. However, the equipment needed to use a solar powered sorption dehumidifier is expensive. To fairly determine the feasibility of the system will require an economic analysis.

The last phase of this study compared the life cycle costs of the systems. This value is the sum of all the costs associated with the energy delivery system over its lifetime or over a selected period of analysis, in today's dollars, and takes into account the time value of money. The basic idea of life cycle costs is that anticipated future costs are brought back to present cost (discounted) by calculating how much would have to be invested at a market discount rate to have the funds available when they will be needed. The market discount rate is the rate of return on the best alternative investment. The dryer, fan, and duct work were considered common to all the systems. Therefore, the numbers presented in Figure 6.6 represent the difference between the base unit and the addition of the solar related equipment.

The solar powered sorption dehumidifier with the auxiliary heater had the largest solar life cycle cost (SLCC) of $2344. The sorption dehumidifier without the auxiliary heater had a SLCC of $2150 for the 15 year economic analysis. The solar collector and auxiliary heater had a SLCC of $558. The heated ambient air, which required the purchase of an auxiliary heater, had a conventional life cycle cost (CLCC) of $200.00. The ambient air system has a $0.0 CLCC since the equipment used is that equipment common to all the systems.

Are there any circumstances under which the sorption dehumidifier might be economically feasible? The restriction of running the solar energy powered dehumidifier for the four days of this study makes it very difficult for the investment to be attractive. Even the use of the sorption dehumidifier for the two to four weeks of corn harvest that occur each year would doubtfully produce economically feasible conditions. The need for other on-farm applications is great. Some examples of other uses for the solar energy powered sorption dehumidifier would include:

1.) The continuous regeneration of silica gel beds that could be stored until needed.

2.) If the dehumidifier could be considered by components,

then certainly the solar collector alone, could
find use in supplying warm air for animal shelters.

The solar energy powered sorption dehumidifier computer model is now in a form that can be used to investigate many parameter variations. For instance, how most energy would have to be supplied to ambient air in the form of heat, to get equivalent drying rates between heated and dehumidifed air? The number of studies that could be performed are numerous.

The GRAIN DRYER SIMULATION coupled with the dehumidifier model, the collector model, the economic analysis, and the weather data information require about 30 minutes (depending upon the specifics of the study) of computer time. Of the average 30 minutes required, approximately 50% of that time was spent in the fixed bed model dryer. This study could not include a more indepth analysis due to the lack of a funding source for the expensive computer time required on the University's large computer.

SUMMARY AND CONCLUSIONS

The main objective of this study was to determine a method of simulating grain drying with a solar powered sorption dehumidifier. The type of grain dryer selected was fixed bed, and the model used was the **GRAIN DRYER SIMULATION** developed at Michigan State University by Bakker-Arkema, et al. Limitations of this model include:

1.) The product temperature can not cross the temperature boundary of 80F without resulting added computer time and expense, due to the multitude of checks that would have to be made to be certain the correct equation was being used at each node of the bed.

2.) The dryer simulation requires a lot of time on the the National Advanced Systems/6620 at KSU. For the four day study, the time required on the computer ranged from 15 to 40 minutes, depending on the system modeled. Some of this time was spent in modeling the dehumidifer bed, the collector and reading the weather data. But, over 50% of the total time was required by the dryer model. While this model is good, it is not practical in its current state. The writer has made a number of suggestions to remedy this problem in **RECOMMENDATIONS FOR FURTHER STUDY**.

3.) This grain dryer simulation was developed to predict the drying characteristics of a certain type of dryer when the entering air properties, such as temperature and humidity, remained constant. The changing of the inlet air properites on an hourly basis, and how this effects the validity of the model are unknown. Research will have to be performed to compare experimental results with the simulated results.

Within the context of this study, the solar powered sorption dehumidifier required an additional investment of about $2144.00, over conventional, fossil fuel dried grain. If this system is to be considered feasible, other on-farm applications will have to be found in addition to the drying of grain.

RECOMMENDATIONS FOR FURTHER STUDY

1.) Due to the expense of running this program on the National Advanced Systems/6620 at KSU, one of two suggestions are made:

    a. Decide upon a microcomputer system and transfer the program to that system so that the money factor is essentially eliminated. Access to weather data will still be needed and a method will have to be determined to obtain that data - whether by the use of a modem, or putting the data on a floppy disk.

    b. Consider a more simplified deep bed drying model that is empirical in nature and can be applied to drying shelled corn. (However, this will limit the application to corn drying unless individual empirical models can be found for each drying use.)

2.) Once the computer model is in a less expensive form, obtain the equipment and instrumentation needed to validate the numerical model.

3.) Model Concurrent, Crossflow, and Counterflow dryers, with the sorption dehumidified air, and validate the models with the necessary equipment and instrumentation.

4.) Develop a design computer model to size the Solar Energy Powered Sorption Dehumidification System.

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APPENDIX

APPENDIX A

OPTIMUM ANGLE FOR A FLAT PLATE SOLAR COLLECTOR FACING DUE SOUTH

FOR A FLAT PLATE COLLECTOR SLOPED TO THE SOUTH, THE ANGLE OF INCIDENCE IS THE ANGLE BETWEEN THE BEAM RADIATION ON THE SURFACE OF THE COLLECTOR, AND THE NORMAL TO THAT SURFACE.

θ = ANGLE OF INCIDENCE

FOR LOCATIONS IN THE NORTHERN HEMISPHERE:

$$\cos\theta = \cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)\sin\delta$$

WHERE:

θ = ANGLE OF INCIDENCE
ϕ = LATITUDE
δ = DECLINATION
β = SLOPE
ω = HOUR ANGLE

DECLINATION

DECLINATION IS THE ANGULAR POSITION OF THE SUN AT SOLAR NOON WITH RESPECT TO THE PLANE OF THE EQUATOR, NORTH POSITIVE. $(-23.45 < \delta < 23.45)$

$$\delta = 23.45 \sin\left[360\left[\frac{284 + n}{365}\right]\right]$$

n = NUMBER OF THE DAY OF THE YEAR

HOUR ANGLE

THE HOUR ANGLE IS THE ANGULAR DISPLACEMENT OF THE SUN EAST OR WEST OF THE LOCAL MERIDIAN DUE TO ROTATION OF THE EARTH ON ITS AXIS AT 15 DEGREES PER HOUR, MORNING NEGATIVE, AFTERNOON POSITIVE.

MAXIMIZE INCIDENT RADIATION

TO MAXIMIZE THE INCIDENT RADIATION, MINIMIZE θ (MAXIMIZE COS θ).

$$\frac{d\cos\theta}{d(\phi-\beta)} = -\sin(\phi-\beta)\cos\delta\cos\omega + \cos(\phi-\beta)\sin\delta = 0$$

REARRANGING:

$$\tan(\phi-\beta) = \frac{\tan\delta}{\cos\omega}$$

$$\beta_{OPT} = \phi - \tan^{-1}\left[\frac{\tan\delta}{\cos\omega}\right]$$

FOR OPTIMUM SLOPE USE THE DECLINATION ANGLE THAT CORRESPONDS TO THE AVERAGE FOR THE MONTH THE STUDY COVERS. (SEE DUFFIE AND BECKMAN, PAGE 12)

TO FIND THE MEAN VALUE FOR COS ω , AN INTEGRABLE FUNCTION, USE THE DEFINITION:

$$\bar{F} = \int_a^b \frac{F(x)dx}{(b-a)}$$

THEREFORE:

$$\overline{\cos W} = 2\int_0^{\pi/4} \frac{\cos\omega \, d\omega}{\pi/4 - (-\pi/4)} = 0.900$$

THIS VALUE FOR THE MEAN VALUE OF COS ω, IS THE AVERAGE FOR EVERYDAY.

THE VALUE THAT SHOULD BE ENTERED IN THE DATA INPUT LINE IS: SL

$$SL = \beta_{OPT} - \text{LATITUDE}$$

APPENDIX B

DeBOER EMC EQUATION FOR SHELLED CORN

The following empirical equations are for the EMC values of shelled corn.

```
Me =(S1*rh**3)/1.02 + (F1/0.17 - 0.028333*S1)rh          0.0 < rh < 0.17

Me =S1(0.34-rh)**3/1.02 + S2(rh-0.17)**3/1.02 + (F2/0.17-0.028333S2)*(rh-0.17)
       + (F1/0.17 - 0.028333S1)*(0.34-rh)                 0.17 < rh < 0.34

Me =S2(0.51-rh)**3/1.02 + F3/0.17(rh-0.34) + (F2/0.17-0.028333S2)*(0.51-rh)
                                                          0.34 < rh < 0.50

Me = S3(rh-0.49)**3/1.02 + [F5/0.17 - 0.028333*S3]*(rh-0.49) + F4/0.17*
       (0.66 -rh)                                         0.50 < rh < 0.66

Me = S3(0.83-rh)**3/1.02 +  S4(rh-0.66)**3/1.02 +[F6/0.17 -0.028333S4]*
       (rh-0.66) + [F5/0.17 - 0.028333S3]*(0.83-rh)       0.66 < rh < 0.83

Me = S4(1.00-rh)**3/1.02 + F7/0.17(rh-0.83) +[F6/0.17 - 0.028333S4]*(1.00-rh)
                                                          0.83 < rh < 1.00
```

where:

rh = relative humidity, decimal
F1 = -0.0003922T + 0.1000
F2 = -0.0004353T + 0.1328
F3 = -0.0005359T + 0.1646
F4 = -0.0005375T + 0.1624
F5 = -0.0007075T + 0.2075
F6 = -0.0007449T + 0.2532
F7 = -0.001071T + 0.3931
S1 = 13.83(-9F1 + 6F2 - F3)
S2 = 13.83(4F3 - 9F2 + 6F1)
S3 = 13.83(4F4 - 9F5 + 6F6 - F7)
S4 = 13.83(4F7 - 9F6 + 6F5 - F4)

APPENDIX C

THOMPSON EQUATION FOR EMC

The Thompson Equation for determining EMC, used in the fixed bed program for temperatures above 235F.

```
EMC = 0.01*SQRT((-ALOG(1.0-RH))/(0.0000382*(T+50.0)))
```

WHERE

EMC = EQUILIBRIUM MOISTURE CONTENT
RH = RELATIVE HUMIDITY, DECIMAL
T   = TEMPERATURE OF THE AIR

APPENDIX D

THE SUBBAH EMPIRICAL DRYING EQUATION FOR CORN

TEMPERATURE RANGE: 36 - 70F

```
MR = EXP [ -k( t**0.664)]
```

where

```
k  =  exp (-x*t**y)

x  =  [6.0142 + (1.453E-04)(rh)**2]**0.5
      - θ ι*[3.353E-04 + (3.0E-08)(rh)**2]**0.5

y  =  0.1245-2.197E-03(rh) + 2.3E-05(rh)θ-5.8E-05*θ
```

APPENDIX E

SHELLED CORN DRYING EQUATIONS FOR THE TEMPERATURE RANGE 90 - 160F
TROEGER AND HUKILL

```
t/60 = p1(Mbar - Me)**q1 - p1(Mo - Me)**q1              Mo > Mbar )Mx1

t/60 = p2(Mbar - Me)**q2 - p2(Mx1 - Me)**q2 + tx1       Mx1 > Mbar > Me

t/60 = p3(Mbar - Me)**q3 - p3(Mx2 - Me)**q3 + tx2       Mx2 > Mbar > Me
```

WHERE

```
Mx1 = 0.40(Min - Me) + Me

Mx2 = 0.12(Min - Me) + Me

tx1 = [p1(Mx1 - Me)**q1 - p1(Min - Me)**q1]/60

tx2 = [p2(Mx2 - Me)**q2 - p2(Mx1 - Me)**q2]/60 +tx1

p1  = exp(-2.45 - (6.42*Min**1.25) - 3.15*rh + (9.62*Min*
          rh**.5) + 0.030*θ - 0.12*Va)

p2  = exp[ 2.82 + 7.49(rh +0.01)**0.67 - 0.0179θ]

p3  = 0.12[(Min - Me)**(q2-q3)]*(p2*q2/q3)

q1  =-3.98 + 2.87Min - [0.019/(rh + 0.015)] + 0.016θ

q2  =-exp(0.810 - 3.11rh)

q3  = -1.0
```

APPENDIX F

COMPUTER LISTING OF THE MAIN PROGRAM USED IN THE MODELING OF THE SOLAR POWERED SORPTION DEHUMIDIFICATION SYSTEM

The main program is listed here due to a number of changes which were made during the writer's study. The changes include:

