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FEASIBILITY STUDY OF A SOLAR ENERGY POWERED SORPTION DEHUMIDIFICATION SYSTEM

by

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NOMENCLATURE

SYMBOL	DEFINITION
English Letter	
A	Solar Collector Area, m^2
c	Drying constant
C	Flag indicating income-producing or nonincome-producing
C_A	Cost per area of solar collector
C_E	Equipment cost
C_f	Cost of fuel
d	Market discount rate
D	Ratio of downpayment to initial investment
DEP	Depreciation tax deduction
F	Fraction of energy supplied by Solar
i	Inflation rate
i_f	Fuel inflation rate
L	Load on Dryer
LCC_c	Life cycle cost - conventional system
LCC_s	Life cycle cost - solar energy system
m	Annual mortgage interest rate
M_E	Commodity initial equilibrium moisture content, Dry Basis
M_s	Ratio of first year miscellaneous costs to initial investment
n	Drying constant
N_d	Depreciation lifetime, in years
N_e	Equipment lifetime, in years
N_L	Term of loan, in years

SYMBOL	DEFINITION
N_{min}	Years over which mortgage payments contribute to the analysis
N'_{min}	Years over which depreciation tax deductions contribute to the analysis
P_1	Ratio of life cycle fuel costs to the first year fuel energy cost
P_2	Ratio of the owning cost to the initial cost
PWF	Present Worth Factor
Q_s	Heat Gain in the Solar Collector
RH	Relative Humidity
R_v	Ratio of resale value at end of the period of the analysis to the initial investment
t	Property tax rate based on assessed value
$\bar{t}$	Effective tax rate
V	Ratio of assessed valuation of the system in the first year to the initial investment in the system

Greek Letter

α	Slope of constant F_i lines on a psychrometric chart
γ	Specific capacity ratios between the moist silica gel and the air water vapor mixture

CHAPTER I

INTRODUCTION

Dehumidified air finds a multitude of applications, including humidity control for marine storage areas, in the production of foods such as breakfast cereals and dried fruits and vegetables, moisture removal from paper and the surface of fresh citrus fruit, reduction of lumping in powered substances manufactured by chemical and pharmaceutical companies, air conditioning for human comfort and the drying of agricultural and lumber products. These applications conventionally utilize fossil fuels, and the rising cost of these fuels has encouraged interest in utilizing solar energy as an alternative.

Two of the researchers in this area, Singer (36) and Ananth (3), have developed experimental and computer models of a solar energy powered sorption dehumidification system to produce dehumidified air. This current study takes one step further towards developing a working system for commercial use.

Since the system is powered by solar energy, the location and time of year of operation will affect the performance of the system. Also, the economic feasibility of the system will be a deciding factor before it will be chosen to be built.

Therefore, the objective of this thesis is to develop a computer model that provides weather data to the computer model of the system, and to incorporate that with an economic analysis. These three parts of the computer program - Weather Data, System and Economic Analysis - may be carried out independently of each other with data supplied from one to the other, or they may be combined into one large computer program.

CHAPTER II

SOLAR ENERGY POWERED SORPTION DEHUMIDIFICATION SYSTEM

The system in this study at Kansas State University was initially developed by Singer (36) and further enhanced by Ananth (3). It utilizes a desiccant to dehumidify air through adsorption, and solar energy to regenerate the desiccant.

The sorption process has been described as the movement of water vapor molecules towards the desiccant surface caused by unbalanced molecular forces occuring at the surface of the desiccant. On a macroscopic level, the mass transfer can be thought of as taking place because of a difference in water vapor partial pressures in the desiccant and in the air. When an active, anhydrous desiccant is brought in contact with moist air, the water vapor partial pressure of the air exceeds the water vapor partial pressure within the desiccant. Passing a heated air stream through the desiccant evaporates the sorbed moisture, thereby regenerating the desiccant.

Sorbent is the term referring to the desiccant which sorbs, in this case, moisture from the moist air stream. The sorbate is the substance sorbed, i.e. moisture from the air. The sorbent can be solid or liquid. Sorption with solid sorbents may be accomplished by either absorption or adsorption, where sorption with liquid sorbents occurs only by absorption. Through absorption, the desiccant reacts with the sorbate, changing either chemically or physically. Lithium chloride is one such desiccant which undergoes a chemical change to a hydrate state, where additional moisture absorption would cause the sorbent to dissolve into solution. Ordinary table salt is another example of an absorbing sorbent. With adsorption, the sorbent will not react chemically or physically with the sorbate. Examples of adsorbing desiccants are activated alumina, silica gel, activated bauxites and activated charcoals.

Much research has been conducted in the areas of solar dehumidification utilizing liquid and solid sorbents. Disadvantages of a liquid system are the solution leakage possibilities, solution entrainment in the processed air, cooling tower requirements, bulky size and increased number of pumps, valves and heat exchangers which would also require maintenance. Disadvantages of a solid desiccant system compared to a liquid desiccant is a higher air stream pressure drop through the desiccant requiring increased fan power. The liquid system can operate isothermally, giving a low dry bulb temperature exiting from the dehumidifier. This is preferable over a solid desiccant system for an application of air conditioning. The solid desiccant system operates adiabatically, yielding a high exit dry bulb temperature, which is better adapted to drying operations. For this study, because of the simplicity of design and additional advantage of inexpensive materials utilized, the solid desiccant system was chosen.

The selection of a solid desiccant should be based on the ease of regeneration, cost, effective lifetime and reactivity with air which would yield undesirable gases such as NO_x, SO_2 and CO_2. The ease of regeneration depends on a regeneration temperature obtainable with flat plate solar collectors and the capacity to adsorb moisture from an air stream. The desiccants taken into consideration for this study included activated alumina, molecular sieve, lithium chloride on a honeycomb matrix, silica gel in a packed bed and silica gel on Teflon. One of the disadvantages of a silica gel bed is the relatively low cost, almost infinite lifetime of regeneration/dehumidification cycling, inert characteristics and superior ease of regeneration, Singer chose a bed of silica gel as the desiccant.

The bed of solid desiccant can either be fixed, or it can rotate. If fixed, the bed is first regenerated and then can process unconditioned air. If a continuous operation is desired, two fixed beds or a rotating bed must be employed. Using two fixed beds, one processes the moist air while the other is regenerated. If a rotating bed is used, one half of the wheel undergoes regeneration while the other half dehumidifies moist air. Disadvantages of these techniques are that the fixed bed requires more ductwork, directional dampers, timers and dew point sensing devices, and with a rotating bed, the air leaks around the wheel seals. Because of the simplicity, the rotating bed was chosen for these initial studies.

SOLAR DEHUMIDIFICATION UTILIZING A ROTATING, SOLID DESICCANT

The system is composed of a rotating sensible heat exchanger, a rotating desiccant bed, flat plate solar collectors, an auxiliary heater, fans and ductwork. The dehumidifier shown schematically in Figure 1 houses the heat exchanger and the desiccant bed. To allow for continuous operation, it is split into two isolated flow paths - the process side and the regeneration side. On the process side flows air which is to be dehumidified, and the regeneration flow stream is used to regenerate the desiccant. The desiccant bed adsorbs moisture on the process half of the bed and is dried by concurrently flowing heated air from the solar collectors on the regeneration side. If cool, dry air is desired, i.e. for air conditioning, the sensible heat exchanger is used. This cools the process air, and preheats regeneration air entering the solar collector. To maintain a particular minimum regeneration air temperature entering the desiccant bed, the auxiliary heater supplies any additional energy required during hours of low insolation.

Figure 2 is a plot of each state of the dehumidification process on a psychrometric chart. On the process side, ambient air to be dehumidified

FIGURE 1

SCHEMATIC OF THE SOLAR
DESICCANT DEHUMIDIFIER SYSTEM

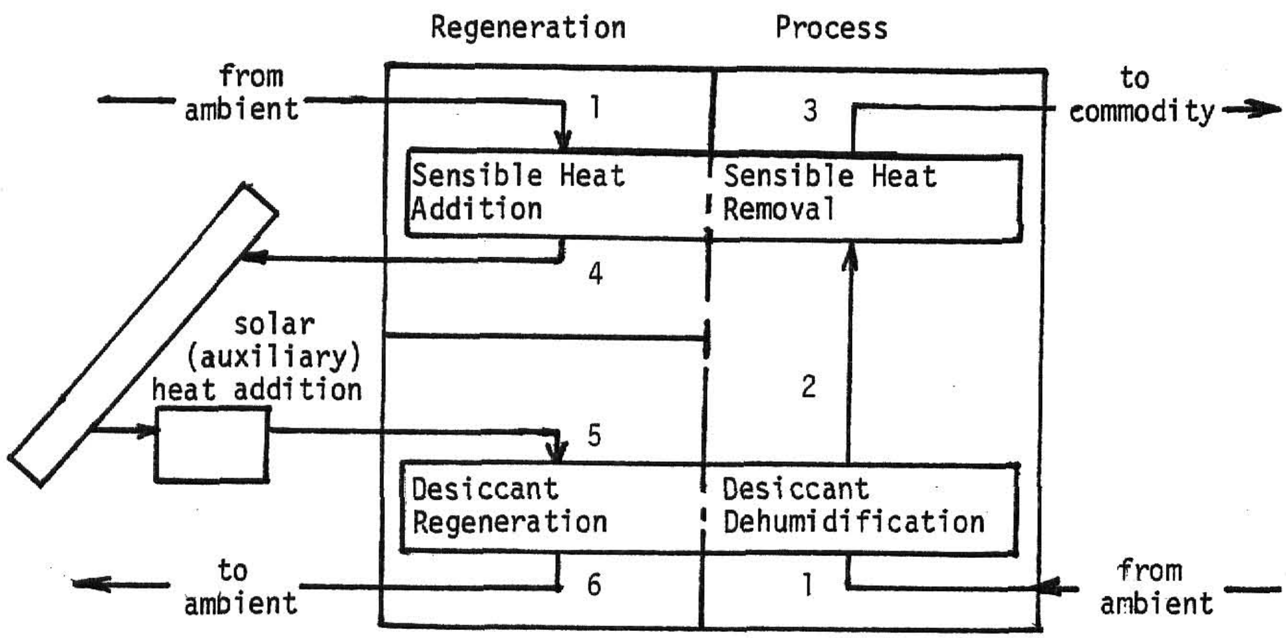
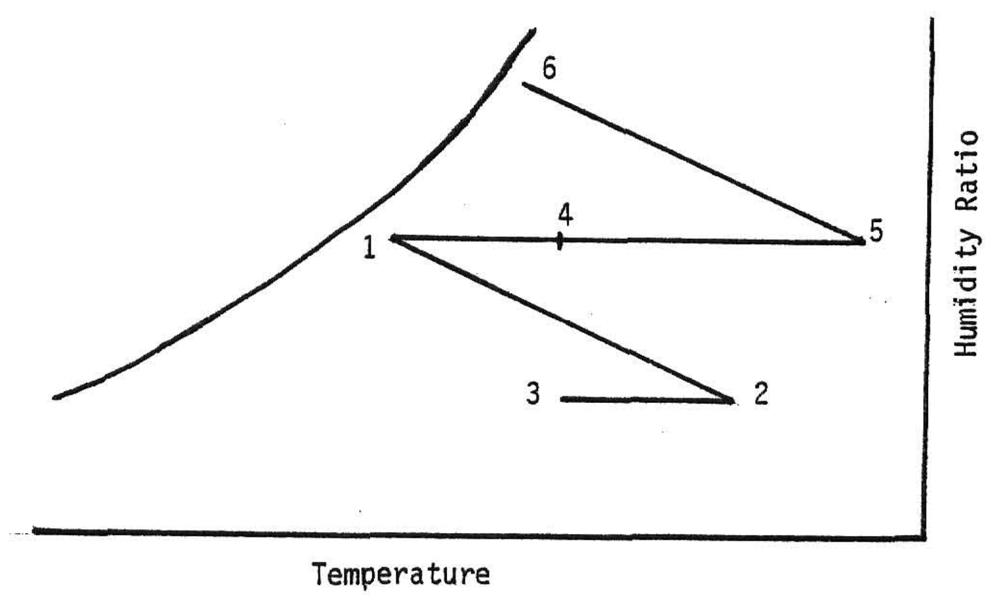