1. The inclusion of new variables in the common data blocks to allow interfacing with the fixed bed dryer simulation.
2. Coding to allow for the calculation and output of the auxiliary costs used to heat the dryer inlet air, and to regenerate the desiccant. This was performed on a daily basis and a total amount was also calculated for the study.
3. Alterations were made to the algorithm needed to read the TMY-SOLMET Weather Tape. The program now has the capabilities to read across month boundaries and to read the first day of the year.
4. Using the amount of moisture removed during the drying process, the data from the dryer simulation was used to calculate the fraction of the load supplied by the system configuration.
5. Coding to enter the dryer simulation, **fixbed**, and to enter the depth loop, **subfix**, during subsequent calculations.

```
//*++SERVICE OVERNITE TIME 60, TAPE9 PRINT VMMSG LOG REGION 400K
//*++LINES 10
// EXEC FORTQCLG,PARM='NOMAP'
//FORT.SYSIN DD *
C        MAIN PROGRAM STARTS HERE
C****************************************************************
      COMMON /GENL/XAT,THT,RHT,DELTA,CFM,XMO,KAB
      COMMON /PRPRTY/SA,CAR,CAP,CV,CW,RHOP,HFG
      COMMON /PRESS/PATM
      COMMON DAY,DBT(10,24),DPT(10,24),IHR(10,24),HENCR(10,24),MO,ND,NH,
     XPERB(10,24),PERD(10,24),REFLEC(10,24),STN,WDIR(10,24),WVEL(10,24)
     X,WAM(10,24),YR,IDATE(10),WOXP(10,24),GTQU,GEMT,WATER,COUNT,TIN
      COMMON AC,AF,ALFA(10,24),ALONG,AMASSP,AMASSR,AUP,AUR,AV,BLEAK,CP,
     XCTYPE,DD,DELPEP,DELPER,DELPR,DELPP,DELT,DTDC,DTCD,DUMMY,EFF(10,24)
     X,FL,FLE,FRIC,GAM(2,2),HMU,I,II,III,INC,INCI,INDIC,ITNUM,J,LL,N,NN
     X,NNN,PHI,PI,PLEAKR,PLEAKP,QAUX(10,24),QDEHU(10,24),QDUCT(10,24),
     XQSURP(10,24),QHEXR(10,24),QU(10,24),RHOF,RLEAK,RPS,SIG(2,2),SL,
     XTAMB,TAU,TC,TCN,TIC(10,24),TIDP(10,24),TIDR(10,24),TIME,TMIN,
     XTOC(10,24),TODR(10,24),TODP(10,24),TRD(10,24),U,VELR,VELP,VOID,W,
     XWC,WCN,WEX,WIDR(10,24),WIDP(10,24),WODR(10,24),WODP(10,24),XE,
     XQTL(10,24),QHEXP(10,24),TPD(10,24),FP(10,24),FR(10,24),IP,TOXR(10,
     X24),AVFR,IFLAG,DTQU(10),DTQAUX(10),PSTNC(10,24),XM(150),THF(150),
     XRHF(151),T(151,2),H(151,2),DEEP(20),FTIME,SQAUX(10)
C        THE FOLLOWING 4 STATEMENTS DECLARE VARIABLES FOR THE WEATHER
C        DATA PORTION OF THE PROGRAM
      INTEGER DAYB,DEND,HRB,HREND,DAYF,MOB,MEND,PDAY,PMO,ND
      INTEGER STN,YR,DAY,CLK(10,24),DIRR(10,24),WDIR,WVEL,DIFR(10,24),
     X WEAT(10,24),SKY(10,24),SNOW(10,24),MINS(10,24)
      DIMENSION PSTN(10,24),PSZA(10,24),OBSR(10,24),EXTR(10,24),
     XSTDYR(10,24),BETA(10,24),BETAF(10,24),PWV(10,24),ENCR(10,24),
     XEMT(10),RH(10,24),POD(10,24),TIDD(10,24),TIDDR(10,24),WOD(10,24)
     X,EM(10,24)
      REAL KT(10,24)
C         THE FOLLOWING TWO DECLARATION STATEMENTS ARE FOR THE ECONOMIC
C         ANALYSIS
      REAL MPIS,NDW,LP,MPIC,LCCS,LCCC,LPP,LADD,AVFR
      INTEGER DOPS,DOPC,CFLAG
C        NOTE, THE FOLLOWING TWO LINES ARE FORTRAN STATEMENT FUNCTIONS
C        TO COMPUTE PRESENT WORTH FACTORS FOR P-ONE AND P-TWO
```

```
      PWF(KK,Y,Z)=(1.-((1.+Y)/(1.+Z))**KK)/(Z-Y)
      PWFP(KKP,YP,ZP)=KKP/(1.+YP)
   10 FORMAT('1'///,T40,'***** TMY WEATHER DATA FOR OMAHA, NEBRASKA ****
     X*')
   11 FORMAT ('-',T6,I2,'/',1X,I2,'/',I2,T99,'STATION NO.',I5)
   12 FORMAT ('0',T6,'NUMBER DAY OF THE YEAR =',I3///)
   13 FORMAT ('0',T6,'TIME',T24,'RADIATION',T49,'SKY',T69,'PRESSURE',T85
     X,'TEMPERATURE',T111,'WIND',T120,'SNOW')
   14 FORMAT (' ','SOLAR CLOCK',3X,'EXT-T',T23,'ENG-C',T31,'BEAM',T37,'D
     XIFFUSE',T49,'COND',T56,'WEATHER',T67,'SEA-L',T77,'STN',T85,'D-B.'
     X,T93,'DEW',T99,'HUMIDITY',T109,'DIR',T115,'VEL',T120,'COVER')
   15 FORMAT (' ',I2,'00',2X,I4,4X,F5.0,2X,F5.0,2X,2(F6.4,2X),2X,I5,2X,
     XI8,3X,2(F7.2,1X),2X,2(F5.1,2X),2X,F7.5,2X,I3,1X,I4,5X,I1)
   17 FORMAT (' ',11('-'),3X,2(5('-'),2X),6('-'),1X,7('-'),5X,4('-'),
     X3X,7('-'),4X,14('-'),4X,11('-'),3X,8('-'),2X,9('-'),2X,5('-'))
   20 FORMAT(9I5)
    1 FORMAT(I5,I2,I2,I2,I2)
    2 FORMAT(I5,I2,I2,I2,I2,2X,I4,F4.0,1X,I4,I5,10X,F5.0,F5.0,
     XF5.0,10X,I2,6X,I5,4X,I8,2F5.2,2F4.1,I3,I4,4X,I1)
  500 FORMAT('1'////,T40,'***** AUXILIARY HEAT SUPPLIED AT DRYER INLET *
     X****')
  501 FORMAT('0',T49,'MINIMUM TEMPERATURE 100F')
  502 FORMAT('0',T40,'MASS FLOW RATE =',F12.2,'     (LBM/HR-FT**2)')
  504 FORMAT(' ',T55,'(F)',T74,'AUXILIARY')
  505 FORMAT(' ',T53,'ENTERING',T74,'ENERGY ADDED')
  506 FORMAT(' ',T30,'HOUR ENDING',T50,'DRY DULB TEMP',T73,'(BTU/HR-FT**
     X2)')
  507 FORMAT(' ',T30,11('-'),T50,13('-'),T72,16('-'))
  508 FORMAT(' ',T35,I2,T52,F7.2,T74,F9.2)
  509 FORMAT('-'/,T34,'COST OF AUXILARY HEAT INTO THE DRYER =$',F8.2)
  510 FORMAT('0',T34,'COST OF LP FUEL IS ESTIMATED AT $10.00/10**6 BTU')
  511 FORMAT('1'//,T10,'TOTAL COST OF AUXILIARY HEAT INTO THE DRYER AND
     XINTO THE DEHUMIDIFIER FOR THE STUDY = $',F12.2)
  512 FORMAT(' ',T35,'COST OF AUXILIARY HEAT TO DEHUMIDIFIER =$',F8.2)
C        SPECIFY THE DAYS, MONTH AND HOURS DESIRED BY USER
      READ (5,20) MOB,DAYB,MEND,DEND,HRB,HREND,ND,PDAY,PMO
      COUNT=0.0
      TCOST=0.0
      ATCOST=0.0
      IZ=24
```

```
      NH=(HREND-HRB)+1
      IF (DAYB.GT.1) DAYF=DAYB-1
      IF (MOB.EQ.1.AND.DAYB.EQ.1) GO TO 513
      IF (DAYB.EQ.1) DAYF=PDAY
      IF (DAYB.EQ.1) MOB=PMO
C        TAPE IS READ BEGINNING JAN 1 UNTIL THE DESIRED DATES ARE FOUND.
   50 READ (3,1)STN,YR,MO,DAY,MHR
      IF(MO.LT.MOB) GO TO 50
      IF(DAY.LT.DAYF) GO TO 50
      IF(MHR.LT.IZ) GO TO 50
  513 CONTINUE
      DO 80 I=1,ND
      TDQAUX=0.0
      DO 81 J=1,NH
   40 READ (3,2)STN,YR,MO,DAY,IHR(I,J),CLK(I,J),EXTR(I,J),DIRR(I,J),DIFR
     X(I,J),OBSR(I,J),ENCR(I,J),STDYR(I,J),MINS(I,J),SKY(I,J),WEAT(I,J),
     XPSEA(I,J),PSTN(I,J),DBT(I,J),DPT(I,J),WDIR(I,J),WVEL(I,J),
     XSNOW(I,J)
C        CALCULATE THE NUMBER DAY OF THE YEAR, ALLOWING FOR LEAP YEARS
C        ILEAP AND MOTEST ARE JUST TO AID IN THE PROGRAM MECHANISM
      ILEAP=YR-48
      IF (ILEAP/4*4.NE.ILEAP) GO TO 913
      MOTEST=MO-2
      IF (MOTEST) 913,913,930
  930 NDAY=DAY+1
      GO TO 914
  913 NDAY=DAY
  914 GO TO (901,902,903,904,905,906,907,908,909,910,911,912),MO
  901 IDATE(I)=NDAY
      GO TO 960
  902 IDATE(I)=NDAY+31
      GO TO 960
  903 IDATE(I)=NDAY+59
      GO TO 960
  904 IDATE(I)=NDAY+90
```

```
    GO TO 960
905 IDATE(I)=NDAY+120
    GO TO 960
906 IDATE(I)=NDAY+151
    GO TO 960
907 IDATE(I)=NDAY+181
    GO TO 960
908 IDATE(I)=NDAY+212
    GO TO 960
909 IDATE(I)=NDAY+243
    GO TO 960
910 IDATE(I)=NDAY+273
    GO TO 960
911 IDATE(I)=NDAY+304
    GO TO 960
912 IDATE(I)=NDAY+334
960 CONTINUE
    IF (J.NE.1) GO TO 61
    WRITE (6,10)
    WRITE (6,11) MO,DAY,YR,STN
    WRITE (6,12) IDATE(I)
    WRITE (6,13)
    WRITE (6,14)
    WRITE (6,17)
 61 CONTINUE
    IF (EXTR(I,J).EQ.9999) EXTR(I,J)=0
    IF (DIRR(I,J).EQ.99999) DIRR(I,J)=0
    IF (DIFR(I,J).EQ.99999) DIFR(I,J)=0
    IF (OBSR(I,J).EQ.99999) OBSR(I,J)=0
    IF (ENCR(I,J).EQ.99999) ENCR(I,J)=0
    IF (STDYR(I,J).EQ.99999) STDYR(I,J)=0
    IF (MINS(I,J).EQ.99) MINS(I,J)=0
    IF (SKY(I,J).EQ.99999) SKY(I,J)=0
    IF (WEAT(I,J).EQ.99999999) WEAT(I,J)=0
    IF (SNOW(I,J).EQ.1) REFLEC(I,J)=0.7
    IF (SNOW(I,J).EQ.0) REFLEC(I,J)=0.2
    IF (SNOW(I,J).NE.9) GO TO 62
```

```
      SNOW(I,J)=0
      REFLEC(I,J)=0.0
   62 CONTINUE
      IF (EXTR(I,J).EQ.0) GO TO 44
      KT(I,J)=ENCR(I,J)/EXTR(I,J)
      IF (KT(I,J).LE.0.35)  PERD(I,J)=1.0-0.249*KT(I,J)
      IF (KT(I,J).GE.0.75)  PERD(I,J)=0.117
      IF ((KT(I,J).GT.0.35).AND.(KT(I,J).LT.0.75)) PERD(I,J)=1.557-1.84*
     XKT(I,J)
      PERB(I,J)=1.0-PERD(I,J)
      GO TO 45
   44 PERB(I,J)=0.0
      PERD(I,J)=0.0
   45 CONTINUE
C          SPECIFY WHICH RADIATION DATA IS USED FOR INSOLATION
      HENCR(I,J)=ENCR(I,J)
C         CALCULATE AMBIENT HUMIDITY FROM DRY BULB AND STATION
C         ATMOSPHERIC PRESSURE DATA USING ASHRAE METHOD
      BETA(I,J)  =374.12-DBT(I,J)
      BETAF(I,J)=BETA(I,J)/100.
      PWV(I,J)=218.167*10**(-BETA(I,J)/(DPT(I,J)+273.15)*(3.2437814+.586
     X826*BETAF(I,J)+0.011702379*BETAF(I,J)**3)/(1.+.2187846*BETAF(I,J))
     X)
      PSTNC(I,J)=PSTN(I,J)*.0098692
      WAM(I,J)=(.62198*PWV(I,J))/(PSTNC(I,J)-PWV(I,J))
      WRITE (6,15) IHR(I,J),CLK(I,J),EXTR(I,J),ENCR(I,J),PFRE(I,J),PERD
     X(I,J),SKY(I,J),WEAT(I,J),PSEA(I,J),PSTN(I,J),DBT(I,J),DPT(I,J),
     XWAM(I,J),WDIR(I,J),WVFL(I,J),SNOW(I,J)
   81 CONTINUE
      CALL SYSTEM
C   INITIALIZED GRAND TOTAL HEATS
      IF(I.GT.1) GO TO 21
      GTQU=0.0
      GTQAUX=0.0
   21 CONTINUE
      GTQU=GTQU+DTQU(I)
      GTQAUX=GTQAUX+DTQAUX(I)
      IF(COUNT.GT.0.0) GO TO 850
      IF(COUNT.EQ.0) CALL FIXBED
```

```
      GO TO 851
  850 CALL SUBFIX
  851 COUNT=COUNT+1.0
C   CHANGE UNITS FROM KJ TO BTU
      SQAUX(I)=SQAUX(I)/1.055
C   CONVERT SQAUX TO 10**6 BTU
      SQAUX(I)=SQAUX(I)/1000000.
C   COST OF LP FUEL IS SET AT $10.00/10**6 BTU
      ACOST=10.00*SQAUX(I)
      ATCOST=ATCOST+ACOST
C   MASS FLOW RATE IN LBM/HR-FT**2
      AMASSP=CFM*5.080*RHOF*0.73739
      PRINT 500
      PRINT 501
      PRINT 502, AMASSP
      PRINT 504
      PRINT 505
      PRINT 506
      PRINT 507
      DO 666 J=1,NH
C CONVERT MINIMUM TEMPERATURE TO DEGREES F.
      TODP(I,J)=9.0/5.0*TODP(I,J)+32.0
      IF(TODP(I,J).GE. 100.0) DQAUX=0.0
      IF(TODP(I,J).GE. 100.0) GO TO 666
C   HEAT SUPPLIED BY AUX HEATER INTO DRYER, DQAUX, IN BTU/HR-FT**2
      DQAUX=AMASSP*CAR*(TIN-TODP(I,J))
      TDQAUX=TDQAUX+DQAUX
  666 PRINT 508,J,TODP(I,J),DQAUX
C CONVERT TDQAUX TO 10**6 BTU/HR-FT**2
      TDQAUX=TDQAUX/1000000.
C COST OF LP FUEL IS SET AT $10.00/10**6 BTU
      COST=10.00*TDQAUX
      PRINT 509,COST
      PRINT 512,ACOST
      PRINT 510
      TCOST=TCOST+COST
   80 CONTINUE
C   CONVERT GEMT FROM LBM TO KG
```

```
      GEMT=WATER*0.45356
C  CHANGE THE UNITS OF HEAT GAIN TO GJ
      GTQU=GTQU/1000000.
      GTQAUX=GTQAUX/1000000.
      TTAUX=TCOST+ATCOST
      PRINT 511,TTAUX
C         THE ECONOMIC ANALYSIS BEGINS HERE
C         READ INFLATION AND TAX RATES
      READ (5,90) FI,GI,FTR,STR
C         READ TERM OF ECONOMIC ANALYSIS, DISCOUNT RATES AND FUEL COSTS
      READ (5,91) NEA,DRS,DRC,CF,CFLAG
C         READ SOLAR MORTGAGE DATA
      READ (5,92) NLS,DS,SMIR,TCR
C         READ SOLAR DEPRECIATION DATA