FIGURE 2

PSYCHROMETRIC PLOT OF
DEHUMIDIFICATION PROCESS



enters the dehumidifier at condition 1 and passes through the desiccant bed. The desiccant adsorbs moisture from the air, decreasing the humidity ratio and raising the air dry bulb temperature. This increase in temperature results from the heat of condensation, released as moisture changes from a vapor to liquid state. The air is dehumidified almost adiabatically, which very nearly follows a constant wet bulb line on the psychrometric chart, and exits the desiccant bed at condition 2.

If the sensible heat exchanger is used, the dry bulb temperature of the air is reduced and exits the dehumidifier at condition 3. For applications desiring hot dry air, the heat exchanger would not be utilized. In this case, the air would exit the dehumidifier hot and dry at condition 2, flowing on to a dryer.

On the regeneration side, ambient air at condition 1 enters the dehumidifier, passes through the sensible heat exchanger gaining the heat lost by the process stream air. The flow stream is then directed through the solar collector followed by the auxiliary heater. Through some combination of the heat exchanger, solar collector and auxiliary heater, the regeneration air is heated to a temperature sufficient for desiccant regeneration at condition 5. The air then flows through the desiccant, regenerating the bed while humidifying the air. Regeneration air exiting the desiccant bed at condition 6 is released to the surrounding atmosphere.

COMPUTER PROGRAM

A major portion of Singer's work was the development of a computer program to predict the performance of the dehumidification system. It is this program which is incorporated as subroutine SYSTEM into the main Weather Data and Economic Analysis computer program of the present study. Singer wrote the program in Fortran Watfiv to use on the KSU IBM 370 digital computer. Ananth rewrote the program in Basic language utilizing the HP 9845 B desk top computer. Ananth also modified the program to accept different humidity ratios, mass flow rates and peripheral leakage rates for the process and regeneration streams. But, to combine this program with the TMY weather data tapes, requires use of the KSU IBM 370 computer. Ananth's program was rewritten in Fortran Watfiv, modified to reduce computation time and combined with the weather data and economic analysis parts of the program. Due to the length, intricacy and modifications made, subroutine SYSTEM deserves some discussion.

The original program consisted of a main program, MAIN and seven subroutines, HUMID, EGV, ALFAV, LEAK, COLPER, COLEFF, and HEATX. The MAIN, renamed as SYSTEM, serves as a source for calling subroutines HUMID, COLPER and HEATX and also allows for data input and output. Subroutine HUMID models the properties of the silica gel bed utilizing subroutines EGV and ALFAV. LEAK subroutine calculates the outlet temperature and humidity conditions of the air streams considering leakages around the rotating wheels. The solar collector performance, or useful heat gain, is calculated in COLPER and calls COLEFF to calculate the collector efficiency. HEATX models the sensible heat exchanger performance.

A flowchart of the modified SYSTEM program is included in Appendix A. The original program required much computation time, hence, most modifications were geared towards decreasing the execution time. All Call statements for subroutines were either simplified or replaced with the actual subroutine called. Since subroutines LEAK, COLEFF and HEATX were fairly short and were called only one or two times, they were deleted as subroutines and replaced the Call statements in their entirety. The remaining subroutines HUMID, EGV, ALFAV, and COLPER were originally called with a list of parameters. To simplify these Call statements, the parameters were deleted. Some difficulty arose because of the freedom within the Fortran Watfiv and Basic languages allowing different names for the same parameter between a subroutine and the main part of the program. This was alleviated by careful manipulation, renaming a multitude of parameters and by setting the appropriate variables in the subroutine equal to their counterpart found previously in the list of parameters. This must be done immediately preceeding and following each Call statement.

Subroutine SYSTEM allows for data input and output. The input read on data cards includes:

1. The program option, indicating if a minimum regeneration temperature for the desiccant is desired.
2. Collector data - air mass flow rates, collector area and slope, latitude and longitude. Note that the slope of the collector is the actual slope from the ground, minus the latitude.
3. Dehumidifier data - duct temperature drops, silica gel bed properties, rotational speed of the wheel, the minimum regeneration temperature, leakage rates and heat exchanger effectiveness.

Input provided by the Weather Data program through the common statement are:

4. Calendar data - month, day, year, hour, number day of the year and number of hours in the study.
5. Ambient dry bulb and dew point temperatures and ambient humidity ratios.
6. Solar radiation, percent diffuse radiation, percent direct radiation and the ground reflectance ratio.
7. Wind direction and velocity.
8. Station Number

Output provided through the common statement for the Economic Analysis is the hourly humidity ratio of the process air exiting the dehumidifier. Other output printed in the program consists of temperature and humidity maps for the process and regeneration sides, heat balance of the dehumidifier and the collector performance, all on an hourly basis. The input parameters included above in items 1-3 are also output to verify correct values.

Singer originally developed the program with the option of using one of four collector types - with manufacturer's performance curves, water collector, air collector with metal/glass flow channels and air with metal/metal flow channels. This option was deleted in the present program and utilizes the manufacturer's performance curves for the Solaron Series 3000 collector.

The HUMID subroutine analytically models the simultaneous heat and mass transfer occuring within the desiccant bed. Solving the equations which model this process is difficult due to the coupled and non-linear characteristics. The coupled nature can be attributed to the dependency of the sorbent equilibrium capacity and liberation of heat of sorption. The equations are non-linear because equilibrium concentrations of the sorbate and the sorbent are not related linearly, and also because the air and desiccant specific heats and the heat of sorption are not linear.

One method to predict desiccant performance was initially developed by Banks (5) in 1971. Transforming the energy and mass conservation equations to characteristic form, they were found to represent two potential kinematic wave equations. Each of these kinematic wave equations describe the propagation of a change in potential, and depend on sorbate concentration and the temperature. Bank's analysis models the transfer of a single sorbate between a stationary porous sorbent and a single phase fluid mixture. The reader is encouraged to refer to Ananth and Singer for further discussion.

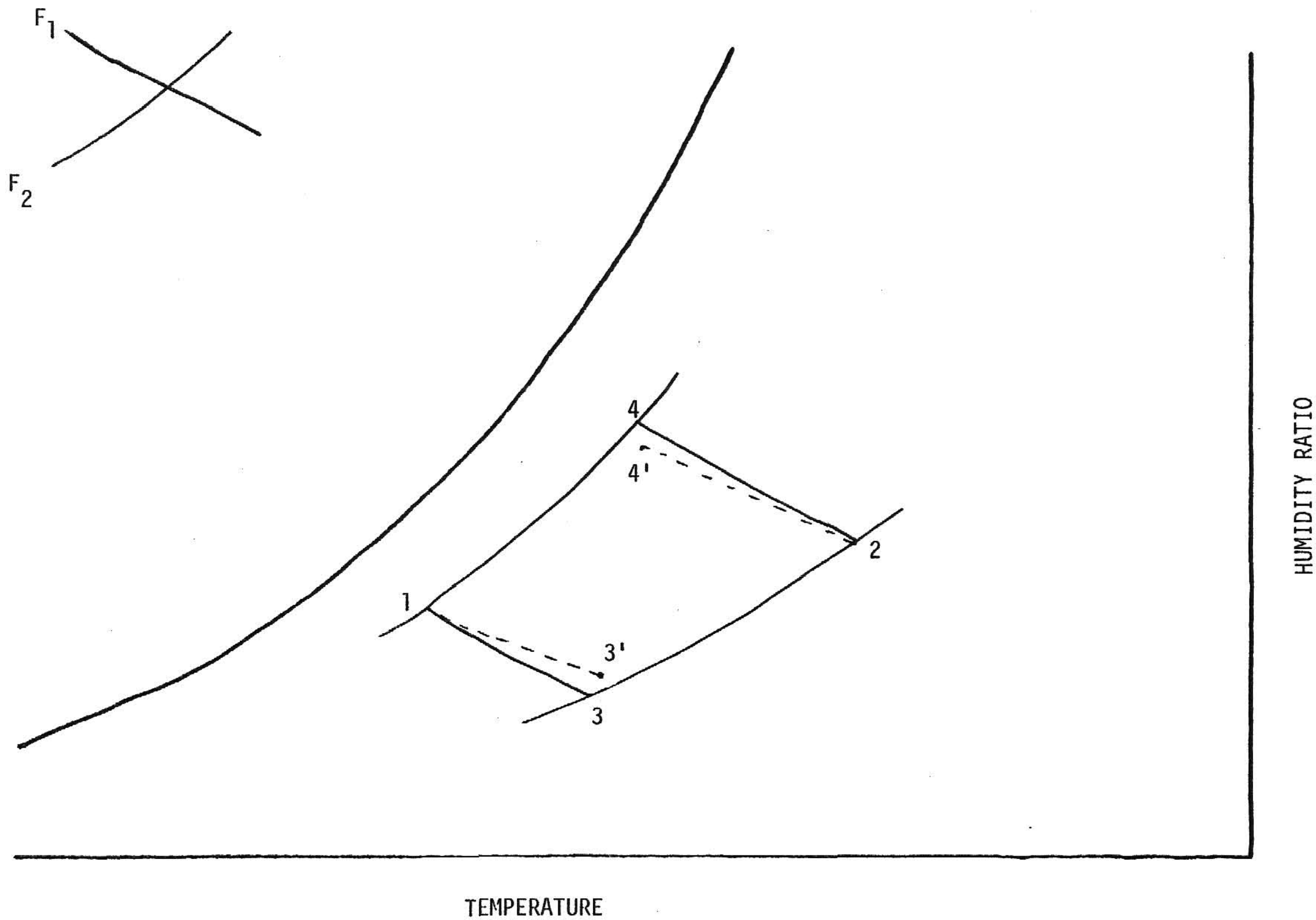
With further study by Close and Banks (11,12) for heat and mass transfer equations between silica gel and an air vapor mixture, they were able to theoretically determine equilibrium outlet conditions of a stationary bed of silica gel, with a step change in inlet air conditions. Their model predicts two wave fronts passing through the bed, the first producing new outlet conditions, which remain constant until the second wave front flows through. After the second wave front passes through the bed, the outlet conditions are identical to the inlet conditions. These wave fronts follow constant F lines on a psychrometric chart as shown in Figure 3. With a rotary dehumidifier, the process air stream changes from state 1 to state 3', and the regeneration air stream proceeds from condition 2 to 4'.

MacLaine-Cross and Banks (30) developed this model further for a rotating bed. This method was computerized by Nelson (33), providing process and regeneration outlet temperatures and humidity ratios. The model does not provide time-temperature-position conditions, but this information is not required for the performance of the dehumidifier for these studies.

Singer based subroutines HUMID, EGV and ALFAV on Nelson's program making minor modifications. Subroutine ALFAV supplies values for α_1, α_2, γ_1 and γ_2 for both the silica gel bed and the air vapor mixture. α_1 and α_2 are the slopes of constant F_1 and F_2 lines respectively on a psychrometric chart. γ_1 and γ_2 are the specific capacity ratios between the air vapor mixture and the moist silica gel. Put another way, this subroutine determines the equilibrium properties of the moist silica gel bed and air water vapor mixture, and determines the path the two air streams will follow when the step change occurs. As these paths of constant F_1 and F_2 lines are followed, subroutine EGV (Equilibrium Gama Values) determines the incremental

FIGURE 3

PSYCHROMETRIC PLOT OF SORPTION PROCESS WITH SILICA GEL



values for temperature and humidity ratio. The HUMID subroutine first calculates inlet points 1 and 2, then it estimates the true points 3 and 4 as the intersection of F_i lines through points 1 and 2 having slopes α_i. Many incremental steps along the constant F lines are taken and the values of α_i for each new state are determined. This process is repeated until the intersection of the F_1 and F_2 lines are found, reaching points 3 and 4. Then the rotating effect of the wheel are corrected, yielding points 3' and 4'.

CHAPTER III

WEATHER DATA COMPUTER MODEL

The second portion of the computer program deals with supplying the necessary weather data. How well a solar energy powered system performs depends not only on properties of the system, but also on the weather conditions. The performance of such a system should be estimated on an hour by hour basis, which then required hourly weather data.

The method of estimating hourly insolation utilizes empirical relationships based on measured daily total insolation, the sunset hour angle, the time away from solar noon and the daily clearness index. The daily clearness index is the ratio of terrestrial to extraterrestrial radiation for a particular day and latitude. This method agrees fairly well with weather data. But one disadvantage is that these estimations of insolation do not account for actual hourly variations in weather, such as storms or sudden cloud cover.

Solar radiation together with other meteorological data have been recorded since 1953 at weather stations across the United States. Insolation data were recorded either on a daily or an hourly basis, depending on the station. Most of these horizontal surface radiation data were recorded instantaneously, and were then either graphically or electronically integrated. Through the years, errors in the data were detected due to instrument sensor deterioration, changes in pyrheliometric scales, calibration errors and moves in station location. To identify and correct these errors, the United States Weather Service developed the SOLMET program in 1978. The purpose of SOLMET was to identify errors in individual instruments and location moves, to correct or 'rehabilitate' earlier data recorded, and to combine all available data into a single source. This was achieved by recording all available data, plus rehabilitated data, on computer tapes in SI units. Details of particular rehabilitation measures taken can be found in Volume I of the SOLMET User's Manual (40).

The SOLMET tape collection comprises an enormous amount of information. In order to use these data in predicting the hourly performance of a solar energy system, one difficulty arises. Since weather on a particular day in one year can vary greatly from weather occuring in another year, the data do not account for annual variations in the weather.

Hall, et al (20) solved this problem with the Typical Meteorological Year tapes. Twenty six SOLMET weather stations (Table 1 and Figure 4) were chosen as Typical Meteorological Year (TMY) sites. Each station recorded 23 years of hourly meteorological and solar radiation data beginning in 1953 and continuing through 1975. The process used statistical methods to select a TMY for a given location, selecting one typical meteorological month for each of the twelve calendar months. Data for one year consists of 12 specific months, i.e. January 1975, February 1955, etc. (Table 2). These months were then catenated to form a typical meteorological year.

The criteria used in selecting a month closest to the composite of all 23 years were dry bulb temperature, dew point temperature, wind velocity and solar radiation on a horizontal surface. Cloud cover and precipitation were not included as criteria for selection of a typical month. Since discontinuities exist between the end of one month in one year and the beginning of the next month in a different year, the pressure, temperatures and wind velocity for the six hourly points on either side of the interface were smoothed.

The TMY data, then, were chosen for this study over another form of weather data for the following reasons:

1. Complete weather data are available on an hourly basis.
2. Daily variations in local cloud cover and yearly fluctuations are

TABLE 1

TYPICAL METEOROLOGICAL YEAR STATIONS

STATION NAME	STATION NUMBER	TAPE LABEL	DATE OF RECORD	LATITUDE	LONGITUDE
Albuquerque, NM	23050	13	7/ 1/52 - 12/31/75	N 35 03	W 106 37
Apalachicola, FL	12832	4	7/ 1/52 - 5 /19/75	N 29 44	W 84 59
			5/20/75 - 12/31/75	N 29 44	W 85 02
Bismarck, ND	24011	17	7/ 1/52 - 12/31/75	N 46 46	W 100 45
Boston, MA	94701	24	7/ 1/52 - 6/ 5/64	N 42 21	W 71 04
			6/ 6/64 - 11/30/68	N 42 22	W 71 03
Brownsville, TX	12919	6	7/ 1/52 - 12/31/75	N 25 54	W 97 26
Cape Hatteras, NC	93729	22	7/ 1/52 - 2/28/57	N 35 13	W 75 41
			3/ 1/57 - 12/31/75	N 35 16	W 75 33
Caribou, ME	14607	10	7/ 1/52 - 12/31/75	N 46 52	W 68 01
Charleston, SC	13880	7	7/ 1/52 - 12/31/75	N 32 54	W 80 02
Columbia, MO	03945	3	7/ 1/52 - 1/23/70	N 38 58	W 92 22
			1/24/70 - 12/31/75	N 38 49	W 92 13
Dodge City, KS	13985	9	7/ 1/52 - 12/31/75	N 37 46	W 99 58
El Paso, TX	23044	12	7/ 1/52 - 12/31/75	N 31 48	W 106 24
Ely, NV	23154	14	12/ 1/51 - 12/31/75	N 39 17	W 114 51
Fort Worth, TX	03927	1	7/ 1/52 - 4/30/53	N 32 49	W 97 21
			5/ 1/53 - 7/31/74	N 32 50	W 97 03
Fresno, CA	93193	21	7/ 1/52 - 12/31/75	N 36 46	W 119 43
Great Falls, MT	24143	18	7/ 1/52 - 12/31/75	N 47 29	W 111 22

TABLE 1, continued

TYPICAL METEOROLOGICAL YEAR STATIONS

STATION NAME	STATION NUMBER	TAPE LABEL	DATE OF RECORD	LATITUDE	LONGITUDE
Lake Charles, LA	03937	2	7/ 1/52 - 10/31/61	N 30 13	W 93 09
			11/ 1/61 - 12/31/75	N 30 07	W 93 13
Madison, WI	14837	11	7/ 1/52 - 12/31/75	N 43 08	W 89 20
Medford, OR	24225	19	12/ 1/51 - 12/31/75	N 42 22	W 122 52
Miami, FL	12839	5	7/ 1/52 - 12/31/75	N 25 48	W 80 16
Nashville, TN	13897	8	7/ 1/52 - 12/31/75	N 36 07	W 86 41
New York, NY	94728	25	7/ 1/52 - 12/31/75	N 40 47	W 73 58
Omaha, NE	94918	26	6/ 1/57 - 12/31/75	N 41 22	W 96 01
Phoenix, AZ	23183	15	7/ 1/52 - 12/31/75	N 33 26	W 112 01
Santa Maria, CA	23273	16	7/ 1/52 - 10/31/54	N 34 56	W 120 25
			11/ 1/54 - 3/31/69	N 34 54	W 120 27
Seattle-Tacoma,WA	24233	20	12/ 1/51 - 12/31/75	N 47 27	W 122 18
Sterling, VA	93734	23	8/ 1/53 - 12/31/60	N 38 50	W 76 57
			11/ 1/60 - 12/31/75	N 38 59	W 77 28