      READ (5,93) DOPS,NDEPS
C         READ SOLAR COST AND VALUE DATA
      READ (5,94) CA,CFS,TAVS,VS,RVS,SMC
C         READ CONVENTIONAL MORTGAGE DATA
      READ (5,95) NLC,DC,CMIR
C         READ CONVENTIONAL DEPRECIATION DATA
      READ (5,96) DOPC,NDEPC
C         READ CONVENTIONAL COST AND VALUE DATA
      READ (5,97) CEC,TAVC,VC,RVC,CMC
   90 FORMAT (4F5.2)
   91 FORMAT(I5,2F5.3,F5.2,I5)
   92 FORMAT(I5,3F5.2)
   93 FORMAT(2I5)
   94 FORMAT(F5.0,F10.0,3F10.2,F5.2)
   95 FORMAT(I5,2F5.2)
   96 FORMAT(2I5)
   97 FORMAT(F10.0,3F10.2,F5.2)
      ZERO=0.0
C         NMINS  IS EQUAL TO THE MINIMUM OF NLS AND NEA
      IF (NEA.GT.NLS) GO TO 82
      NMINS=NEA
      GO TO 83
   82 NMINS=NLS
   83 CONTINUE
```

```
C        NMINPS IS EQUAL TO THE MINIMUM OF NEA AND NDEPS
      IF (NEA.GT.NDEPS) GO TO 84
      NMINPS=NEA
      GO TO 85
   84 NMINPS=NDEPS
   85 CONTINUE
      NDEPPS=NDEPS-1.
      NDEPPC=NDEPC-1.
      DIS=-2./NDEPS
      DIC=-2./NDEPC
      TBAR=FTR+STR-FTR*STR
C        DEFINE THE PRESENT WORTH FACTORS FOR THE SOLAR ENERGY SYSTEM
      IF (FI.NE.DRS) PWAS=PWF(NEA,FI,DRS)
      IF (FI.EQ.DRS) PWAS=PWFP(NEA,FI,DRS)
      IF (ZERO.NE.DRS) PWBS=PWF(NMINS,ZERO,DRS)
      IF (ZERO.EQ.DRS) PWBS=PWFP(NMINS,ZERO,DRS)
      IF (ZERO.NE.SMIR) PWCS=PWF(NLS,ZERO,SMIR)
      IF (ZERO.EQ.SMIR) PWCS=PWFP(NLS,ZERO,SMIR)
      IF (SMIR.NE.DRS) PWDS=PWF(NMINS,SMIR,DRS)
      IF (SMIR.EQ.DRS) PWDS=PWFP(NMINS,SMIR,DRS)
      IF (GI.NE.DRS) PWES=PWF(NEA,GI,DRS)
      IF (GI.EQ.DRS) PWES=PWFP(NEA,GI,DRS)
      IF (DIS.NE.DRS) PWFS=PWF(NMINPS,ZERO,DRS)
      IF (DIS.EQ.DRS) PWFS=PWFP(NMINPS,ZERO,DRS)
      IF (DIS.NE.DRS) PWGS=PWF(NDEPPS,DIS,DRS)
      IF (DIS.EQ.DRS) PWGS=PWFP(NDEPPS,DIS,DRS)
      IF (DIS.NE.ZERO) PWHS=PWF(NDEPPS,DIS,ZERO)
      IF (DIS.EQ.ZERO) PWHS=PWFP(NDEPPS,DIS,ZERO)
      IF (ZERO.NE.DRS) PWIS=PWF(NDEPS,ZERO,DRS)
      IF (ZERO.EQ.DRS) PWIS=PWFP(NDEPS,ZERO,DRS)
      IF (ZERO.NE.DRS) PWJS=PWF(NDEPPS,ZERO,DRS)
      IF (ZERO.EQ.DRS) PWJS=PWFP(NDEPPS,ZERO,DRS)
      PWKS=1./(1.+DRS)
      PWLS=PWKS*PWKS
      PONES=(1.-CFLAG*TBAR)*PWAS
      MPIS=(1.-DS)*PWBS/PWCS
      TDIS=(1.-DS)*TBAR*(PWDS*(SMIR-1./PWCS)+PWBS/PWCS)
      DMCS=(1.-CFLAG*TBAR)*SMC*PWES
      PTCS=TAVS*(1.-TBAR)*VS*PWES
```

```
C         STRAIGHT LINE DEPRECIATION IF DOPS=1, DECLINING BALANCE IF
C         DOPS=2,   SUM OF DIGITS IF DOPS=3, ACCELERATED COST RECOVERY
C         IF DOPS=4
      GO TO (801,802,803,804),DOPS
  801 DEPS=CFLAG*TBAR*PWFS/NDEPS
      GO TO 800
  802 DEPS=TBAR*CFLAG*(1.+2./NDEPS*(PWGS-PWHS/((1.+DRS)**NDEPS)))
      GO TO 800
  803 DEPS=CFLAG*2.*TBAR/(NDEPS*(NDEPS+1.))*(PWIS+(NDEPS-1.-PWJS)/DRS)
      GO TO 800
  804 DEPS=(0.2*PWKS+0.32*PWLS+0.24*PWKS*PWIS+0.16*PWLS*PWLS+0.08*PWKS*
     X*PWLS*PWLS)*TBAR
  800 CONTINUE
C        THE TERM FOR DECLINING BALANCE DEPRECIATION INCLUDES THE RESALE
C        VALUE
      IF (DOPS.EQ.2) RVS=0.
      DRVS=RVS/((1.+DRS)**NEA)
      PTWOS=DS+MPIS-TDIS+DACS+PTCS-DEPS-DRVS-TCR
C        NMINC IS EQUAL TO THE MINIMUM OF NLC AND NEA
      IF (NEA.GT.NLC) GO TO 86
      NMINC=NEA
      GO TO 87
   86 NMINC=NLC
   87 CONTINUE
C        NMINPC IS EQUAL TO THE MINIMUM OF NEA AND NDEPC
      IF (NEA.GT.NDEPC) GO TO 88
      NMINPC=NEA
      GO TO 89
   88 NMINPC=NDEPC
   89 CONTINUE
C        DEFINE THE PRESENT WORTH FACTORS FOR THE CONVENTIONAL SYSTEM
      IF (FI.NE.DRC) PWAC=PWF(NEA,FI,DRC)
      IF (FI.EQ.DRC) PWAC=PWFP(NEA,FI,DRC)
      IF (ZERO.NE.DRC) PWBC=PWF(NMINC,ZERO,DRC)
      IF (ZERO.EQ.DRC) PWBC=PWFP(NMINC,ZERO,DRC)
      IF (ZERO.NE.CMIR) PWCC=PWF(NLC,ZERO,CMIR)
      IF (ZERO.EQ.CMIR) PWCC=PWFP(NLC,ZERO,CMIR)
```

```
      IF (CMIR.NE.DRC) PWDC=PWF(NMINC,CMIR,DRC)
      IF (CMIR.EQ.DRC) PWDC=PWFP(NMINC,CMIR,DRC)
      IF (GI.NE.DRC) PWEC=PWF(NEA,GI,DRC)
      IF (GI.EQ.DRC) PWEC=PWFP(NEA,GI,DRC)
      IF (DIC.NE.DRC) PWFC=PWF(NMINPC,ZERO,DRC)
      IF (DIC.EQ.DRC) PWFC=PWFP(NMINPC,ZERO,DRC)
      IF (DIC.NE.DRC) PWGC=PWF(NDEPPC,DIC,DRC)
      IF (DIC.EQ.DRC) PWGC=PWFP(NDEPPC,DIC,DRC)
      IF (DIC.NE.ZERO) PWHC=PWF(NDEPPC,DIC,ZERO)
      IF (DIC.EQ.ZERO) PWHC=PWFP(NDEPPC,DIC,ZERO)
      IF (ZERO.NE.DRC) PWIC=PWF(NDEPC,ZERO,DRC)
      IF (ZERO.EQ.DRC) PWIC=PWFP(NDEPC,ZERO,DRC)
      IF (ZERO.NE.DRC) PWJC=PWF(NDEPPC,ZERO,DRC)
      IF (ZERO.EQ.DRC) PWJC=PWFP(NDEPPC,ZERO,DRC)
      PWKC=1./(1.+DRC)
      PWLC=PWKC*PWKC
      PONEC=(1.-CFLAG*TBAR)*PWAC
      MPIC=(1.-DC)*PWBC/PWCC
      TDIC=(1.-DC)*TBAR*(PWDC*(CMIR-1./PWCC)+PWBC/PWCC)
      DMCC=(1.-CFLAG*TBAR)*CMC*PWEC
      PTCC=TAVC*(1.-TBAR)*VC*PWEC
C        STRAIGHT LINE DEPRECIATION IF DOPC=1, DECLINING BALANCE IF
C        DOPC=2,   SUM OF DIGITS IF DOPC=3,  ACCELERATED COST RECOVERY
C        IF DOPC=4
      GO TO (701,702,703,704),DOPC
  701 DEPC=TBAR*PWFC/NDEPC
      GO TO 700
  702 DEPC=TBAR*(1.+2.*CFLAG/NDEPC*(PWGC-PWHC/((1.+DRC)**NDEPC)))
      GO TO 700
  703 DEPC=2.*TBAR/(NDEPC*(NDEPC+1.))*(PWIC+(NDEPC-1.-PWJC)/DRC)
      GO TO 700
  704 DEPC=(0.2*PWKC+0.32*PWLC+0.24*PWKC*PWLC+0.16*PWLC*PWLC+0.08*PWKC*
     X*PWLC*PWLC)*TBAR
  700 CONTINUE
C        THE TERM FOR DECLINING BALANCE DEPRECIATION INCLUDES THE RESALE
C        VALUE
      IF (DOPC.EQ.2) RVC=0.
      DRVC=RVC/((1.+DRC)**NEA)
      PTWOC=DC+MPIC-TDIC+DMCC+PTCC-DEPC-DRVC
```

```
C         OUTPUT FOR ECONOMIC ANALYSIS PARAMETERS
C         MULTIPLY THE FOLLOWING BY 100 FOR PERCENTAGES
      DRSP=DRS*100.
      DRCP=DRC*100.
      DSP=DS*100.
      DCP=DC*100.
      SMIRP=SMIR*100.
      CMIRP=CMIR*100.
      SMCP=SMC*100.
      CMCP=CMC*100.
      TCRP=TCR*100.
      FIP=FI*100.
      GIP=GI*100.
      FTRP=FTR*100.
      STRP=STR*100.
      WRITE (6,100)
      WRITE (6,101)
      WRITE (6,102) DRSP,DRCP
      WRITE (6,103) NLS,NLC
      WRITE (6,104) DSP,DCP
      WRITE (6,105) SMIRP,CMIRP
      WRITE (6,106) NDEPS,NDEPC
      WRITE (6,107) TAVS,TAVC
      WRITE (6,108) VS,VC
      WRITE (6,109) RVS,RVC
      WRITE (6,110) SMCP,CMCP
      WRITE (6,111) CES,CEC
      WRITE (6,112) CA
      WRITE (6,113) TCRP
      WRITE (6,114) FIP
      WRITE (6,115) GIP
      WRITE (6,116) FTRP
      WRITE (6,117) STRP
      WRITE (6,118) CF
      WRITE (6,119) NEA
      GO TO (120,121,122,127),DOPS
  120 WRITE (6,124)
      GO TO 123
  121 WRITE (6,125)
      GO TO 123
  122 WRITE (6,126)
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```
    GO TO 123
127 WRITE (6,128)
123 CONTINUE
    GO TO (130,131,132,137),DOPC
130 WRITE (6,134)
    GO TO 133
131 WRITE (6,135)
    GO TO 133
132 WRITE (6,136)
    GO TO 133
137 WRITE (6,138)
133 CONTINUE
    ICFLAG=CFLAG+1
    GO TO (142,143),ICFLAG
142 WRITE (6,140)
    GO TO 144
143 WRITE (6,141)
144 CONTINUE
100 FORMAT ('1'//T6,'******  ECONOMIC ANALYSIS PARAMETERS  ******')
101 FORMAT('-',T45,'SOLAR ENERGY',T65,'CONVENTIONAL'/T45,'DEHUMIDIFIER
   X',T65,'DEHUMIDIFIER'/T44,14('_'),T64,14('_'))
102 FORMAT('-',T5,'MARKET DISCOUNT RATE - PERCENT',T48,F5.1,T68,F5.1)
103 FORMAT('0',T5,'TERM OF MORTGAGE - YEARS',T46,I5,T66,I5)
104 FORMAT('0',T5,'DOWNPAYMENT - PERCENT',T48,F5.1,T68,F5.1)
105 FORMAT('0',T5,'MORTGAGE INTEREST RATE - PERCENT',T48,F5.1,T68,F5.1
   X)
106 FORMAT('0',T5,'TERM OF DEPRECIATION - YEARS',T46,I5,T66,I5)
107 FORMAT('0',T5,'PROPERTY TAX - DOLLARS',T43,F10.2,T63,F10.2)
108 FORMAT('0',T5,'ASSESSED VALUATION - DOLLARS',T43,F10.2,T63,F10.2)
109 FORMAT('0',T5,'RESALE VALUE - DOLLARS',T43,F10.2,T63,F10.2)
110 FORMAT('0',T5,'MISCELLANEOUS COSTS - PERCENT',T48,F5.1,T68,F5.1)
111 FORMAT('0',T5,'FIXED COST OF EQUIPMENT',T44,F10.0,T64,F10.0)
112 FORMAT('0',T5,'COST PER COLLECTOR AREA',T48,F5.0,T69,5('-'))
113 FORMAT('0',T5,'FEDERAL TAX CREDIT - PERCENT',T48,F5.1,T69,5('-'))
114 FORMAT('-',T25,'FUEL INFLATION RATE',T54,'= ',F5.1,'  PERCENT')
115 FORMAT('0',T25,'GENERAL INFLATION RATE',T54,'= ',F5.1,'  PERCENT')
116 FORMAT('0',T25,'FEDERAL TAX RATE',T54,'= ',F5.1,'  PERCENT')
117 FORMAT('0',T25,'STATE TAX RATE',T54,'= ',F5.1,'  PERCENT')
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  118 FORMAT('0',T25,'FUEL PRICE',T54,'= ',F5.2,'  DOLLAR/GJOULE')
  119 FORMAT('0',T25,'TERM OF ECONOMIC ANALYSIS',T54,'= ',I5,'  YEARS')
  124 FORMAT('-',T25,'STRAIGHT LINE DEPRECIATION - SOLAR')
  125 FORMAT('-',T25,'DECLINING BALANCE DEPRECIATION - SOLAR')
  126 FORMAT('-',T25,'SUM OF DIGITS DEPRECIATION - SOLAR')
  128 FORMAT('-',T25,'ACCELERATED COST RECOVERY DEPRECIATION - SOLAR')
  134 FORMAT('0',T25,'STRAIGHT LINE DEPRECIATION - CONVENTIONAL')
  135 FORMAT('0',T25,'DECLINING BALANCE DEPRECIATION - CONVENTIONAL')
  136 FORMAT('0',T25,'SUM OF DIGITS DEPRECIATION - CONVENTIONAL')
  138 FORMAT('0',T25,'ACCELERATED COST RECOVERY DEPRECIATION - CONVENTIO
     XNAL')
  140 FORMAT('0',T25,'NON-INCOME PRODUCING SYSTEM')
  141 FORMAT('0',T25,'INCOME PRODUCING SYSTEM')
      WRITE (6,151)
      WRITE (6,152)
      WRITE (6,153)
      LADD=0.
      DO 150 KOUNT=1,16
C        LATENT HEAT OF VAPORIZATION IS 0.00240 GJOULE PER KILOGRAM
      LP=GEMJ*0.00240
      LPP=LP+LADD
      F=GTQU/LPP
      FF=F*100.
      EF=1./(1.-F)
C        LPP IS IN GJOULE
      LCCS=PTWOS*(CA*TAC+CES)+PTWOC*CEC+PONES*CF*LPP*(1.-F)
      LCCC=PTWOC*(CEC)+PONEC*CF*LPP
      WRITE (6,154) LP,LADD,LPP,FF,LCCS,LCCC,EF
      LADD=LADD+0.025
  150 CONTINUE
      WRITE (6,155) PONES,PONEC
      WRITE (6,156) PTWOS,PTWOC
      WRITE (6,157)
  151 FORMAT ('1'////T6,'******  ECONOMIC ANALYSIS  ******')
  152 FORMAT ('-',T53,'SOLAR ENERGY',T87,'CONVENTIONAL'/T14,'LOAD SUPPLI
     XED BY'/T45,'FRACTION OF'/T15,'SUPPLEMENTARY',T44,'LOAD SUPPLIED',
     XT113,'DRYER'/
     XT2,'DEHUMIDIFIER',T19,'HEATER',T32,'TOTAL',T47,'BY SOLAR',T60,'LIF
     XE CYCLE COST',T85,'LIFE CYCLE COST',T111,'EFFICIENCY')
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153 FORMAT (' ',T2,12('-'),T15,13('-'),T31,7('-'),T43,15('-'),T59,17('
   X-'),T84,17('-'),T111,12('-'))
154 FORMAT ('0',T2,F10.3,T14,F10.3,T28,F10.4,T44,F9.1,T60,F10.2,T86,F1
   X0.2,T109,F10.4)
155 FORMAT ('-'///T53,'P-ONE = ',F8.4,T84,'P-ONE = ',F8.4)
156 FORMAT ('-',T53,'P-TWO = ',F8.4,T84,'P-TWO = ',F8.4)
157 FORMAT ('-',T6,'MOISTURE EVAPORATED IN KILOGRAMS'/T6,'LOAD IN GJOU
   XLE '/T6,'SOLAR FRACTION IN PERCENT'/T6,'LIFE CYCLE COSTS IN DOLLAR
   XS')
    STOP
    END
```