FIGURE 4

SOLAR RADIATION DATA REHABILITATION STATIONS

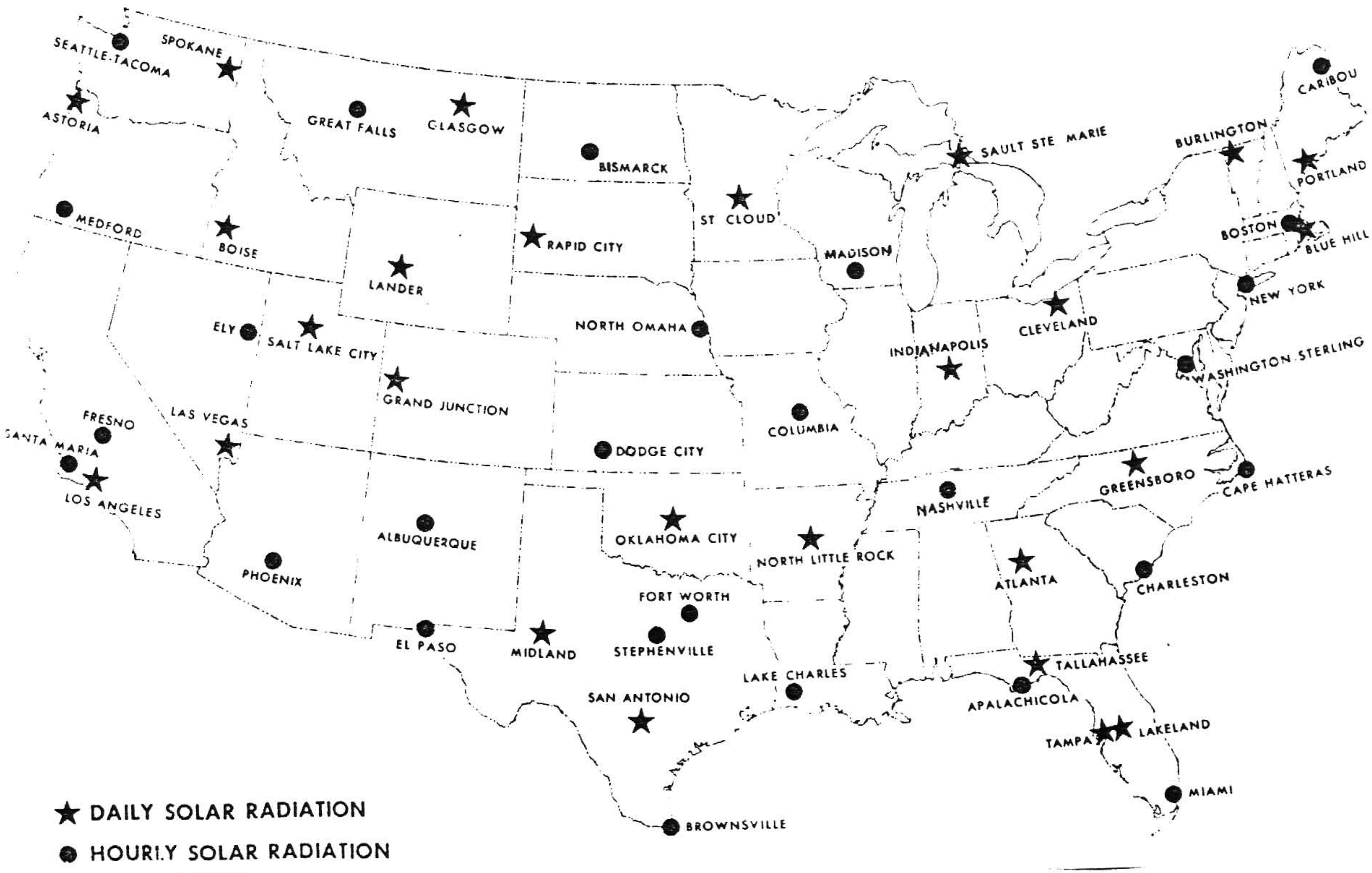


TABLE 2

THE YEAR OF THE
TYPICAL METEOROLOGICAL MONTHS COMPRISING
TYPICAL METEOROLOGICAL YEAR FOR 26 STATIONS

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Albuquerque	58	53	65	66	64	69	57	54	67	65	59	54
Apalachicola	60	60	64	63	67	63	58	55	66	55	59	65
Bismarck	60	71	57	54	57	75	69	55	57	68	67	67
Boston	66	53	61	60	62	65	53	56	62	57	61	61
Brownsville	64	61	56	65	71	64	61	66	68	53	68	75
Cape Hatteras	65	55	56	69	54	69	68	71	64	66	74	66
Caribou	59	70	70	69	71	53	74	53	72	73	74	60
Charleston	60	60	75	59	73	61	53	67	60	65	71	75
Columbia	65	55	54	70	58	64	62	63	67	74	71	64
Dodge City	60	73	54	62	55	63	61	60	66	54	71	67
El Paso	74	67	75	74	54	61	71	61	71	67	71	56
Ely	74	71	71	71	56	75	58	73	66	66	63	65
Fort Worth	72	61	62	66	66	59	65	55	57	68	71	62
Fresno	64	75	68	53	68	62	54	73	68	66	74	68
Great Falls	68	65	71	63	70	59	54	62	73	71	71	65
Lake Charles	67	72	56	74	64	59	70	55	64	72	67	65
Madison	65	60	72	64	53	57	73	63	58	74	65	54
Medford	66	62	53	69	64	59	69	63	62	60	62	61
Miami	62	74	67	59	64	53	57	63	57	65	61	68
Nashville	54	59	64	74	63	68	75	73	58	69	66	66
New York	58	59	59	74	74	61	60	72	58	56	71	67
Omaha	72	59	59	63	58	72	61	60	66	68	74	62
Phoenix	68	75	63	57	68	56	74	72	72	68	59	66
Santa Maria	63	59	57	57	56	64	53	62	61	62	53	62
Seattle	75	71	62	72	61	59	62	70	62	66	68	56
Sterling	65	70	67	67	56	75	73	65	73	73	73	61

included. The weather data are most representative of weather one could anticipate at any location.

3. The data include 26 locations within the United States. This gives a good choice of locations for a variety of dehumidification applications.
4. The data are stored on a magnetic tape and easily incorporated into a computer program.

TMY WEATHER TAPE

The tape available through the KSU Meteorological Service is 1600 bpi density, 9 track, EBCDIC mode and can be executed using either Fortran or Watfiv compilers. Each block of the tape contains the data for one day, is 3168 bytes long and consists of 24 logical records. Each logical record is 132 bytes long and contains the data for one hour. The tape can be read with or without a format; see Figure 5 for the JCL necessary to read the tape unformatted, and Figures 6a and 6b for a sample of an unformatted block.

However, to use the data in calculations requires a format. The tape density, block length, record length, track and station location (Table 1) must be specified in the JCL of the program. The JCL specifies which tape the computer should read and the physical characteristics of the tape. The fortran deck controls when and in what format the tape is read. See Figures 7 and 8 for the required Watfiv and Fortran JCL.

The tape positions can be read as integers (I5 for a 5 character integer), as real numbers (F5.2 or 2PF5.0 for a real number with two decimal places) or can be skipped over (5X to skip five positions). Refer to Table 3 for the contents of the TMY tape. The first five positions on the tape contain the number assigned to the station. This acts as a check to assure that the correct

FIGURE 5

LISTING OF PROGRAM FOR
UNFORMATTED TMY WEATHER DATA

```
/*TAPE9
// EXEC DSLIST,PARM=(,,,3)
//SYSIN DD DSN=TMY,UNIT=TAPE16ØØ,VOL=SER=9TMYØ3,LABEL=26
```

Where:

PARM=(,,,3) - refers to the number of blocks read, in this case, three

UNIT=TAPE16ØØ - the 16ØØ specifies the tape bpi density

VOL=SER=9TMYØ3 - refers to the name of the tape

LABEL=26 - is the tape label for the station, 26 is for Omaha, Nebraska (Table 1)