APPENDIX G

THE FIXED BED DRYER SIMULATION AND SUBROUTINES

```
C***********************************************************************
      SUBROUTINE FIXBED
C***********************************************************************
C     THIS IS A GRAIN DRYER SIMULATION DEVELOPED AT MICHIGAN STATE UNIV
C     AUTHORS: F.W. BAKKER-ARKEMA, PROJECT LEADER  L.E. LEREW, PROGRAMMER
C     DESCRIPTION
C     PROGRAM FOR THE SIMULATION OF A FIXED BED DRYER
      COMMON /GENL/XMT,THT,RHT,DELTA,CFM,XMO,KAB
      COMMON /PRPRTY/SA,CAR,CAP,CV,CW,RHOP,HFG
      COMMON /PRESS/PATM
      COMMON DAY,DBT(10,24),DPT(10,24),IHR(10,24),HENCR(10,24),MO,ND,NH,
     XPERB(10,24),PERD(10,24),REFLEC(10,24),STN,WDIR(10,24),WVEL(10,24)
     X,WAM(10,24),YR,IDATE(10),WOXP(10,24),GTQU,GEMT,WATER,COUNT,TIN
      COMMON AC,AF,ALFA(10,24),ALONG,AMASSP,AMASSR,AUP,AUR,AV,BLEAK,CP,
     XCTYPE,DD,DELPEP,DELPER,DELPR,DELPP,DELT,DTDC,DTCD,DUMMY,EFF(10,24)
     X,FL,FLE,FRIC,GAM(2,2),HMU,I,II,III,INC,INCI,INDIC,ITNUM,J,LL,N,NN
     X,NNN,PHI,PI,PLEAKR,PLEAKP,QAUX(10,24),QDEHU(10,24),QDUCT(10,24),
     XQSURP(10,24),QHEXR(10,24),QU(10,24),RHOF,RLEAK,RPS,SIG(2,2),SL,
     XTAMB,TAU,TC,TCN,TIC(10,24),TIDP(10,24),TIDR(10,24),TIME,TMIN,
     XTOC(10,24),TODR(10,24),TODP(10,24),TRD(10,24),U,VELR,VELP,VOID,W,
     XWC,WCN,WEX,WIDR(10,24),WIDP(10,24),WODR(10,24),WODP(10,24),XE,
     XQTL(10,24),QHEXP(10,24),TFD(10,24),FP(10,24),FR(10,24),IP,TOXR(10,
     X24),AVFR,IFLAG,DTQU(10),DTQAUX(10),PSINC(10,24),XM(150),THF(150),
     XRHF(151),T(151,2),H(151,2),DEEP(20),FTIME,SQAUX(10)
C     ******************************************************************
C                               FORMATS
C     ******************************************************************
  200 FORMAT(3F5.0,2I5)
  211 FORMAT('1','DEPTH',F8.2,F12.2,8(F11.2))
  210 FORMAT('1'///,T41,'F I X E D   B E D   D R Y E R   M O D E L')
  212 FORMAT(///,6X,'TIME =',F6.2,25X,'ENERGY INPUT =',F9.2,15X,'H20 REM
```

```
   1OVED =',F7.2,/,6X,'AVERAGE MC =',F6.4,19X,'BTU/LBH2O =',F9.2,/)
213 FORMAT('0','AIR TEMP',15(F8.3,3X))
214 FORMAT('0','PROD TEMP',F7.3,14(4X,F7.3))
215 FORMAT('0','MC DB',2X,F7.3,6X,14(F6.4,5X))
216 FORMAT('0','REL HUM',1X,15(F8.5,3X))
217 FORMAT('0','ABS HUM',1X,15(F8.5,3X))
220 FORMAT('-',T41,'USES TROEGER THINLAYER EQUATION FOR CORN')
221 FORMAT('-',T41,'*****INPUT PROPERTIES AND CONDITIONS*****')
222 FORMAT('-',T7,'AIR TEMP(F)',5X,'PROD TEMP(F)',5X,'REL HUM(DECIMAL)
   X',5X,'ABS HUM(DECIMAL)',5X,'DB MC(DECIMAL)',5X,'EQUIL MC(DECIMAL)'
   X)
223 FORMAT('0',T8,F9.4,7X,F9.4,11X,F6.4,14X,F6.4,14X,F6.4,14X,F6.4)
224 FORMAT('-',T7,'AIR FLOW RATE(CFM/FT**2)',6X,'(LB/HR-FT**2)')
225 FORMAT('0',T9,F9.4,20X,F10.4)
226 FORMAT('-'///,T7,'HEAT CAPACITIES(BTU/LB-R):',8X,'AIR',17X,'PRODUC
   XT',13X,'WATER VAPOR',9X,'WATER LIQUID')
227 FORMAT('0',T39,F6.4,17X,F6.4,15X,F6.4,15X,F6.4)
228 FORMAT('-',T17,'H T COEF CONV',11X,'ATMOS PRESS',8X,'LAT HEAT EVAP
   X',7X,'BULK DEN DRY PROD',4X,'SPEC SURF AREA')
229 FORMAT('0',T18,F9.4,15X,F9.4,11X,F9.4,12X,F9.4,11X,F9.4)
230 FORMAT('-',T52,'PROGRAM CONTROLS')
231 FORMAT('-',T29,'SIMULATE A DEPTH OFF',F5.2,'FT BY INCREMENTS OF',F
   X7.4,'FT PRINTING EVERY',F5.2,'FT')
232 FORMAT(' ',T29,'FOR A TOTAL TIME OF',F6.2,'HR PRINTING EVERY',F5.
   X2,'HR')
233 FORMAT(' ',T29,'OR UNTIL THE AVERAGE MC FALLS BELOW ',F8.6)
234 FORMAT('0',T10,'ENTERING ABSOLUTE HUMIDITY =',F8.5)
235 FORMAT(' ',T10,'ENTERING AIR TEMPERATURE (F) =',F6.2)
236 FORMAT(2F5.0,F10.0)
    F(T)=T+459.69
    RHC=0.9999999999
    D=0.0
    PRT=0.0
    FTIME=0.00
    ITERCT=0
    IEXIT=0
    KCON=0
```

```
      KAB=0
      KDAY=I
      JHR=1
C   INPUT CONDITIONS OF DRYER TO BE READ IN
      READ (5,200) XMO,THIN,DEPTH,INDPR,NLPF
      READ (5,236) TT,TBTPR,XMEND
C   CFM CURRENTLY BASED UPON 1 FT**2
      CFM=AVFR/0.4719
      TIN=100.0
      HIN=WODP(KDAY,JHR)
C   COMPUTE STEP SIZE, NUMBER OF NODES AND DEPTH BETWEEN PRINTS
      DELX=1./NLPF
      IND=NLPF*DEPTH
      IND1=IND+1
      DBTPR=INDPR*DELX
C   COMPUTE OUTPUT DEPTHS FOR PRINTING
      JK=0
      DO 100 IF=1,IND1,INDPR
      JK=JK+1
      DEEP(JK)=D
      D=D+DBTPR
  100 CONTINUE
C   COMPUTE INLET RH AND INITIALIZE ALL ARRAY POSTIONS NECESSARY
      RTIN=F(TIN)
      RHIN=RHDBHA(RTIN,HIN)
      DO 101 IF=1,IND
      IP1=IF+1
      XM(IF)=XMO
      THF(IF)=THIN
      H(IP1,1)=HIN
      T(IP1,1)=TIN
      RHF(IP1)=RHIN
  101 CONTINUE
      T(1,1)=TIN
      T(1,2)=TIN
      H(1,1)=HIN
      H(1,2)=HIN
      RHF(1)=RHIN
      THF(1)=(TIN+THIN)/2.
```

```
C    CONVERT AIRFLOW TO LB/HR AND COMPUTE CONVECTIVE HEAT TRANSFER
C    COEFFICIENT AND EQUILIBRIUM  MOISTURE CONTENT
       RTHIN=P(THIN)
       GA=60.*CFM/VSDBHA(RTHIN,HIN)
       IF(GA-500.) 2,1,1
     1 HC=.363*GA**.59
       GO TO 3
     2 HC=.69*GA**.49
     3 XME=EMC(RHIN,TIN)
C    PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
       PRINT 210
       PRINT 220
       PRINT 221
       PRINT 222
       PRINT 223,TIN,THIN,RHIN,HIN,XMO,XME
       PRINT 224
       PRINT 225,CFM,GA
       PRINT 226
       PRINT 227,CAR,CAP,CV,CW
       PRINT 228
       PRINT 229,HC,PATM,HFG,RHOP,SA
       PRINT 230
       PRINT 231,DEPTH,DELX,DBTPR
       PRINT 232,TT,TBTPR
       PRINT 233,XMEND
C    PRINT DEPTHS FOR WHICH LATER OUTPUT CORRESPONDS
       PRINT 211,(DEEP(IF),IF=1,JK)
C    COMPUTE CONSTANTS USED BY EQUATIONS WITHIN LOOP
       CON1=2.*GA*CAR
       CON2=2.*GA*CV
       CON3=HC*SA*DELX
       CON4=RHOP*CAP
       CON5=RHOP*CW
       CON6=2.*CON3
C    BEGIN TIME LOOP
C    COMPUTE SIZE OF THIS TIME STEP, INCREMENT TIME AND COMPUTE
C    TIME DEPENDENT CONSTANTS
       ENTRY SUBFIX
```

```
      KDAY=I
      JHR=1
    4 HIN=WODP(KDAY,JHR)
      TIN=100.0
      CON7=GA*(CAR+CV*HIN)*(TIN-THIN)
      H(1,1)=HIN
      H(1,2)=HIN
      T(1,1)=TIN
      T(1,2)=TIN
      DELTA=2.*DELX*(CON4+CON5*XM(1))/(CON1+CON2*H(IND1,1))*.9
      FTIME=FTIME+DELTA
      SCON1=GA*DELTA/DELX
      SCON2=RHOP/SCON1
      SCON3=HC*SA*DELTA
C     BEGIN DEPTH LOOP
      DO 102 JF=2,IND1
      JM=JF-1
      THT=(THF(JM)+T(JM,2))/2.
      XMT=XM(JM)
C     SKIP THE THETA EQUATION ON THE FIRST TIME STEP
      IF(ITERCT-0) 5,6,5
    5 IF(XMT.LT..17) HFG=(1094.-.57*THT)*(1.+4.349*EXP(-28.25*XMT))
      TMTH=(T(JM,1)+T(JF,1))/2.-THF(JM)
C     THETA EQUATION
      THF(JM)=THF(JM)+(SCON3*TMTH-(HFG+CV*TMTH)*SCON1*(H(JF,1)-H(JM,1)
     1))/(CON4+CON5*XMT)
      GO TO 7
    6 THT=(T(JM,2)+2.*T(JM,1)+T(JF,1))/4.
    7 HT=((H(JM,1)+H(JF,1))/2.+H(JM,2))/2.
      RTHT=F(THT)
      RHT=RHDBHA(RTHT,HT)
C     CALL SUBROUTINE CONTAINING H EQUATION
      CALL LAYEQ2
      HFG=1000.
C     H EQUATION
      H(JF,2)=H(JM,2)-SCON2*(XMT-XM(JM))
      HT=(H(JM,2)+H(JF,2))/2.
```

```
C     T EQUATION
      T(JF,2)=(T(JM,2)*(CON1+CON2*HT-CON3)+THF(JM)*CON6)/(CON1+CON2*HT+
     1CON3)
      TABS=F(T(JF,2))
C     COMPUTE RH AND CHECK FOR CONDENSATION
      RHF(JF)=RHDBHA(TABS,H(JF,2))
      IF (RHF(JF)-RHC) 9,8,8
C     CONDENSATION SIMULATOR
    8 TWBA=WBDBHA(TABS,H(JF,2),TABS,TABS+20.,.01)
      HS=H(JF,2)
C     T=WETBULB TEMPERATURE, H=WETBULB HUMIDITY RATIO
      T(JF,2)=TWBA-459.69
      H(JF,2)=HADBRH(TWBA,RHC)
      RHF(JF)=RHC
      KCON=KCON+1
      XMT=XMT+(HS-H(JF,2))/SCON2
    9 XM(JM)=XMT
C     END DEPTH LOOP
  102 CONTINUE
      SUM=0.0
C     SHIFT ARRAYS AND COMPUTE AVERAGE MOISTURE CONTENT
      DO 103 JF=2,IND1
      T(JF,1)=T(JF,2)
      H(JF,1)=H(JF,2)
      SUM=SUM+XM(JF-1)
  103 CONTINUE
      XMAVE=SUM/IND
      ITERCT=ITERCT+1
      NODES=IND*ITERCT
C     CHECK IF TIME TO END, MOISTURE CONTENT LOW ENOUGH, OR TIME TO
C     PRINT...IF NONE OF THESE GO TO BEGINNING OF TIME LOOP
      IF(FTIME+DELTA-TT) 10,10,12
   10 IF(XMAVE-XMEND) 12,12,11
   11 IF(FTIME-PRT) 4,13,13
C     SET FLAG IF EXIT CONDITION MET
   12 IEXIT=1
```

```
C    MAKE FINAL CALCULATIONS AND PRINT
   13 PRT=PRT+TBTPR
      ENERGY=CON7*FTIME
      WATER=(XMO-XMAVE)*RHOP*DEPTH
      BTUH2O=ENERGY/WATER
      PRINT 212,FTIME,ENERGY,WATER,XMAVE,BTUH2O
      PRINT 234, HIN
      PRINT 235, TIN
      PRINT 213,(T(IF,2),IF=1,IND1,INDPR)
      PRINT 214,THF(1),(THF(IF),IF=INDPR,IND,INDPR)
      PRINT 215,XM(1),(XM(IF),IF=INDPR,IND,INDPR)
      PRINT 216,(RHF(IF),IF=1,IND1,INDPR)
      PRINT 217,(H(IF,2),IF=1,IND1,INDPR)
      JHR=JHR+1.0
      IF(JHR.GT.NH) RETURN
C    CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGINNING
C    OF TIME LOOP
      IF(IEXIT-1) 4,14,4
   14 CONTINUE
      RETURN
      END
C**********************************************************************
      BLOCKDATA
      COMMON/PRPRTY/SA,CAR,CAP,CV,CW,RHOP,HFG
      COMMON/PRESS/PATM
      DATA SA,CAR,CAP,CV,CW,RHOP,HFG/239.,.242,.268,.45,1.,38.71,1000./
      DATA PATM/14.30/
      END
C**********************************************************************
      FUNCTION EMC(RH,T)
C**********************************************************************
C                              S.F. DEBOER, PROGRAMMER
C    DESCRIPTION
C      FUNCTION SUBROUTINE TO COMPUTE EQUILIBRUIM MOISTURE CONTENT
C      OF CORN FROM A RELATIVE HUMIDITY AND TEMPERATURE.
C      EQUATIONS BY DEBOER FOR T LESS THAN 235 F AND BY T.L. THOMPSON
C      FOR T GREATER THAN 235 F
C    CHECK TEMPERATURE TO DETERMINE EQUATION TO BE USED
      IF(T-235.) 234,235,235
```

```
C                          DEBOER EQUATION
C   CHECK IF RH IS GREATER THAN .50 ...IF IT IS GO TO SECOND PART
  234 IF(RH-.50) 300,300,309
C   PART1----RH .LE. .50 ONLY
C   COMPUTE CONSTANTS
  300 F1 = -.0003922*T+.1000
      F2 = -.0004353*T+.1328
      F3 = -.0005359*T+.1646
      S1 = 13.838 *(-9.*F1+6.*F2-F3)
      S2 = 13.838 *(4.*F3-9.*F2+6.*F1)
      B = RH-.17
C   FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
C   CONTENT
      IF(B)301,301,302
  301 EMC =(S1*RH*RH*RH/1.02+(F1/.17-S1*.02833)*RH)
      RETURN
  302 IF(RH-.34)303,303,304
  303 A = .34-RH
      EMC =(S1*A*A*A/1.02+S2*B*B*B/1.02+(F2/.17-S2*.02833)*B+(F1/.17-S1*
     1.02833)  *A)
      RETURN
  304 A=.51-RH
      EMC = S2*A*A*A/1.02+(F3/.17)*(RH-.34)+(F2/.17-S2*.028333)*A
      RETURN
C   PART 2---RH .GT. .50 ONLY
C   COMPUTE CONSTANTS
  309 F0 = -.0005373*T+.1624
      F1 = -.0007075*T+.2075
      F2 = -.0007449*T+.2532
      F3 = -.001071*T+.3931
      S1 = 13.838*(4.*F0-9.*F1+6.*F2-F3)
      S2 = 13.838*(4.*F3-9.*F2+6.*F1-F0)
      B= RH-.66
      IF(B)305,305,306
```

```
C   FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
C   CONTENT
  305 A=RH-.49
      EMC=S1*A*A*A/1.02+(F1/.17-S1*.02833)*A+(F0/.17)*(.66-RH)
      RETURN
  306 IF(RH-.83)307,307,308
  307 A=.83-RH
      EMC=S1*A*A*A/1.02+S2*B*B*B/1.02+(F2/.17-S2*.02833)*B+(F1/.17-S1*
     1.028333)*A
      RETURN
  308 A=1.0-RH
      EMC=S2*A*A*A/1.02+(F3/.17)*(RH-.83)+(F2/.17-S2*.028333)*A
      RETURN
C--------------------THOMPSON EQUATION---------------------------
C--------------------T .GE. 235 F--------------------------------
C   COMPUTE EQUILIBRIUM MOISTURE CONTENT
  235 EMC=.01*SQRT((-ALOG(1.-RH))/(.0000382*(T+50.)))
      RETURN
      END
C*********************************************************************
      SUBROUTINE LAYEQ2
C*********************************************************************
C   DESCRIPTION
C     SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUATIONS
C     BY J.M. TROEGER AND P.M. DEL GIUDICE
      COMMON /GENL/XMC,TH,RH,DELTA,CFM,XMO,KAB
      COMMON DAY,DBT(10,24),DPT(10,24),IHR(10,24),HENCR(10,24),MO,ND,NH,
     XPERB(10,24),PERD(10,24),REFLEC(10,24),STN,WDIR(10,24),WVEL(10,24)
     X,WAM(10,24),YR,IDATE(10),WOXP(10,24),GTQU,GEMT,WATER,COUNT,TIN
```

```
      COMMON AC,AF,ALFA(10,24),ALONG,AMASSP,AMASSR,AUP,AUR,AV,BLEAK,CP,