FIGURE 6a

TMY UNFORMATTED DATA FOR
Jan. 3, 11:00 at Omaha Nebraska

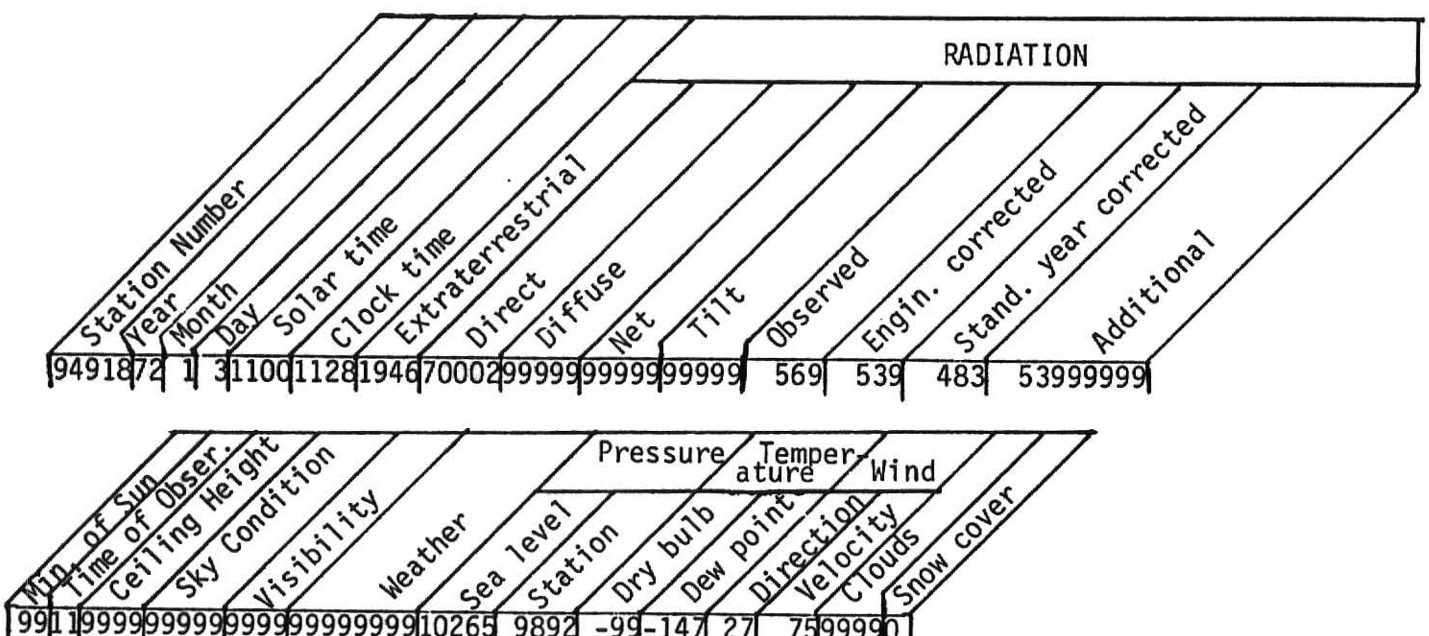


FIGURE 6b

TMY UNFORMATTED DATA FOR
Jan. 1, at Omaha, Nebraska

```
KSU DATA SET LISTER  2/22/83 DSN=TMY,VOL=(3400-6,26,SL,6250)=9TMY03                                PAGE NO.    1

9491872 1 1 100 12899999999999999999999999999999999999999 1999999999999999910152 9      BLOCK     1, LENGTH  3168
790   0 -22170  2199999          9491872 1 1 200 22899999999999999999999999999999999999999
99 2999999999999999999910152 9790   0 -22170  2199999          9491872 1 1 300 328999999999999999999
9999999999999999999999999 3 366 6000 209          010152 9790   0 -22170  2110109          9491
872 1 1 400 42899999999999999999999999999999999999999999999 4999999999999999999910151 9789
 -1 -21227  2199999          9491872 1 1 500 52899999999999999999999999999999999999999999 5
99999999999999999910151 9788  -3 -21283  2199999          9491872 1 1 600 6289999999999999999999999
9999999999999999999999999 6 274 6000 193          010150 9787  -6 -22340  2110109          9491872
1 1 700 728999999999999999999999999999999999999999 7999999999999999999910155 9791   0
-19343  3199999          9491872 1 1 800 828 1157000999999999999   25   24   21   24999999 89999
9999999999999999910159 9796   5 -18347  4199990          9491872 1 1 900 928 82070003999999999999999
 163  157  139  1579999999 9 305 6000 193          010164 9800  11 -17350  5110100          9491872 1 11
00010281472700059999999999999  385  371  329  3719999999109999999999999999999910167 9803  15 -183
5C  4899990          9491872 1 1110011281932701419999999999999  732  706  626  70699999991199999999
99999999999910171 9807  18 -19350  4499990          9491872 1 1120012282171701539999999999999  824
  795  705  7959999999912 366 2460 193          010174 9810  22 -22350  4110100          9491872 1 113001
32821717002899999999999999  640  617  547  61799999991399999999999999999999910166 9802  22 -25  0
3699990          9491872 1 11400142819327019999999999999999  761  734  651  73499999991499999999999
9999999910158 9795  22 -28 10  3199990          9491872 1 11500152814727045299999999999999  803  77
5  687  7759999999915 762 4000 193          010150 9787  22 -33 20  26 8 70          9491872 1 116001628
82071710999999999999999  569  549  487  54999999916999999999999999999999910149 9786  17 -36 13  1799
990          9491872 1 117001728 11570346999999999999999  96  92  82  92999999917999999999999999
99999910149 9784  11 -39  7  999990          9491872 1 11800182899999999999999999999999999999999
9999999999999187777  0 209          010148 9783  6 -44  0  0 0 09          9491872 1 119001928999999
9999999999999999999999999999999999999999999999199999999999999999999910147 9782  -4 -49337  799999
          9491872 1 1200020289999999999999999999999999999999999999999999999920999999999999999999
910146 9781 -16 -54313  1499999          9491872 1 12100212899999999999999999999999999999999999999
999999999217777  0 209          010145 9780 -28 -61290  21 0 09          9491872 1 12200222899999999
99999999999999999999999999999999999992299999999999999999999910139 9774 -34 -64313  1499999
    9491872 1 1230023289999999999999999999999999999999999999999999999239999999999999999999999101
34 9769 -42 -67337  799999          9491872 1 12400  2899999999999999999999999999999999999999999
999999 07777 2200 209          010128 9763 -50 -72  0  0 5 39
```

FIGURE 7

<u>WATFIV JCL FOR TMY WEATHER DATA TAPE</u>

```
/*ROUTE  PRINT VM___
/*TAPE9
/*REGICN         400K
// EXEC WATFIV,PARM='SIZE=(1000K,8K)'
//SYSIN      DD *
$JOB             AFA,TIME=(,30),PAGES=30
C
C
C
C          } FCRTRAN DECK
C
C
C
$ENTRY
C
C
C          } CATA SOURCE
C
C
//GO.FT03F001 DD DSN=TMY,UNIT=TAPE1600,VOL=SER=9TMY03,LABEL=(3,,,IN),
// DCB=(RECFM=FB,LRECL=132,BLKSIZE=3168)
```

FIGURE 8

FORTRAN JCL FOR TMY WEATHER DATA TAPE

```
/*ROUTE  PRINT VM___                                                        JCL00010
/*TAPE9                                                                     JCL00020
// EXEC FORTQCLG,PARM=NOMAP                                                 JCL00030
//FORT.SYSIN DD *                                                           JCL00040
C                                                                           JCL00050
C                                                                           JCL00060
C                                                                           JCL00070
C            } FORTRAN DECK                                                 JCL00080
C                                                                           JCL00090
C                                                                           JCL00100
C                                                                           JCL00110
//GO.FT03F001 DD DSN=TMY,UNIT=TAPE1600,VOL=SER=9TMY03,LABEL=(26,,,IN),      JCL00120
// DCB=(RECFM=FB,LRECL=132,BLKSIZE=3168)                                    JCL00130
//GO.SYSIN DD *                                                             JCL00140
C                                                                           JCL00150
C                                                                           JCL00160
C            } DATA SOURCE                                                  JCL00170
C                                                                           JCL00180
C                                                                           JCL00190
```

TABLE 3

CONTENTS OF TMY TAPE

TAPE POSITION	FORMAT TO READ OFF TAPE	ELEMENT
1-5	I5	Station Number
6-7	I2	Year of observation- last two digits only
8-9	I2	Month of observation
10-11	I2	Day of observation
12-15	I4	Solar time- end of the hour in hours and minutes
16-19	I4	Clock time- local standard time in hours and minutes
		RADIATION - in kJ/m^2
20-23	I4/F4.0	Extraterrestrial
24-28	I5/1x,I4	Direct- with data code indicator
29-33	I5	Diffuse
34-38	I5	Net
39-43	I5	Tilt
44-48	I5/F5.0	Observed
49-53	I5/F5.0	Engineering corrected
54-58	I5/F5.0	Standard year corrected
59-68	I10	Additional
69-70	I2	Minutes of Sunshine
		METEOROLOGICAL DATA
71-72	I2	Time of observation
73-76	I4	Ceiling height
77-81	I5	Sky condition- coded in ascending layers: 0 = clear or less than 10% cover 1 = thin scattered (10-50% cover) 2 = opaque scattered (10-50% cover) 3 = thin broken (60-90% cover) 4 = opaque broken (60-90% cover) 5 = thin overcast (100% cover) 6 = opaque overcast (100% cover) 7 = obscuration 8 = partial obscuration

TABLE 3, continued

CONTENTS OF TMY TAPE

TAPE POSITION	FORMAT TO READ OFF TAPE	ELEMENT
82-85	I4	Visibility- prevailing horizontal visibility
86-93	I8	Weather
86		Occurrence of Thunderstorm, tornado or squall 0 = none 1 = Thunderstorm 2 = Heavy Thunderstorm 3 = Tornado reported 4 = Squall
87		Occurrence of rain, rain showers or freezing rain ranging from 0 - 8 with 0 = none
88		Occurrence of drizzle, freezing drizzle ranging from 0 - 8 with 0 = none
89		Occurrence of snow, snow pellets or ice crystals ranging from 0 - 8 with 0 = none
90		Occurrence of snow showers and snow grains, ranging from 0 - 8 with 0 = none
91		Occurrence of sleet, sleet showers or hail, ranging from 0 - 8 with 0 = none
92		Occurrence of fog, blowing dust or blowing sand 0 = none 1 = fog 2 = ice fog 3 = ground fog 4 = blowing dust 5 = blowing sand
93		Occurrence of smoke, haze, dust, blowing snow, blowing spray
94-98	F5.2/2PF5.0	Pressure - sea level in kPa, atmospheric
99-103	F5.2/2PF5.0	Pressure - at the station, atmospheric
104-107	F4.1/PF4.0	Dry bulb temperature
108-111	F4.1/PF4.0	Dew point temperature
112-114	I3	Wind direction, measured clockwise from the North
115-118	I4	Wind speed
119-122	I4	Clouds, coded
123	I1	Snow cover indicator
124-132		Positions left blank

portion of the tape is read. Refer to Table 1 for the stations and their corresponding numbers.

The year of observation lists only the last two digits, so that a 66 is actually 1966. The solar time refers to the end of the hour in hours and minutes. Clock time is the local standard time in hours and minutes corresponding to the solar time.

All radiation values are in kilojoules per meter squared. The extra-terrestrial radiation is the radiation received at the top of the atmosphere during the solar hour based on a solar constant 1377 J/m^2-s. Any elements encoded with a '9' beginning with the extraterrestrial radiation to the end of the tape indicate missing or unknown data.

For the following radiation data, the first position contains a data code indicator and the next four positions contain the recorded insolation. The data code indicator describes whether the value is observed, or if it was estimated from another model. The data code indicator is not always included.

The direct radiation is that portion of insolation received directly from the sun at the pyrheliometer. Diffuse radiation is the amount of radiant energy received indirectly from reflection and scattering. The net radiation refers to the difference of incoming and outgoing radiation. A constant of 5000 was added to all net radiation data. Tilt radiation indicates the global radiation (total of direct and diffuse) received on a tilted surface. Observed radiation is that observed value on a horizontal surface. Engineering corrected data is the observed value corrected for known scale changes, recorder and sensor calibration changes, station moves, etc. Standard year corrected radiation is the observed value adjusted by a regression estimate based on cloud, sky condition and sunshine data. This models the expected clear sky irradiance received on a horizontal surface. The Additional radiation allows tape positions for any supplemental radiation measurements that may have been taken at any particular station.

The time of observation refers to the Local Standard hour which comes closest to the midpoint of the solar hour. Ceiling height in dekameters is defined as 0.6 or greater sky cover. A recording of 0000-3000 equals 0 to 30,000 meters, 7777 is coded as unlimited or clear, and 8888 refers to an unknown height of ciroform ceiling. Sky condition codes four layers of cloud cover in ascending order. Visibility indicates the horizontal visibility in hectometers (hm = m x 100). If encoded with 8888, the visibility is unlimited.

The weather portion of the tape indicates the type and quantity of precipitation, the occurance of thunderstorms, tornados, fog, etc. Refer to Table 3 for details of the code.

The pressures are measured in kilopascals. The range from 08000 to 10999 indicate pressures of 80 to 109.99 kPa. Temperatures range from -70 to 60 °C, and are recorded as -700 to 0600.

The wind direction is the azimuth angle measured in degrees. The wind speed is in tenths, so that 1500 equals 150.0 m/s. The code for clouds describes the type and height of cloud cover. A more detailed description can be found in SOLMET User's Guide (40). The snow cover indicator records a '0' for no snow or just a trace of snow on the ground, and a '1' for more than a trace of snow. The last nine positions of the record are empty.

THE COMPUTER PROGRAM

The program must first locate the desired date. The segment of tape for each station begins at the first hour of the first day of the year and must be scanned until the desired day is found. Since the shortest readable unit is one block, the hour immediately preceeding the desired date must be found. The following segment will then be the record length of the next block corresponding to the first hour of the desired day. This method must be followed because of the two separate Read statements in the program (Appendix B). Data is assigned to variables in the form of arrays for later computations in subroutine SYSTEM. The Read statement that lies inside two nested Do loops assigns the data to the arrays. One Do loop controls the hour and the other controls the day. The Read statement preceeding the Do loops locates the desired day. If the first record for the desired day is used to locate the beginning of the study, then the weather data within that record cannot be assigned to an array.

After locating the correct date, the program then proceeds to read one entire record length which contains weather data for one hour. For the first hour of the day, the number of day of the year is calculated, which is required later in subroutine SYSTEM. For every hour of the day, the program uses weather data to calculate the percentage of direct and diffuse radiation following equations from Duffie and Beckman (15), and the humidity ratio following ASHRAE (4) equations. Since the TMY tape contains several values for radiation, one is specified as the horizontal radiation desired for later calculations.

At this point, the computer should have all of the weather data necessary for one day and calls subroutine SYSTEM for that day. For the general case, subroutine SYSTEM can be any computer program, written in Fortran Watfiv describing the daily hour by hour performance of a solar energy powered system. Subroutine SYSTEM is called for every day, internally computes and prints the hourly performance and returns to the main program. The moisture evaporated each hour is calculated next. Chapter four contains the discussion for the method used to calculate the evaporated moisture. The system operating totals are tabulated for the moisture evaporated, solar heat gain and the auxiliary heat supplied. It then proceeds to read the weather data for the next day and repeats this procedure. The Economic Analysis follows after completing all calculations for all days included.

The Weather Data program need not be accompanied by a SYSTEM subroutine. It may be of value to the user to scan the weather of a particular month for the location in mind, before choosing acceptable system operating dates. Because of this, the Weather Data program was developed to read the TMY tape and print out hourly insolation, atmospheric pressures, dry bulb temperature, dew point temperature, humidity ratio, wind direction and speed and the amount of snow cover. This program is listed in Appendix C, accompanied by two days of output.

In order to use this program, the user must specify the beginning and the ending month, days and hours in the data cards, the tape label corresponding to the desired station and the tape specifications in the JCL, the station name in Format statement 10, and correctly dimension the parameter arrays. The Dimension and Integer statements dimension parameter arrays for the number of days and hours, i.e. DBT(30,24) dimensions the dry bulb temperature for thirty days with twenty four hours per day. These arrays should be declared to allow adequate storage for the number of days and hours desired. Two limitations exist with this program. First, the beginning and ending month must be identical. The program, as is, does not allow for a study beginning, for example on June 30 and ending July 3. Because of this, and the necessity to locate the hour preceeding the first day of the study, the second limitation is that the first day of the month cannot be read. These limitations may be annoying to the user, but can be dealt with.

CHAPTER IV

ECONOMIC ANALYSIS COMPUTER MODEL

Once the performance of a solar energy system with a particular length of operation and location has been estimated, the next step is to determine the economic feasibility. Unit costs may be an indicator of this feasibility, but to adequately evaluate any system, it must be incorporated with a system in operation and related to current energy costs. This can be done by comparing the life cycle cost of a solar energy powered system to that of a conventional system.

The P_1, P_2 method outlined by Duffie and Beckman (15) relates present worth factors for the life cycle costs to the first year costs in one ratio. One can then determine the life cycle cost, which is merely the present worth of all costs. This method applied to both a conventional and a solar energy powered system provides a foundation for comparing the costs of these systems.

The cost of either system includes two parts, the cost of fuel and the cost of equipment. P_1 is the ratio of life cycle fuel costs to the first year fuel cost and yields the present worth of an inflating series. P_1 multiplied by the present day cost of fuel and the load, determines the total fuel cost. P_2 is the ratio of life cycle expenditures due to any additional capital investment, divided by the initial investment. This yields the present worth of equipment mortgage payments, depreciation tax deduction, etc. The life cycle equipment cost is calculated by multiplying P_2 times the cost of equipment.

For the conventional system, the Life Cycle Cost can be written:

$$LCC_c = P_{2c} C_{Ec} + P_{1c} C_f L \qquad (4.1)$$

A solar energy system must consider two additional points. First, part of the equipment has a fixed size, hence also fixed cost, and part varies with the size of the system. Second, the fraction of auxiliary fuel used must be taken into consideration. The Life Cycle Cost for a solar energy system with a conventional system as a backup can be written as

$$LCC_s = P_{2s}(C_A A + C_{Es}) + P_{2c}C_{Ec} + P_{1s}C_f \, L\,(1 - F) \qquad (4.2)$$

The present worth factor is given by:

$$PWF(N,i,d) = \begin{cases} \dfrac{1}{(d - i)}\left[1 - \left(\dfrac{1 + i}{1 + d}\right)^N\right] & i \neq d \\[2ex] \dfrac{N}{(1 + i)} & i = d \end{cases} \qquad (4.3)$$

Any cost that is proportional to the first year fuel cost can be included in P_1. For this study,

$$P_1 = (1 - C\bar{t})\ PWF(N_e, i_f, d) \qquad (4.4)$$

where $\bar{t}$ is the effective tax rate given as (4.5)

$$\bar{t} = \text{Federal tax Rate} + \text{State tax Rate} - \left[\text{Federal tax Rate} \times \text{State tax Rate}\right]$$

Likewise, any capital cost that is proportional to the initial cost can be included in P_2. For the general case:

$$P_2 = D + (1-D)\left[\frac{PWF(N_{min},\emptyset,d)}{PWF(N_{min},\emptyset,m)}\right] + (1- C\bar{t})\ M_s\ PWF(N_e,i,d)$$
$$- (1-D)\bar{t}\left[PWF(N_{min},m,d) \times \left(m - \frac{1}{PWF(N_L,\emptyset,m)}\right) + \frac{PWF(N_{min},\emptyset,d)}{PWF(N_L,\emptyset,m)}\right]$$
$$+ t\,(1-\bar{t})\ V\ PWF(N_e,i,d) - DEP - \frac{R_v}{(1+d)^{N_e}} \qquad (4.6)$$

This can be more understandably written as:

$$P_2 = \text{Downpayment} + \begin{matrix}\text{Cost of the mortgage}\\ \text{principal and interest}\end{matrix} + \begin{matrix}\text{Miscellaneous costs}\\ \text{(maintenance, insurance,}\\ \text{parasitic power, etc.)}\end{matrix}$$

$$- \begin{matrix}\text{Income Tax}\\ \text{Deductions from}\\ \text{the interest}\end{matrix} + \begin{matrix}\text{Net Property}\\ \text{tax costs}\end{matrix} - \begin{matrix}\text{Depreciation}\\ \text{tax deduction}\end{matrix} - \text{Resale value}$$

For straight line depreciation,

$$DEP = \frac{C\bar{t}}{N_d} PWF(N_{min},\emptyset,d) \tag{4.7}$$

The terms used for double declining balance and sum of digits depreciation are given by Duffie and Beckman. It should be noted that the double declining balance method includes the resale value. For accelerated cost recovery, a system depreciating in five years follows this schedule:

Year	Percent of Initial Value
1	20
2	32
3	24
4	16
5	8

The percentage for each year, multiplied by the present worth of that specific year, yields the total present worth. So that the term can be expressed as

$$DEP = C\bar{t}\left[0.20 \times \frac{1}{(1+d)^1} + 0.32 \times \frac{1}{(1+d)^2} + 0.24 \times \frac{1}{(1+d)^3} + 0.16 \times \frac{1}{(1+d)^4} + 0.08 \times \frac{1}{(1+d)^5}\right] \tag{4.8}$$

All terms in P_1 and P_2 include only the present worth factors and ratios in proportion to the initial investment. Any applicable term may be added to or deleted from P_1 or P_2. They are dependant only on the economic parameters available and do not vary with the size of the system. The conventional system uses the general forms of P_1 and P_2, given previously in equations 4.4 and 4.6. The solar energy system includes an additional term in P_2 for tax credits, which are eligible to such a system, and uses the general form for P_1.

The life cycle cost of a solar energy system varies with the performance of the system and with the fraction of energy supplied by auxiliary methods. The required auxiliary energy in turn depends on the collector area or the load. Optimizing the life cycle cost can be done by one of two methods. Referring to equation 4.2, either the load or the collector size must be fixed. With a fixed load, the collector area can be increased or decreased, which respectively decreases or increases the fraction of auxiliary energy required, (1-F). With a fixed collector area, the load must be altered. A change in load yields a directly proportional change in the fraction of auxiliary energy required.