     XCTYPE,DD,DELPEP,DELPER,DELPR,DELPP,DELT,DTDC,DTCD,DUMMY,EFF(10,24)
     X,FL,FLE,FRIC,GAM(2,2),HMU,I,II,III,INC,INCI,INDIC,ITNUM,J,LL,N,NN
     X,NNN,PHI,PI,PLEAKR,PLEAKP,QAUX(10,24),QDEHU(10,24),QDUCT(10,24),
     XQSURP(10,24),QHEXR(10,24),QU(10,24),RHOF,RLEAK,RPS,SIG(2,2),SL,
     XTAMB,TAU,TC,TCN,TIC(10,24),TIDP(10,24),TIDR(10,24),TIME,TMIN,
     XTOC(10,24),TODR(10,24),TODP(10,24),TRD(10,24),U,VELR,VELP,VOID,W,
     XWC,WCN,WEX,WIDR(10,24),WIDP(10,24),WODR(10,24),WODP(10,24),XE,
     XQTL(10,24),QHEXP(10,24),TFD(10,24),FP(10,24),FR(10,24),IP,TOXR(10,
     X24),AVFR,IFLAG,DTQU(10),DTQAUX(10),PSTNC(10,24),XM(150),THF(150),
     XRHF(151),T(151,2),H(151,2),DEEP(20),FTIME,SQAUX(10)
C    STATEMENT FUNCTIONS
      P1(XM,R,T)=EXP(-2.45+6.42*XM**1.25-3.15*R+9.62*XM*SQRT(R)+.03*T-.0
     102*CFM)
      P2(R,T)=EXP(2.82+7.49*(R+.01)**.67-.0179*T)
      P3(P,Q)=-(.12*(XMO-XME))**(Q+1.)*P*Q
      Q1(XM,R,T)=-3.98+2.87*XM-(.019/(R+.015))+.016*T
      Q2(R)=-EXP(.81-3.11*R)
      TF(P,Q,XO,XF,TO)=P*(XF-XME)**Q-P*(XO-XME)**Q+TO
      XMN(P,Q,XO,TI,TO)=((TI-TO)/P+(XO-XME)**Q)**(1./Q)+XME
C
C                       PROGRAM
C    CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS
      CALL READYT(TXMO,DELM,XME,IOOPS,XMR)
C    CHECK ABSORPTION FLAG...IF SET GO TO ABSORPTION SIMULATION
      IF(IOOPS-1)1,6,1
C    COMPUTE TRANSITION M,P1,Q1, AND FIRST TRANSITION TIME
    1 X1M=.4*DELM+XME
      X2M=.12*DELM+XME
      TINC=DELTA*60.
      P=P1(TXMO,RH,TH)
      Q=Q1(TXMO,RH,TH)
      TX=TF(P,Q,TXMO,X1M,0.0)
C    CHECK IF PRESENT M IS IN FIRST REGION...IF IT IS COMPUTE EQUIVALENT
C    TIME AND ADD TINC
      IF(XMC.LT.X1M) GO TO 3
      TI=TF(P,Q,TXMO,XMC,0.0)+TINC
```

```
C     CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME....
C     IF IT IS COMPUTE NEW M AND RETURN
         IF(TI.GT.TX) GO TO 2
         XMC=XMN(P,Q,TXMO,TI,0.0)
         RETURN
C     EQUIVALENT TIME+TINC IS IN SECOND REGION--COMPUTE P2,Q2 AND
C     NEW M THEN RETURN
      2 P=P2(RH,TH)
         Q=Q2(RH)
         XMC=XMN(P,Q,X1M,TI,TX)
         RETURN
C     M IS NOT IN FIRST REGION--COMPUTE P2,Q2 AND SECOND TRANSITION TIME
      3 P=P2(RH,TH)
         Q=Q2(RH)
         TX1=TX
         TX=TF(P,Q,X1M,X2M,TX1)
C     CHECK IF PRESENT M IS IN SECOND REGION..IF IT IS COMPUTE EQUIVALENT
C     TIME AND ADD TINC
         IF(XMC.LT.X2M) GO TO 5
         TI=TF(P,Q,X1M,XMC,TX1)+TINC
C     CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME...IF IT
C     IS COMPUTE M AND RETURN
         IF(TI.GT.TX) GO TO 4
         XMC=XMN(P,Q,X1M,TI,TX1)
         RETURN
C     EQUIVALENT TIME+TINC IS IN THIRD REGION--COMPUTE P3, Q3 AND NEW M
C     THEN RETURN
      4 P=P3(P,Q)
         Q=-1.0
         XMC=XMN(P,Q,X2M,TI,TX)
         RETURN
C     M IS NOT IN SECOND REGION--COMPUTE P3, Q3, EQUIVALENT TIME+TINC AND
C     NEW M THEN RETURN
      5 P=P3(P,Q)
         Q=-1.0
         TI=TF(P,Q,X2M,XMC,TX)+TINC
         XMC=XMN(P,Q,X2M,TI,TX)
         RETURN
```

```
C    ABSORTION SIMULATION
C    FIND NEW M AND INCREMENT COUNTER
    6 DIV=-.625*PSDB(TH+459.69)**(.466*RH)*RH*RH*RH
      XMC=(XMC-XME)*EXP(DIV*DELTA)+XME
      KAB=KAB+1
      RETURN
      END
C*********************************************************************
      SUBROUTINE READYT(TXMO,DELM,XME,IOOPS,XMR)
C*********************************************************************
C    DESCRIPTION
C      SUBROUTINE TO MAKE PRELIMINARY CHECK AND CALCULATIONS FOR
C      THINLAYER EQUATIONS
      COMMON /GENL/XMC,TH,RH,DELTA,CFM,XMO,KAB
      COMMON DAY,DBT(10,24),DPT(10,24),IHR(10,24),HENCR(10,24),MO,ND,NH,
     XPERB(10,24),PERD(10,24),REFLEC(10,24),STN,WDIR(10,24),WVEL(10,24)
     X,WAM(10,24),YR,IDATE(10),WOXP(10,24),GTQU,GEMT,WATER,COUNT,TIN
      COMMON AC,AF,ALFA(10,24),ALONG,AMASSP,AMASSR,AUP,AUR,AV,BLEAK,CP,
     XCTYPE,DD,DELPEP,DELPER,DELPR,DELPP,DELT,DTDC,DTCD,DUMMY,EFF(10,24)
     X,FL,FLE,FRIC,GAM(2,2),HMU,I,II,III,INC,INCI,INDIC,ITNUM,J,LL,N,NN
     X,NNN,PHI,PI,PLEAKR,PLEAKP,QAUX(10,24),QDEHU(10,24),QDUCT(10,24),
     XQSURP(10,24),QHEXR(10,24),QU(10,24),RHOF,RLEAK,RPS,SIG(2,2),SL,
     XTAMB,TAU,TC,TCN,TIC(10,24),TIDP(10,24),TIDR(10,24),TIME,TMIN,
     XTOC(10,24),TODR(10,24),TODP(10,24),TRD(10,24),U,VELR,VELP,VOID,W,
     XWC,WCN,WEX,WIDP(10,24),WIDP(10,24),WODR(10,24),WODP(10,24),XE,
     XQTL(10,24),QHEXP(10,24),TFD(10,24),FP(10,24),FR(10,24),IP,TOXR(10,
     X24),AVFR,IFLAG,DTQU(10),DTQAUX(10),PSTNC(10,24),XM(150),THF(150),
     XRHF(151),T(151,2),H(151,2),DEEP(20),FTIME,SQAUX(10)
      IOOPS=0
C    COMPUTE EQUILIBRIUM MOISTURE CONTENT, COMPARE TO PRESENT
C    MOISTURE CONTENT...IF GREATER SET IOOPS=1
      XME=EMC(RH,TH)
      IF(XME-XMC)2,1,1
    1 IOOPS=1
C    COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT
```

```
C     SET TXMO=THE LARGER VALUE
    2 IF(XMO-XMC) 3,4,4
    3 TXMO=XMC
      GO TO 5
    4 TXMO=XMO
C     COMPUTE MOISTURE RATIO
    5 DELM=TXMO-XME
      XMR=(XMC-XME)/DELM
      RETURN
      END
C**********************************************************************
C     SYCHART PACKAGE
C     L.E.LEREW, PROGRAMMER
C     DESCRIPTION
C       GROUP OF HIGHLY INTERACTIVE FUNCION SUBPROGRAMS BASED
C       ON EQUATIONS BY BROOKER (1967,1970) AND A ROOT FINDING SUB-
C       ROUTINE BASED ON AN ALGORITHM BY DEKKER (1967) USED TO FIND
C       AND CONVERT PSYCHROMETRIC PROPERTIES
C**********************************************************************
      FUNCTION HADBRH(DB,RH)
      HADBRH=HAPV(RH*PSDB(DB))
      RETURN
      END
C**********************************************************************
      FUNCTION HADP(DP)
      HADP=HAPV(PSDB(DP))
      RETURN
      END
C**********************************************************************
      FUNCTION HAPV(PV)
      COMMON/PRESS/PATM
      HAPV=.6219*PV/(PATM-PV)
      RETURN
      END
```

```
C*********************************************************************
      FUNCTION RHPSPV(D1,D2)
      A=D1
      B=D2
      GO TO 1
      ENTRY RHDBHA(D1,D2)
      A=PSDB(D1)
      B=PVHA(D2)
    1 RHPSPV=B/A
      RETURN
      END
C*********************************************************************
      FUNCTION PVDBWB(DB,WB)
      COMMON/PRESS/PATM
      A=PSDB(WB)
      B=.62194*HLDB(WB)*PATM
      C=.2405*(A-PATM)*(WB-DB)
      PVDBWB=(A*B-C*PATM)/(B+.15577*C)
      RETURN
      END
C*********************************************************************
      FUNCTION PVDBVS(DB,VS)
      COMMON/PRESS/PATM
      PVDBVS=PATM-53.35*DB/VS/144.
      RETURN
      END
C*********************************************************************
      FUNCTION PVHA (HA)
      COMMON/PRESS/PATM
      PVHA=HA*PATM/(.6219+HA)
      RETUPN
      END
```

```
C*****************************************************************
      FUNCTION PSDB (DB)
      DATA R,A,B,C,D,E,F,G/.3206182232E04,-.2740552583614 26E05,.54189607
     A632895 1E02,-.45137038411 2655E-1,.2153211916 36354E-4,-.46202 6656819
     B982E-8,.2416127209874E01,.12154651670 6055E-2/
      IF(DB-491.69) 1,2,2
    1 PSDB=EXP(23.3924-11286.6489/DB-.46057*ALOG(DB))
      RETURN
    2 PSDB=R*EXP((A+DB*(B+DB*(C+DB*(D+DB*E))))/(DB*(F-G*DB)))
      RETURN
      END
C*****************************************************************
      FUNCTION HLDB (DB)
      IF(DB-491.69) 1,2,2
    1 HLDB=1220.884-.05077*(DB-459.69)
      RETURN
    2 IF(DB-609.69) 3,4,4
    3 HLDB=1075.8965-.56983*(DB-459.69)
      RETURN
    4 HLDB=SQRT(1354673.214-.9125275587*DB*DB)
      RETURN
      END
C*****************************************************************
      FUNCTION VSDBHA (DB,HA)
      COMMON /PRESS/PATM
      VSDBHA=53.35*DB*(.6219+HA)/144./.6219/PATM
      RETURN
      END
C*****************************************************************
      FUNCTION ENDBDP (DB,DP)
      COMMON/PRESS/ PATM
      HA=HADP(DP)
      T1=.2405*(DB-459.69)+HLDB(DP)*HA+.448*HA*(DB-DP)
      IF(DP-491.69) 1,2,2
    1 ENDBDP=T1-HA*(143.35+.485*(491.69-DP))
      RETURN
    2 ENDBDP=T1+HA*(DP-491.69)
      RETURN
      END
```

```
C***********************************************************************
      FUNCTION WDDBHA(DB,HA,G1,G2,EPS)
      EXTERNAL WBL
      COMMON /SPECIA/PV,TB,XTRA
      A=G1
      B=G2
      TB=DB
      PV=PVHA(HA)
      CALL ZEROIN (A,D,EPS,WBL)
      WBDBHA=(A+B)/2.
      RETURN
      END
C***********************************************************************
      FUNCTION WBL(TWB)
      COMMON /PRESS/PATM
      COMMON /SPECIA/PV,DB,XTRA
      PWB=PSDB(TWB)
      WBL=TWB-DB-(PWB-PV)/(.2405*(PWB-PATM)*(1.+.15577*PV/PATM))*(.62194
     1*HLDB(TWD))
      RETURN
      END
C***********************************************************************
      FUNCTION DPHAS(HA,G1,G2,EPS)
      COMMON /SPECIA/PV,DB,XTRA
      EXTERNAL DPL1
      PV=PVHA(HA)
      A=G1
      B=G2
      CALL ZEROIN (A,B,EPS,DPL1)
      DPHAS=(A+B)/2.
      RETURN
      END
C***********************************************************************
      FUNCTION DPL1(TDP)
      COMMON /SPECIA/PV,DB,XTRA
      DPL1=PV-PSDB(TDP)
      RETURN
      END
```

```
C*****************************************************************
      FUNCTION DPDBEN(DB,EN,G1,G2,EPS)
      COMMON /SPECIA/PV,TB,XTRA
      EXTERNAL DPL2
      A=G1
      B=G2
      XTRA=.2405*(DB-459.69)-EN
      TB=DB
      CALL ZEROIN (A,B,EPS,DPL2)
      DPDBEN=(A+B)/2.
      RETURN
      END
C*****************************************************************
      FUNCTION DPL2 (TDP)
      COMMON /SPECIA/PV,DB,XTRA
      HA=HADP(TDP)
      T2=HA*HLDB(TDP)+.448*HA*(DB-TDP)
      IF(TDP-491.69) 1,2,2
    1 DPL2=XTRA+T2-HA*(143.35+.485*(491.69-TDP))
      RETURN
    2 DPL2=XTRA+T2+HA*(TDP-491.69)
      RETURN
      END
C*****************************************************************
      FUNCTION DBPSS(PS,G1,G2,EPS)
      COMMON /SPECIA/PV,TB,XTRA
      EXTERNAL DBL
      A=G1
      B=G2
      XTRA=PS
      CALL ZEROIN (A,B,EPS,DBL)
      DBPSS=(A+B)/2.
      RETURN
      END
```

```
C**********************************************************************
      FUNCTION DBL(T)
      COMMON /SPECIA/PV,TB,PS
      DBL=PS-PSDB(T)
      RETURN
      END
C**********************************************************************
      SUBROUTINE ZEROIN(A,B,EPS,FUNC)
      REAL I,M
      FA=FUNC(A)
      FB=FUNC(B)
      FC=FA
      C=A
      IF(SIGN(1.,FB).NE.SIGN(1.,FC)) GO TO 1
  200 FORMAT(///,5X,'WARNING--NO ROOTS OR MULTIPLE ROOTS BETWEEN INITIAL
     1 GUESS TO ZEROIN',2X,'GUESSES ARE',E21.14,'AND',E21.14)
      PRINT 200,A,B
    1 IF(ABS(FC)-ABS(FB)) 2,3,3
    2 C=B
      B=A
      A=C
      FC=FB
      FB=FA
      FA=FC
    3 IF(ABS(C-B)-2.*EPS) 12,12,4
    4 I=(B-A)*FB/(FB-FA)
      M=(C+B)/2.
    5 I=-I+B
      CHINT=(B-I)*(M-I)
      IF(CHINT) 8,8,7
    7 I=M
    8 IF(ABS(B-I)-EPS) 9,10,10
    9 I=SIGN(1.,(C-B))*EPS+B
   10 A=B
      B=I
      FA=FB
      FB=FUNC(B)
      IF(SIGN(1.,FB)-SIGN(1.,FC)) 1,11,1
```

```
   11 C=A
      FC=FA
      GO TO 1
   12 A=(C+B)/2.
      FA=FUNC(A)
      IF(SIGN(1.,FA).EQ.SIGN(1.,FB)) B=C
      RETURN
      END
//GO.FT03F001 DD DSN=TMY,UNIT=TAPE1600,VOL=SER=9TMY03,LABEL=(26,,,IN),
// DCB=(RECFM=FB,LRECL=132,BLKSIZE=3168)
//GO.SYSIN DD *
   10   20   10   23    0   23    4   19    9
    2
 5663      1049      4137       960
    0    1
      1962  034   75   0016667       121         80
      1281      0031      1463       592   00   00   00   00    0
.3333   80    5   15   15
   96    1         .08
   13    6   30    5
   15  120  120 1200    1
    5   10   12   55
    4    5
  300      1000         0         0         0    2
    5   10   12
    4    5
      2000         0         0         0    2
```