The latter method was chosen for this study to facilitate the computer program. A change in collector area changes the performance of the system. Because of this, subroutine SYSTEM would be called every time the collector area changed. This would require much computer time and expense. In contrast, varying the load can be accomplished entirely within the economic analysis portion of the main program.

For a drying operation, the energy required to evaporate moisture from the commodity determines the load. The amount of moisture removed by the air from the commodity is a function of the commodity initial moisture content and drying properties, and of the process air dry bulb and wet bulb temperatures. Air will come to equilibrium with the moisture content of a hygroscopic commodity described by an equilibrium moisture curve for that commodity at a specific temperature. If the air relative humidity is lower than the equilibrium moisture content of the commodity, then the air will gain moisture from the commodity. When dry air is passed through a moist commodity, the relative humidity of air exiting the dryer will be in equilibrium with the initial moisture content of the commodity. The relative humidity can then be determined with an equation which models the equilibrium moisture curves. Such equations have been developed by Henderson (21) and by Chung and Pfost (9). Henderson's equation gives valid results for relative humidities ranging from 4 to 70% for a variety of commodities, see Table 4. The equation developed by Chung and Pfost is applicable for 7 to 90% relative humidity for shelled corn, corn products and wheat. Henderson's equation was chosen due to the wider range of commodities and the equation describes the equilibrium moisture curves adequately for these initial studies. This equation is given by:

$$1 - R.H. = e^{(-c\ T\ M_E^n)} \qquad (4.9)$$

where the temperature is the dry bulb temperature in degrees Rankine, and c and n are drying constants for a particular commodity.

Air entering a dryer at state 1 in Figure 9 will ideally follow a constant wet bulb temperature line and exit at state 2 where the relative humidity is in equilibrium with the commodity initial moisture content. The moisture evaporated will be the difference in humidity ratios of states 1 and 2 multiplied by the airflow rate. However, two assumptions are made, of which the reader should be aware. The air will follow a constant wet bulb temperature line assuming the drying process is adiabatic, and assuming the temperature of the commodity is already the same as the wet bulb temperature of the air entering the dryer. More likely, the commodity will gain some heat, thereby lowering the air wet bulb temperature and the air will follow the dotted line in Figure 9. The air will exit the dryer with a lower relative

FIGURE 9

PSYCHROMETRIC PLOT OF DRYING PROCESS

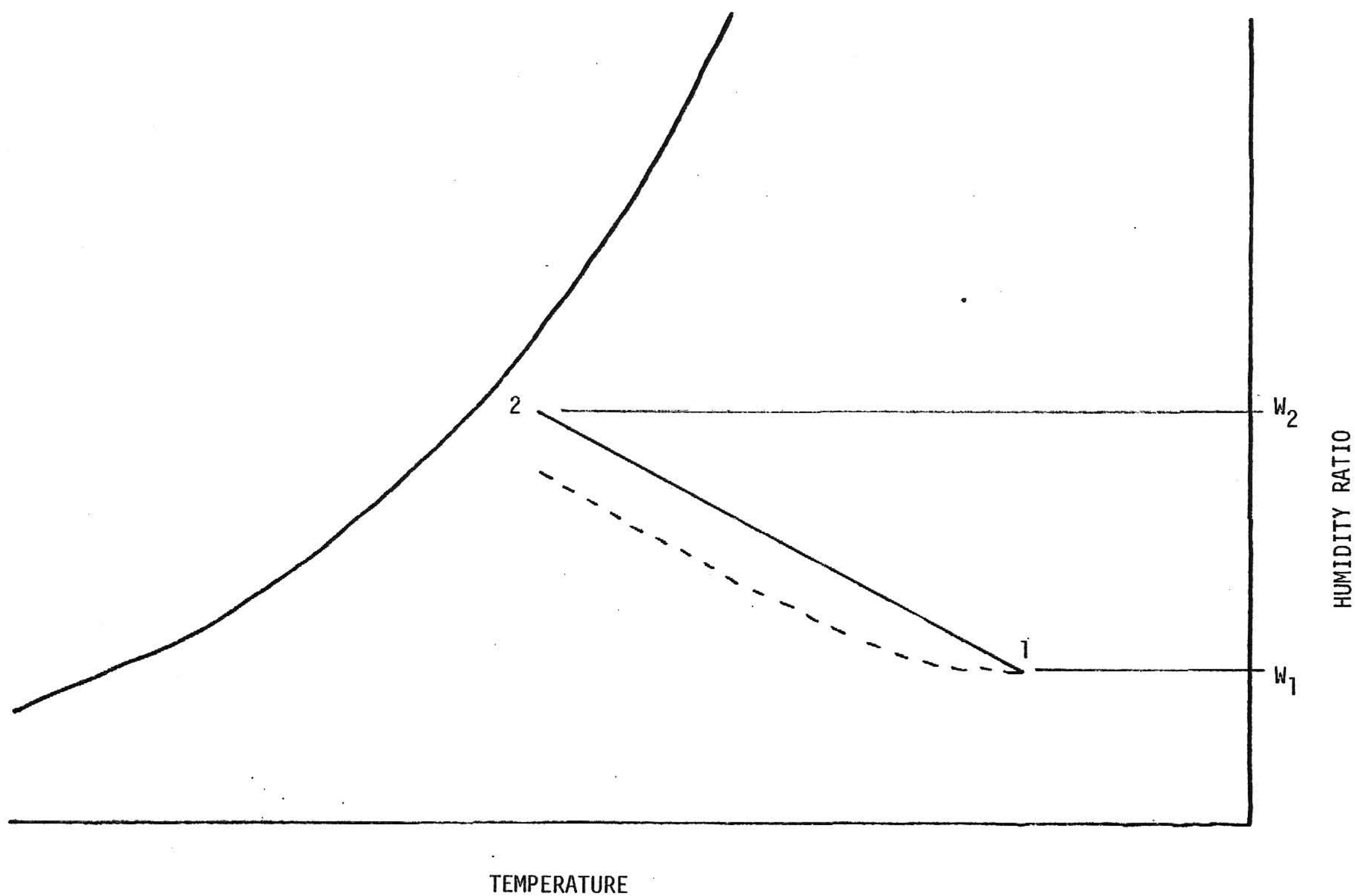


TABLE 4

EQUILIBRIUM CONSTANTS FOR HENDERSON'S EQUATION

MATERIAL	$c \times 10^{-5}$	n
Corn, shelled	1.10	1.90
Cotton	4.91	1.70
Eggs, spray-dried	2.95	2.00
Flaxseed	0.689	2.02
Natural clay	7.53	1.72
Peaches, dried	41.1	0.564
Prunes, dried	12.5	0.865
Raisins	7.13	1.02
Sorghum	0.340	2.31
Soybeans	3.20	1.52
Wheat	0.0559	3.03
Wood	5.34	1.41

humidity since the temperature is lower (Equation 4.9), hence, a lower humidity ratio. This will cause a lower efficiency than that predicted by the equations.

Another problem arises in determining the wet bulb temperature of the air entering the dryer. The condition of the air exiting the dehumidifier and entering the dryer are the same. Because of hourly differences in ambient temperature, humidity ratio and insolation, the dehumidifier air exits the dehumidifier at various wet bulb temperatures. Figure 10 shows, that for October 21 in Omaha, Nebraska, the wet bulb temperature varies from 11.2 to 20 °C. With an air flow rate of 0.02836 kg/sec, this is a difference of 0.3675 kilograms of water for every hour, see Table 5. The wet bulb temperature can be determined analytically by numerical methods or by trial and error which can be incorporated into a computer model, or with use of a psychrometric chart, which is not easily incorporated into a computer model.

As the reader can see, much work is needed to develop useable methods predicting the process of commodity drying. Additional study should incorporate transient energy and mass balances on the commodity and the drying air with changing inlet air conditions. With given initial commodity conditions, and varying inlet air conditions, the method developed should accurately predict transient outlet air and commodity conditions and be incorporated into a computer model.

For the present study, it is assumed that the drying process follows a constant wet bulb temperature line and an alternative to estimating the wet bulb temperature was chosen. This alternative method chooses a set wet bulb temperature and either cools or heats the air to that condition before it enters the dryer. Figure 11 shows this process on a psychrometric chart for several hours of operation. Under practical considerations, the air will be heated and not cooled. Once the wet bulb temperature is set, the dry bulb