APPENDIX H

GLOSSARY FOR MAIN VARIABLES USED IN SYSTEMS 1, 1A, 2, 2A, 3, AND 3A

AC = AREA OF COLLECTOR
AF = FRONTAL AREA OF BED
ALONG = COLLECTOR LOCATION LONGITUDE
AMASSP = AIR MASS FLOW RATE, PROCESS SIDE
AMASSR = AIR MASS FLOW RATE, REGENERATION SIDE
AV = INTERNAL SURFACE AREA OF DESSICANT PER UNIT VOLUME
AVFR = AIR VOLUME FLOW RATE IN LITERS PER SECOND
BETA = INTERMEDIATE VALUE USED TO DETERMINE AMBIENT ABSOLUTE HUMIDITY
BETAF = FRACTIONAL FORM OF BETA
BLEAK = BYPASS LEAKAGE RATE
BTUH2O = ENERGY INPUT PER WATER REMOVED (BTU/LB-H2O)
CA = UNIT COST VARYING WITH SIZE OF SOLAR ENERGY SYSTEM
CAP = HEAT CAPACITY OF DRY PRODUCT
CAR = HEAT CAPACITY OF DRY AIR
CFM = AIRFLOW RATE AT INLET AIR TEMPERATURE FT**3/MIN/FT**2
CEC = EQUIPMENT COST - CONVENTIONAL
CES = EQUIPMENT COST - SOLAR
CF = COST OF FUEL IN DOLLARS
CFLAG = PROGRAMMING FLAG TO DESIGNATE THE DIFFERENCE BETWEEN INCOME PRODUCING AND NON-INCOME PRODUCING SOLAR SYSTEMS
CLK = CLOCK HOUR UNDER CONSIDERATION
CMC = CONVENTIONAL RATIO OF MISC. COSTS TO INITIAL INVESTMENT
CMCP = PERCENTAGE FORM OF CMC
CMIR = ANNUAL MORTGAGE INTEREST RATE - CONVENTIONAL
CMIRP = PERCENTAGE FORM OF CMIR
COST = DAILY COST OF AUXILIARY HEAT SUPPLIED AT DRYER INLET
CV = HEAT CAPACITY OF WATER VAPOR (BTU/LB-F)
CW = HEAT CAPACITY OF LIQUID WATER (BTU/LB-F)
DAY = DAY UNDER CONSIDERATION
DAYB = BEGINNING DAY OF STUDY
DAYF = CONTROL TO AID IN OBTAINING THE PREVIOUS DAY NUMBER WHEN CROSSING MONTH BOUNDARIES
DBT = DRY BULB TEMPERATURE
DBTPR = DEPTH BETWEEN DESIRED OUTPUT IN X-DIRECTION
DC = DOWNPAYMENT - CONVENTIONAL
DCP = PERCENTAGE FORM OF DC
DD = DESICCANT CHAR DIMENSION
DEEP = DEPTHS AT WHICH OUTPUT OCCURS (FT)
DELT = TIME INCREMENT (HR)
DELX = DEPTH INCREMENT OR WIDTH INCREMENT (FT)
DEND = ENDING DAY OF STUDY
DEPC = DEPRECIATION TAX DEDUCTION - CONVENTIONAL
DEPS = DEPRECIATION TAX DEDUCTION - SOLAR
DEPTH = TOTAL BED DEPTH
DIFR = DIFFUSE RADIATION
DIRR = DIRECT RADIATION
DIC = DEPRECIATION INFLATION RATE - USED FOR DECLINING BALANCE - CONVENTIONAL
DIS = DEPRECIATION INFLATION RATE - USED FOR DECLINING BALANCE - SOLAR
DMCC = DISCOUNTED VALUE OF MISC. COSTS - CONVENTIONAL (INSURANCE,ETC.)
DMCS = DISCOUNTED VALUE OF MISC. COSTS - SOLAR
DDPC = FLAG INDICATING WHICH DEPRECIATION SCHEDULE IS UTILIZED-CONVENTIONAL

DDPS = FLAG INDICATING WHICH DEPRECIATION SCHEDULE IS UTILIZED-SOLAR
DPT = DEW POINT TEMPERATURE
DQAUX = AUXILIARY HEAT SUPPLIED AT INLET OF DRYER
DRC = MARKET DISCOUNT RATE - CONVENTIONAL
DRCP = PERCENTAGE FORM OF DRC
DRS = MARKET DISCOUNT RATE - SOLAR
DRSP = PERCENTAGE FORM OF DRS
DRVC = DISCOUNTED RESALE VALUE - CONVENTIONAL
DRVS = DISCOUNTED RESALE VALUE - SOLAR
DS = DOWNPAYMENT - SOLAR
DSP = PERCENTAGE FORM OF DS
DTCD = TEMP DROP THROUGH DUCTING, COLLECTOR TO DEHUMIDIFIER
DTDC = TEMP DROP THROUGH DUCTING, DEHUMIDIFIER TO COLLECTOR
DTQU = DAILY TOTAL HEAT GAINED IN THE COLLECTOR
DTQAUX = DAILY TOTAL AUX HEAT SUPPLIED FOR REGENERATION OF DESICCANT
EFF = EFFICIENCY
ENCR = ENGINEERING CORRECTED RADIATION
ENERGY = ENERGY INPUT (CUMMULATIVE) (BTU/HR-FT**2)
EXTR = EXTRATERRESTRIAL RADIATION
F = FRACTION OF HEAT SUPPLIED BY SOLAR, WITH RESPECT TO THE TOTAL HEAT SUPPLIED (1-F IS THE PERCENT AUXILIARY AND ADDITIONAL HEAT SUPPLIED)
FF = PERCENTAGE FORM OF F
FI = FUEL INFLATION RATE
FIP = PERCENTAGE FORM OF FI
FL = LENGTH OF DESICCANT WHEEL IN FLOW DIRECTION
FP = COLLECTOR FACTOR FRUL
FR = COLLECTOR FACTOR FRTA
FRIC = DESICCANT FRICTION FACTOR
FTR = FEDERAL TAX RATE
FTRP = PERCENTAGE FORM OF FTR
GA = DRY AIRFLOW RATE
GEMT = GRAND TOTAL EVAPORATED MOISTURE
GI = GENERAL INFLATION RATE
GIP = PERCENTAGE FORM OF GI
GTQU = GRAND TOTAL OF SOLAR HEAT GAIN
GTQAUX = GRAND TOTAL OF AUX. HEAT USED FOR REGENERATION OF DESICCANT
HC = CONVECTIVE HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-F)
HFG = LATENT HEAT OF WATER IN GRAIN (BTU/LB)
HIN = INLET HUMIDITY RATIO (LB-H2O/LB-DRYAIR)
HRB = BEGINNING HOUR OF STUDY
HEND = ENDING HOUR OF STUDY
HMU = AIR TO DESICCANT MASS RATIO IN DESICCANT WHEEL
I = DAY COUNTER
IDATE = NUMBER DAY OF THE YEAR
IFLAG = FLAG TO SIGNAL AUXILIARY HEATER INTO DEHUMIDIFIER
IHR = SOLAR HOUR
ILEAP = PROGRAM AID TO DETERMINE THE NUMBER DAY OF THE YEAR TAKING INTO CONSIDERATION LEAP YEAR
INDPR = NUMBER OF NODES BETWEEN PRINTS
IZ = CONTROL TO AID IN SETTING TAPE TO THE ZERO HOUR OF THE DAY DATA IS TO BE READ
J = HOUR COUNTER
KT = HOURLY CLEARNESS INDEX
LADD = ADDITIONAL LOAD VARIED TO DETERMINE OPTIMUM LIFE CYCLE COST
LCCC = LIFE CYCLE COSTS - CONVENTIONAL
LCCS = LIFE CYCLE COSTS - SOLAR

LP = LOAD DRIED BY DEHUMIDIFIER
LPP = LOAD DRIED BY DEHUMIDIFIER AND SUPPLEMENTAL SOURCE
MEND = ENDING MONTH OF STUDY
MHR = TAPE HOUR READ
MINS = MINUTES OF SUNSHINE
MO = MONTH
MOB = BEGINNING MONTH OF STUDY
MOTEST = PROGRAM AID TO DETERMINE THE NUMBER DAY OF THE YEAR
MPIC = DISCOUNTED MORTGAGE PRINCIPAL AND INTEREST - CONVENTIONAL
MPIS = DISCOUNTED MORTGAGE PRINCIPAL AND INTEREST - SOLAR
ND = NUMBER OF DAYS INCLUDED IN STUDY
NDAY = NUMBER OF DAY IN A GIVEN MONTH
NDEPC = TERM OF DEPRECIATION - CONVENTIONAL
NDEPS = TERM OF DEPRECIATION - SOLAR
NDEPPC = TERM OF DEPRECIATION, USED FOR D. B. AND S. O. D. - CONVENTIONAL
NDEPPS = TERM OF DEPRECIATION, USED FOR D. B. AND S. O. D. - SOLAR
NEA = TERM OF THE ECONOMIC ANALYSIS
NH = NUMBER OF HOURS IN THE STUDY
NLC = TERM OF THE LOAD - CONVENTIONAL
NLPF = NUMBER OF LAYERS PER FOOT
NLS = TERM OF THE LOAN - SOLAR
NMINC = YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS - CONVENTIONAL EQUAL TO THE MINIMUM OF NLC AND NEA
NMINS = YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS - SOLAR EQUAL TO THE MINIMUM OF NLS AND NEA
NMINPC = YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS FOR THE EQUIPMENT - CONVENTIONAL
NMINPS = YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS FOR THE EQUIPMENT - SOLAR
EQUAL TO THE MINIMUM OF NEA AND NDEPS
OBSR = OBSERVED RADIATION
PATM = ATMOSPHERIC PRESSURE
PDAY = CALENDAR NUMBER OF THE DAY PRECEDING THE REQUESTED BEGINNING DAY OF STUDY
PERB = PERCENTAGE OF BEAM RADIATION BASED ON EXTRATERRESTRIAL RADIATION
PERD = PERCENTAGE OF DIFFUSE RADIATION BASED ON EXTRATERRESTRIAL RADIATION
PHI = COLLECTOR LOCATION LATITUDE
PLEAKP = PERIPHERY LEAKAGE RATE, PROCESS SIDE
PLEAKR = PERIPHERY LEAKAGE RATE, REGENERATION SIDE
PONEC = RATIO OF LIFE CYCLE FUEL COSTS TO FIRST YEAR FUEL COSTS - CONVENTIONAL
PONES = RATIO OF LIFE CYCLE FUEL COSTS TO FIRST YEAR FUEL COSTS - SOLAR
PMO = NUMBER OF THE MONTH PRECEDING THE REQUESTED BEGINNING MONTH
PSEA = ATMOSPHERIC PRESSURE AT SEA LEVEL
PSTN = ATMOSPHERIC PRESSURE AT THE STATION
PSTNC = ATMOSPHERIC PRESSURE AT THE STATION CORRECTED
PTCC = DISCOUNTED PROPERTY TAX COSTS - CONVENTIONAL
PTCS = DISCOUNTED PROPERTY TAX COSTS - SOLAR
PTWOC = LIFE CYCLE COSTS OF ADDITIONAL CAPITAL INVESTMENT TO INITIAL INVESTMENT - CONVENTIONAL
PTWOS = LIFE CYCLE COSTS OF ADDITIONAL CAPITAL INVESTMENT TO INITIAL INVESTMENT - SOLAR
PW_C = PRESENT WORTH FACTOR FOR CALCULATING A TERM IN PONE OR PTWO - CONVENTIONAL
PWF = PRESENT WORTH FACTOR, SEE PG 386 DUFFIE AND BECKMAN
PWFP = SECOND FORM OF PWF, SEE ABOVE
PW_S = PRESENT WORTH FACTOR FOR CALCULATING A TERM IN PONE OR PTWO -

SOLAR

PWV = PARTIAL PRESSURE OF WATER VAPOR

QDEHU = RATE OF HEAT TRANSFERRED IN DEHUMIDIFIER, WATTS

QDUCT = RATE OF HEAT LOST FROM DUCTING, WATTS

QHEXP = RATE OF HEAT TRANSFERRED IN HEAT EXCHANGER, WATTS

QU = RATE OF HEAT GAINED IN COLLECTOR, WATTS

QAUX = RATE OF HEAT SUPPLIED BY AUXILIARY HEATER INTO DEHUMIDIFIER, WATTS

QSURP = SURPLUS SOLAR HEAT AVAILABLE, WATTS

REFLEC = GROUND RELECTANCE RATIO

RH = RELATIVE HUMIDITY

RHC = SATURATION RELATIVE HUMIDITY = 0.9999999999

RHIN = INLET RELATIVE HUMIDITY (DECIMAL)

RHOF = AVERAGE DENSITY OF AIR FLOW STREAM

RHOP = DRY BULK DENSITY OF GRAIN (LB/FT**3)

RLEAK = RECIRCULATION LEAK RATE

RPS = REV PER SEC

RVC = RATIO OF RESALE VALUE AT END OF PERIOD OF ANALYSIS TO INITIAL INVESTMENT - CONVENTIONAL

RVS = RATIO OF RESALE VALUE AT END OF PERIOD OF ANALYSIS TO INITIAL INVESTMENT - SOLAR

SKY = SKY CONDITIONS, TYPE AND EXTENT OF CLOUD COVER

SL = SLOPE OF COLLECTOR (OPTIMUM ANGLE-LATITUDE)

SMC = SOLAR RATIO OF MISC. COSTS TO INITIAL INVESTMENT

SMCP = PERCENTAGE FORM OF SMC

SMIR = ANNUAL MORTGAGE INTEREST RATE - SOLAR

SMIRP = PERCENTAGE FORM OF SMIR

SNOW = INDICATOR OF SNOW COVERAGE

STDYR = STANDARD YEAR RADIATION

STN = STATION NUMBER

STR = STATE TAX RATE

STRP = PERCENTAGE FORM OF STR

TAC = TOTAL COLLECTOR AREA

TAVC = PROPERTY TAX RATE BASED UPON ASSESSED VALUE - CONVENTIONAL

TAVS = PROPERTY TAX RATE BASED UPON ASSESSED VALUE - SOLAR

TBAR = EFFECTIVE TAX RATE

TBTPR = TIME BETWEEN OUPUTS

TCOST = TOTAL COST OF AUXILIARY HEAT TO DRYER INLET FOR THE STUDY

TCR = TAX CREDIT RATE

TCRP = PERCENTAGE FORM OF TCR

TOIC = DISCOUNTED VALUE OF INCOME TAX DEDUCTIONS ON THE INTEREST - CONVENTIONAL

TOIS = DISCOUNTED VALUE OF INCOME TAX DEDUCTIONS ON THE INTEREST - SOLAR

TOQAUX = DAILY TOTAL HEAT PROVIDED BY AUX HEATER TO DRYER INLET

THIN = INLET OR INITIAL GRAIN TEMPERATURE (F)

TIC = TEMPERATURE INTO COLLECTOR

TIOO = DRY BULB TEMPERATURE INTO THE DRYER

TIOR = TEMPERATURE INTO DEHUMIDIFIER, REGENERATION SIDE

TIDW = WET BULB TEMPERATURE INTO THE DRYER

TIME = TIME (CUMMULATIVE) (HR)

TIN = INLET AIR TEMPERATURE (F)

TMIN = MINIMUM TEMP OF DESICCANT REGENERATION AIR (OPTION #2)

TOC = TEMPERATURE OUT OF COLLECTOR

TOOP = OUTLET TEMPERATURE OF DEHUMIDIFIER, PROCESS SIDE

TOOR = OUTLET TEMPERATURE OF DEHUMIDIFIER, REGENERATION SIDE

TOXP = OUTLET TEMPERATURE OF SENSIBLE HEAT EXCHANGER, PROCESS SIDE

TOXR = OUTLET TEMPERATURE OF SENSIBLE HEAT EXCHANGER, REGENERATION SIDE
TQAUX = TOTAL AUXILIARY HEAT SUPPLIED, KJ, TO DEHUMIDIFIER REGENERATION SIDE
TQU = TOTAL HEAT GAIN IN COLLECTOR, KJ
TQDEHU = HEAT TRANSFERRED IN DEHUMIDIFIER, KJ
TQDUCT = HEAT LOST FROM DUCTING, KJ
TQHEX = HEAT TRANSFERRED IN HEAT EXCHANGER, KJ
TQSURP = TOTAL SURPLUS SOLAR HEAT AVAILABLE, KJ
TRO = INLET TEMPERATURE TO AUXILIARY HEATER, REGENERATION SIDE
TT = TOTAL TIME (IN HOURS) OF STUDY
U = EFFECTIVE CONDUCTANCE BETWEEN DESICCANT AND AIR STREAM
VC = RATIO OF ASSESSED VALUATION OF THE SYSTEM IN FIRST YEAR TO THE INITIAL INVESTMENT OF THE SYSTEM - CONVENTIONAL
VOID = VOID FRACTION OF DESICCANT MATERIAL
VS = RATIO OF ASSESSED VALUATION OF THE SYSTEM IN FIRST YEAR TO THE INITIAL INVESTMENT OF THE SYSTEM - SOLAR
WAM = AMBIENT HUMDITY RATIO
WATER = AMOUNT OF H2O REMOVED (CUMMULATIVE)
WEAT = WEATHER CONDITIONS, SNOW , RAIN, ETC.
WDIR = WIND DIRECTION
WIDP = INLET HUMIDITY DEHUMIDIFIER, PROCESS SIDE
WIDR = INLET HUMIDITY DEHUMIDIFIER, REGENERATION SIDE
WODP = OUTLET HUMIDITY DEHUMIDIFIER, PROCESS SIDE
WODR = OUTLET HUMIDITY DEHUMIDIFIER, REGENERATION SIDE
WOXP = OUTLET HUMIDITY HEAT EXCHANGER, PROCESS SIDE
WOXR = OUTLET HUMIDITY HEAT EXCHANGER, REGENERATION SIDE
WVEL = WIND VELOCITY
XE = SENSIBLE HEAT EXCHANGER EFFICIENCY
XMAVE = AVERAGE MOISTURE CONTENT IN X-DIRECTION (DECIMAL,DB)
XME = EQUILIBRIUM MOISTURE CONTENT (DECIMAL,DB)
XMEND = FINAL DESIRED MOISTURE CONTENT (DECIMAL, DB)
XMO = INLET OF INITIAL MOISTURE CONTENT (DECIMAL, DB)
YR = YEAR

APPENDIX I

SAMPLE OUTPUT
OF
DRYER SIMULATION

```
                                   F I X E D   B E D   D R Y E R   M O D E L

                                   USES TROEGER THINLAYER EQUATION FOR CORN

                                   *****INPUT PROPERTIES AND CONDITIONS*****

AIR TEMP(F)     PROD TEMP(F)     REL HUM(DECIMAL)     ABS HUM(DECIMAL)     DB MC(DECIMAL)     EQUIL MC(DECIMAL)
 100.0000         80.0000            0.0                  0.0                 0.3333              0.0

AIR FLOW RATE(CFM/FT**2)       (LB/HR-FT**2)
   120.0042                      514.9529



HEAT CAPACITIES(BTU/LB-R):          AIR                 PRODUCT             WATER VAPOR         WATER LIQUID
                                  0.2420                0.2680                0.4500              1.0000

         H T COEF CONV              ATMOS PRESS         LAT HEAT EVAP       BULK DEN DRY PROD   SPEC SURF AREA
           14.4494                    14.3000             1040.6409             38.7100             239.0000

                                                 PROGRAM CONTROLS

                       SIMULATE A DEPTH OF 5.00FT BY INCREMENTS OF 0.0667FT PRINTING EVERY 1.00FT
                       FOR A TOTAL TIME OF 96.00HR PRINTING EVERY 1.00HR
                       OR UNTIL THE AVERAGE MC FALLS BELOW 0.080000
```

```
DEPTH    0.0         1.00        2.00        3.00        4.0C        5.00


     TIME =  0.01                           ENERGY INPUT =    27.93                 H2O REMOVED =   0.14
     AVERAGE MC =0.3326                     BTU/LBH2O =   199.17

       ENTERING ABSOLUTE HUMIDITY = 0.0
       ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     80.000      80.000      80.000      81.603      81.682

PROD TEMP 90.000     00.000      80.000      80.000      80.000      80.000

MC DB     0.333      0.3321      0.3323      0.3324      0.3332      0.3333

REL HUM   0.0        0.35917     0.67676     0.94183     1.00000     1.00000

ABS HUM   0.0        0.00802     0.01529     0.02148     0.02413     0.02419


     TIME =  1.00                           ENERGY INPUT =  2492.49                 H2O REMOVED =   5.5E
     AVERAGE MC =0.3024                     BTU/LBH2O =   416.46

       ENTERING ABSOLUTE HUMIDITY = 0.0
       ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     83.355      68.844      59.509      57.113      56.606

PROD TEMP 99.265     83.303      68.802      59.489      57.110      56.605

MC DB     0.289      0.2770      0.3012      0.3177      0.3225      0.3226

REL HUM   0.0        0.15482     0.45178     0.79447     0.91C88     0.93597

ABS HUM   0.0        0.00383     0.00693     0.00882     0.00929     0.00938


     TIME =  2.00                           ENERGY INPUT =  4996.75                 H2O REMOVED =  10.81
     AVERAGE MC =0.2774                     BTU/LBH2O =   462.09

       ENTERING ABSOLUTE HUMIDITY = 0.00017
       ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     09.623      77.859      67.274      59.750      57.667

PROD TEMP 99.393     89.586      77.825      67.242      59.733      57.664

MC DB     0.253      0.2335      0.2673      0.2950      0.3161      0.3215

REL HUM   0.0        0.08605     0.25161     0.51366     0.80712     0.91004

ABS HUM   0.00017    0.00259     0.00521     0.00748     0.00905     0.00947
```

```
      TINE =  3.00                              ENEPGY INPUT =  7485.24              H2O REMLVED =  15.55
      AVERAGE MC =0.2530                        BIU/LBH2O =    481.42

         ENTERING ABSOLUTE HUMIDITY = 0.00015
         ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     93.457     83.794     74.642     65.471     59.239

PROO TEMP 99.584     93.433     83.765     74.613     65.444     59.227

NC DB    0.231      0.2012     0.2376     0.2669     0.2965     0.3163

REL HUN  0.0        0.04979    0.15483    0.31638    0.57514    0.83458

ABS HUM  0.00015    0.00169    0.00388    0.00590    0.00787    0.00919


      TINE =  4.00                              ENERGY INPUT =  9972.64              H2O REMCVED =  19.58
      AVERAGE MC =0.2301                        BTU/LBH2O =    499.22

         ENTERING ABSOLUTE HUMIDITY = 0.00012
         ENTERING AIR TENPERATURE (F) =100.00

AIR TENP 100.000     95.593     88.200     80.019     71.800     63.696

PROD TEMP 99.694     95.577     88.176     79.995     71.772     63.673

NC DB    0.215      0.1796     0.2106     0.2422     0.2714     0.2998

REL HUN  0.0        0.03232    0.09955    0.21163    0.38352    0.64120

ABS HUM  0.00012    0.00117    0.00287    0.00470    0.00650    0.00825


      TIME =  5.01                              ENERGY INPUT = 12481.76              H2O REMOVED =  23.89
      AVERAGE MC =0.2099                        BTU/LBH2C =    522.53

         ENTERING ABSOLUTE HUNIDITY = 0.00008
         ENTERING AIR TENPERATURE (F) =100.00

AIR TEMP 100.000     96.786     91.357     84.180     76.981     69.176

PROD TENP 99.773     96.775     91.338     84.158     76.959     69.150

NC DB    0.203      0.1652     0.1875     0.2192     0.2480     0.2774

REL HUM  0.0        0.02143    0.06450    0.14526    0.26340    0.45240

ABS HUM  0.00008    0.00080    0.00205    0.00369    0.00530    0.00702


      TIME =  6.00                              ENERGY INPUT = 14965.09              H2O REMOVED =  27.13
      AVERAGE NC =0.1931                        BTU/LBH2C =    551.55
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```
        ENTERING ABSOLUTE HUMIDITY = 0.0
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     97.822     93.796     87.787     81.023     74.155

PROD TEMP 99.837     97.814     93.781     87.767     81.002     74.132

MC DB    0.195      0.1561     0.1697     0.1977     0.2273     0.2548

REL HUM  0.0        0.01259    0.03967    0.09652    0.18625    0.31624

ABS HUM  0.0        0.00049    0.00136    0.00275    0.00427    0.00580


      TIME =  7.00                              ENERGY INPUT = 17456.64                 H2O REMOVED =  29.87
      AVERAGE MC =0.1790                        BTU/LBH2O =   584.34

        ENTERING ABSOLUTE HUMIDITY = 0.0
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.182     95.137     90.229     84.246     78.067

PROD TEMP 99.858     98.176     95.126     90.213     84.228     78.048

MC DB    0.188      0.1491     0.1567     0.1791     0.2080     0.2350

REL HUM  0.0        0.01035    0.02960    0.06967    0.13778    0.23457

ABS HUM  0.0        0.00040    0.00106    0.00214    0.00350    0.00489


      TIME =  8.00                              ENERGY INPUT = 19954.67                 H2O REMOVED =  32.25
      AVERAGE MC =0.1667                        BTU/LBH2O =   618.76

        ENTERING ABSOLUTE HUMIDITY = 0.00021
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     97.643     94.690     90.685     85.932     80.716

PROD TEMP 99.813     97.636     94.680     90.672     85.917     80.700

MC DB    0.178      0.1413     0.1460     0.1651     0.1917     0.2100

REL HUM  0.0        0.01892    0.03827    0.07036    0.12170    0.19570

ABS HUM  0.00021    0.00073    0.00135    0.00219    0.00327    0.00445


      TIME =  9.00                              ENERGY INPUT = 22442.69                 H2O REMOVED =  34.20
      AVERAGE MC =0.1566                        BTU/LBH2O =   656.24

        ENTERING ABSOLUTE HUMIDITY = 0.0
```

```
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.722     96.923     93.850     89.254     83.998

PROD TEMP 99.094     98.718     96.917     93.839     89.239     83.982

MC DB    0.173      0.1371     0.1389     0.1529     0.1757     0.2015

REL HUM  0.0        0.00699    0.01739    0.03793    0.07721    0.13867

ABS HUM  0.0        0.00028    0.00065    0.00130    0.00230    0.00350


     TIME = 10.00                         ENERGY INPUT = 24960.68            H2O REMOVED =  35.50
     AVERAGE MC =0.1478                   BTU/LBH2O =    695.26

        ENTERING ABSOLUTE HUMIDITY = 0.00067
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     97.327     95.242     93.043     89.845     85.838

PROD TEMP 99.754     97.321     95.236     93.036     89.834     85.825

MC DB    0.161      0.1305     0.1329     0.1451     0.1639     0.1879

REL HUM  0.0        0.03250    0.04660    0.06334    0.09195    0.13792

ABS HUM  0.00067    0.00124    0.00167    0.00212    0.00279    0.00369


     TIME = 11.01                         ENERGY INPUT = 27486.31            H2O REMOVED =  37.28
     AVERAGE MC =0.1407                   BTU/LBH2O =    737.37

        ENTERING ABSOLUTE HUMIDITY = 0.00112
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     97.688     95.917     94.029     91.792     88.199

PROD TEMP 99.757     97.683     95.912     94.023     91.785     88.188

MC DB    0.150      0.1252     0.1279     0.1392     0.1543     0.1761

REL HUM  0.0        0.04152    0.05356    0.06789    0.08723    0.12460

ABS HUM  0.00112    0.00160    0.00196    0.00235    0.00281    0.00360


     TIME = 12.01                         ENERGY INPUT = 29999.60            H2O REMOVED =  38.43
     AVERAGE MC =0.1348                   BTU/LBH2O =    780.73

        ENTERING ABSOLUTE HUMIDITY = 0.00134
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.009     98.036     96.469     94.781     92.778     89.973
```

```
PROD TEMP 99.801     98.032     96.465     94.776     92.772     89.963

MC DB     0.140      0.1206     0.1235     0.1340     0.1479     0.1656

REL HUM   0.0        0.04464    0.05520    0.06779    0.08460    0.11169

ABS HUM   0.00134    0.00174    0.00205    0.00240    0.00201    0.00341


      TIME = 13.00                        ENERGY INPUT = 32503.05              H20 REMOVED =  39.23
      AVERAGE MC =0.1298                  BTU/LBH2O =   825.30

        ENTERING ABSOLUTE HUMIDITY = 0.00156
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.325     96.935     95.424     93.627     91.461

PROD TEMP 99.837     98.321     96.931     95.419     93.622     91.454

MC DB     0.133      0.1167     0.1196     0.1294     0.1422     0.1571

REL HUM   0.0        0.04838    0.05773    0.06886    0.08360    0.10366

ABS HUM   0.00156    0.00190    0.00218    0.00248    0.00285    0.00331


      TIME = 14.01                        ENERGY INPUT = 35020.37              H20 REMOVED =  40.22
      AVERAGE MC =0.1255                  BTU/LBH2O =   870.71

        ENTERING ABSOLUTE HUMIDITY = 0.00173
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.535     97.204     95.919     94.297     92.344

PROD TEMP 99.863     98.531     97.280     95.915     94.292     92.330

MC DB     0.127      0.1132     0.1162     0.1253     0.1371     0.1508

REL HUM   0.0        0.05117    0.05955    0.06949    0.08253    0.10008

ABS HUM   0.00173    0.00203    0.00227    0.00254    0.00288    0.00329


      TIME = 15.00                        ENERGY INPUT = 37456.59              H20 REMOVED =  41.07
      AVERAGE MC =0.1211                  BTU/LBH2O =   911.97

        ENTERING ABSOLUTE HUMIDITY = 0.00094
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.455     97.119     95.689     94.033     92.092

PROD TEMP 99.860     98.451     97.115     95.685     94.028     92.086

MC DB     0.121      0.1095     0.1126     0.1211     0.1321     0.1447
```

```
REL HUM  0.0         0.03143     0.03949     0.04897     0.06117     0.07724

ABS HUM  0.00094     0.00124     0.00150     0.00170     0.00211     0.00251


      TIME = 16.01                               ENERGY INPUT = 39959.52            H2O REMOVED =  41.66
      AVERAGE MC =0.1170                         BTU/LBH2O =    954.65

        ENTERING ABSOLUTE HUMIDITY = 0.00088
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000      98.579      97.326      95.981      94.438      92.635

PROD TEMP 99.875      98.575      97.322      95.977      94.433      92.629

MC DB    0.116       0.1062      0.1092      0.1172      0.1274      0.1391

REL HUM  0.0         0.02905     0.03639     0.04500     0.05597     0.07028

ABS HUM  0.00088     0.00115     0.00139     0.00165     0.00196     0.00233


      TIME = 17.00                               ENERGY INPUT = 42448.37            H2O REMOVED =  42.58
      AVERAGE MC =0.1133                         BTU/LBH2O =    997.02

        ENTERING ABSOLUTE HUMIDITY = 0.00084
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000      98.689      97.513      96.253      94.810      93.136

PROD TEMP 99.888      98.685      97.510      96.249      94.806      93.131

MC DB    0.112       0.1031      0.1061      0.1136      0.1231      0.1340

REL HUM  0.0         0.02735     0.03406     0.04190     0.05182     0.06462

ABS HUM  0.00084     0.00109     0.00131     0.00155     0.00183     0.00217


      TIME = 18.01                               ENERGY INPUT = 44887.81            H2O REMOVED =  43.23
      AVERAGE MC =0.1094                         BTU/LBH2O =   1036.01

        ENTERING ABSOLUTE HUMIDITY = 0.00013
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000      98.554      97.263      95.909      94.403      92.700

PROD TEMP 99.878      98.550      97.259      95.905      94.398      92.695

MC DB    0.107       0.0997      0.1027      0.1099      0.1187      0.1289

REL HUM  0.0         0.00996     0.01658     0.02422     0.03370     0.04573

ABS HUM  0.00013     0.00039     0.00063     0.00088     0.00118     0.00151
```

```
     TIME = 19.00                                    ENERGY INPUT = 47372.27                 H2O REMOVED =  44.01
     AVERAGE MC =0.1059                              BTU/LBH2O =  1076.42

        ENTERING ABSOLUTE HUMIDITY = 0.00013
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.678     97.476     96.211     94.806     93.222

PROD TEMP 99.891     98.675     97.473     96.207     94.802     93.218

MC DB    0.103      0.0967     0.0997     0.1064     0.1140     0.1243

REL HUM  0.0        0.00945    0.01546    0.02241    0.03097    0.04176

ABS HUM  0.00013    0.00037    0.00059    0.00083    0.00109    0.00141


     TIME = 20.00                                    ENERGY INPUT = 49871.93                 H2O REMOVED =  44.63
     AVERAGE MC =0.1027                              BTU/LBH2O =  1117.55

        ENTERING ABSOLUTE HUMIDITY = 0.00021
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.810     97.709     96.543     95.246     93.785

PROD TEMP 99.904     98.806     97.706     96.540     95.242     93.781

MC DB    0.099      0.0939     0.0969     0.1033     0.1112     0.1201

REL HUM  0.0        0.01068    0.01611    0.02238    0.03009    0.03975

ABS HUM  0.00021    0.00043    0.00062    0.00083    0.00108    0.00136
   .

     TIME = 21.01                                    ENERGY INPUT = 52382.82                 H2O REMOVED =  45.19
     AVERAGE MC =0.0998                              BTU/LBH2O =  1159.23

        ENTERING ABSOLUTE HUMIDITY = 0.00029
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.919     97.906     96.829     95.629     94.278

PROD TEMP 99.914     98.917     97.903     96.825     95.626     94.274

MC DB    0.096      0.0915     0.0944     0.1005     0.1079     0.1163

REL HUM  0.0        0.01192    0.01687    0.02257    0.02955    0.03824

ABS HUM  0.00029    0.00048    0.00065    0.00085    0.00107    0.00133
```

```
     TIME = 22.00                                    ENERGY INPUT = 54883.74              H2O REMOVED =  45.60
     AVERAGE MC =0.0973                              BTU/LBH2O =  1261.38

        ENTERING ABSOLUTE HUMIDITY = 0.00045
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     99.040     98.124     97.148     96.056     94.823

PROD TEMP 99.924     99.037     98.121     97.145     96.052     94.819

MC DB     0.093     0.0893     0.0922     0.0979     0.1049     0.1128

REL HUM   0.0       0.01541    0.01988    0.02504    0.03133    0.03914

ABS HUM   0.00045   0.00062    0.00078    0.00095    0.00115    0.00138


     TIME = 23.00                                    ENERGY INPUT = 57336.37              H2O REMOVED =  46.20
     AVERAGE MC =0.0946                              BTU/LBH2O =  1240.99

        ENTERING ABSOLUTE HUMIDITY = 0.0
        ENTERING AIR TEMPERATURE (F) =100.00

AIR TEMP 100.000     98.954     97.969     96.933     95.798     94.541

PROD TEMP 99.918     98.951     97.966     96.930     95.794     94.537

MC DB     0.090     0.0870     0.0898     0.0953     0.1019     0.1093

REL HUM   0.0       0.00444    0.00888    0.01396    0.02006    0.02753

ABS HUM   0.0       0.00018    0.00035    0.00053    0.00073    0.00096
```

```
***** AUXILIARY HEAT SUPPLIED AT DRYER INLET *****

              MINIMUM TEMPERATURE 100F

       MASS FLOW RATE =      543.93    (LBM/HR-FT**2)
                               (F)             AUXILIARY
                            ENTERING         ENERGY ADDED
HOUR ENDING              DRY BULB TEMP      (BTU/HR-FT**2)
-----------              -------------     ----------------
     1                       71.41             3763.95
     2                       69.91             3960.97
     3                       64.73             4642.10
     4                       64.74             4641.46
     5                       64.75             4639.90
     6                       64.81             4631.57
     7                       71.92             3696.38
     8                       79.20             2738.34
     9                       83.67             2149.77
    10                       96.83              417.70
    11                      106.16                0.0
    12                      118.16                0.0
    13                      118.74                0.0
    14                      119.59                0.0
    15                      120.11                0.0
    16                      118.20                0.0
    17                      112.78                0.0
    18                      106.90                0.0
    19                      104.46                0.0
    20                       97.79              291.07
    21                       91.15             1164.42
    22                       91.82             1076.96
    23                       92.30             1013.62
    24                       96.85              415.27


    COST OF AUXILARY HEAT INTO THE DRYER =$     0.39
     COST OF AUXILIARY HEAT TO DEHUMIDIFIER =$    3.31

    COST OF LP FUEL IS ESTIMATED AT $10.00/10**6 BTU
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VITA

Kathy A. Riblett

Candidate for the degree of

MASTER OF SCIENCE

Thesis: The Feasibility of a Solar Powered Sorption Dehumidification System Applied to Grain Drying

Major Field: Mechanical Engineering

Biographical:

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Professional Experience: Employed as a cooperative education student with the John Deere Component Works: January 1979 to May 1979, Materials Engineering, August 1979 to January 1980, Quality Engineering, May 1980 to August 1980, Manufacturing Engineering, May 1981 to August 1981, Industrial Engineering. General Physics I Lab Instructor and Coordinator (81-82). Employed as a graduate research assistant at Kansas State University from January 1983 to May 1983 and from March 1984 to May 1984.

THE FEASIBILITY OF A SOLAR POWERED SORPTION DEHUMIDIFICATION SYSTEM APPLIED TO GRAIN DRYING

by

KATHY A. RIBLETT

B. S., Kansas State University, 1982

ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1984

ABSTRACT

The feasibility of drying grain using dehumidified air was studied. The dehumidified air was produced by a solar energy powered sorption dehumidifier. A grain drying model was coupled with an existing computer model of the sorption dehumidifier. Drying grain with dehumidified air was compared to drying grain with ambient air, solar heated air, and auxiliary heated air. The air that was dehumidified was found to dry faster than air that had been heated only. The cost per bushel was found to be about $1.46 for the conventional system. The dehumidified air costs were $1.17/bu. and the dehumdified/auxiliary heated air cost $1.28/bu. The cost per bushel of the solar/auxiliary heated drying air was $1.11. A study of the life cycle costs of the solar energy powered sorption dehumdifier showed the costs of such a system to be about $2000.00 greater than a conventional drying system that uses liquified petroleum gas. A grain drying system that uses a solar collector to provide part of the energy needed, was found to have a life cycle cost of about $350 more than the conventional system.