FIGURE 10

PSYCHROMETRIC PLOT OF
DEHUMIDIFIER OUTLET AIR CONDITIONS
OCTOBER 21 Omaha, Nebraska

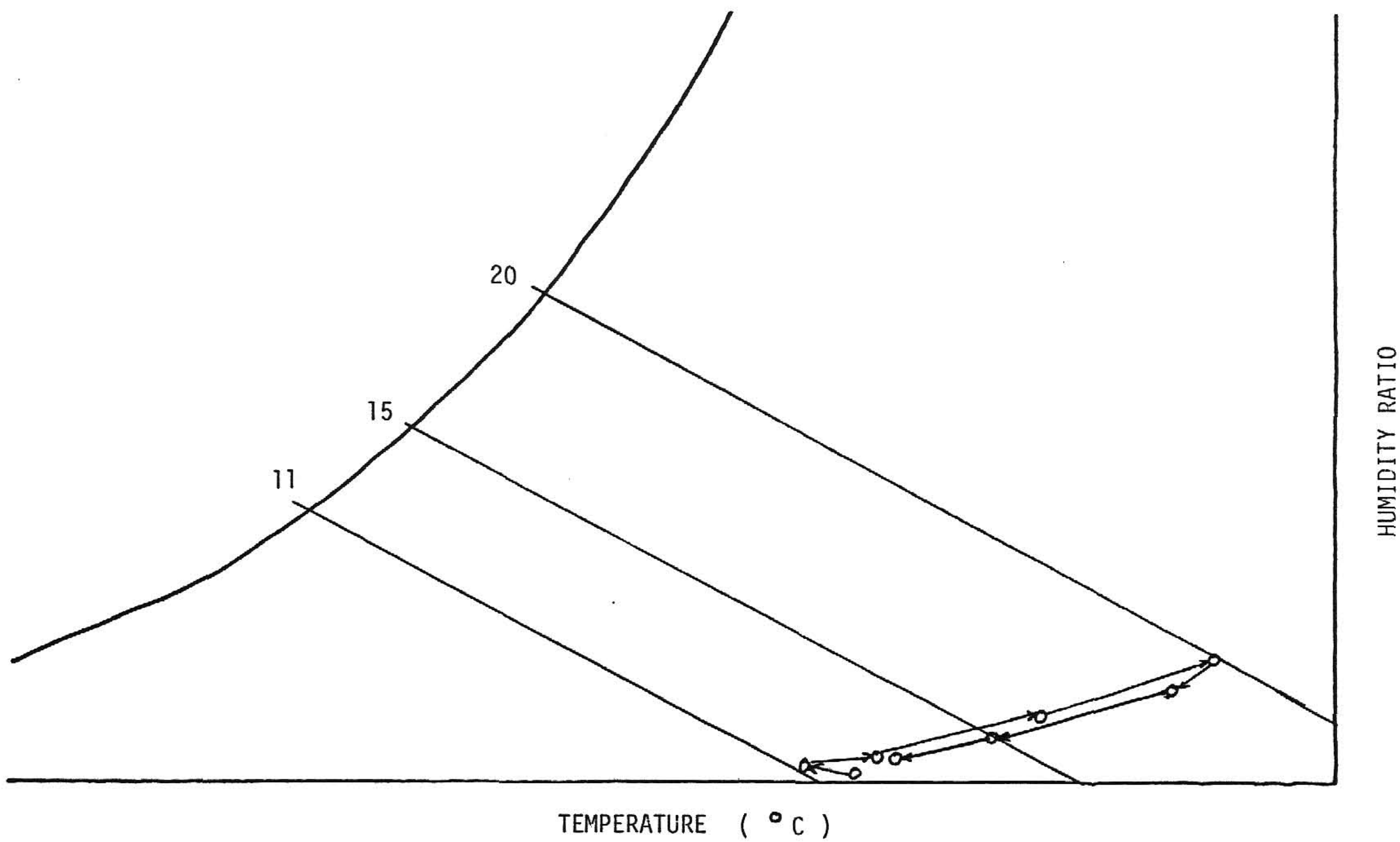


TABLE 5

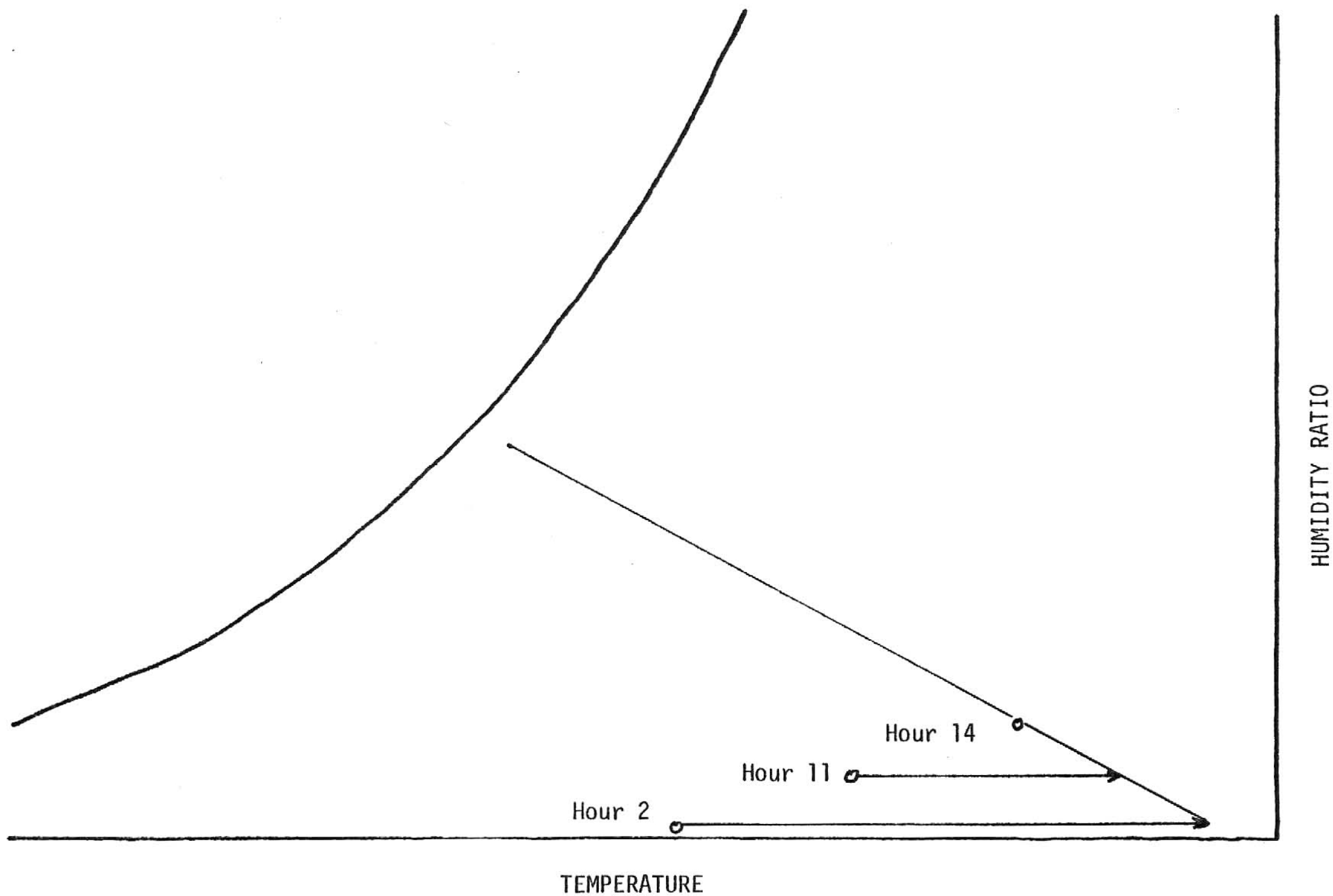
October, 21 Omaha, Nebraska
Moisture Evaporated With Various
Constant Wet Bulb Temperatures

HOUR	Dehumidifier Outlet Temperature	Dehumidifier Outlet Humidity	Wet Bulb Temperature	Sat. Humidity Ratio	Change in Humidity Ratio	Moisture Evaporated *
2	32.5	.0005	12.0	.0088	.0083	0.8473
5	30.4	.0009	11.2	.0083	.0074	0.7555
8	33.1	.0009	12.8	.0093	.0084	0.8576
11	39.8	.0020	16.2	.0116	.0096	0.9801
14	46.4	.0038	20.0	.0148	.0110	1.123
17	44.6	.0029	18.6	.0136	.0107	1.092
20	37.7	.0017	15.0	.0106	.0089	0.9086
23	33.8	.0009	13.0	.0093	.0084	0.8576

Temperatures in °C
* Moisture Evaporated in Kilogram per Hour,
based on an air flowrate of 0.02836 kg/s

FIGURE 11

PSYCHROMETRIC PLOT OF DRYING MODEL
FOR COMPUTER PROGRAM



temperature for each hour can be calculated for use in equation 4.9 and the moisture evaporated during one hour can be determined.

Then, multiplying the system grand total of moisture evaporated by the latent heat of vaporization determines the load handled by the silica gel dehumidifier. The supplementation of an additional heater increases the load. The fraction of energy supplied by solar, F, equals the solar collector heat gain divided by the total load supplied by the silica gel dehumidifier and the additional heater. The quantity, 1 - F, is then the amount of auxiliary heat required, which when multiplied by the load, the cost of fuel and P_{1s}, determines the life cycle cost of the fuel (equation 4.2).

This method of determing the load is developed with one configuration of the system, that is, a continuous operation with one desiccant bed and one set of solar collectors. However, this does not take full advantage of many configurations possible with this system. As presented so far in this study, this system would be used only at harvest time and would otherwise sit idle. But, the solar collectors could be utilized in a variety of ways throughout the rest of the year. Two of these uses are to heat buildings, for human or livestock habitation, or to regenerate beds of desiccant to seal, store and save for later use during harvest. Aldis, et al (2) studied the use of silica gel in drying corn and milo, and report a 15% loss of drying potential when the silica gel is stored for 87 days. Utilizing one set of solar collectors and several desiccant beds would take advantage of sunny days throughout the spring and summer, allow for more continuous operation during harvest independent of the weather, and, in general, better utilize the facility. Further study and incorporation of this configuration into the Economic Analysis computer model would shed light on some interesting alternatives and applications for such a system.

THE COMPUTER PROGRAM

The computer program calculates the life cycle costs for a solar energy and a conventional drying system so that they may be compared. Computations are carried out independently, allowing different economic parameters for each system. The parameters common to both systems are:

1. Inflation rates - fuel
   - general
2. Tax rates - Federal
   - State
3. Term of economic analysis
4. Fuel cost
5. Income or Non-income producing operation

The parameters that can be different for either system are denoted by an S or C for Solar or Conventional respectively, and are:

6. Market discount rate
7. Mortgage - term
   - downpayment
   - interest rate
8. Depreciation - life
   - method
9. Equipment cost
10. Property Tax rate
11. Assessed Valuation
12. Resale value
13. Miscellaneous costs
14. Federal Tax Credit - Note that this applies only to the Solar Energy System

These data are read at the beginning of the Economic Analysis portion of the program. Data required to vary the load are provided both through the common block and by cards. The parameters supplied in the common block are:

15. Solar collector heat gain

16. Solar collector area

17. Hourly dehumidifier exit humidity ratios

18. Air mass flowrate

Data provided by cards include:

19. Commodity equilibrium moisture content

20. Drying constants

21. Specified Wet Bulb Temperature

22. Enthalpy of air corresponding to the wet bulb Temperature

23. Hourly station atmospheric pressure

The economic analysis portion of program MAIN can be used without calling subroutine SYSTEM. In this case however, the variables 15-23 listed above must be provided as input to the program, along with the number of hours per day and number of days included in the study: Parameters are dimensioned in arrays with the number of days and hours similar to the arrays in the Weather Data program. The program first calculates the hourly moisture evaporated utilizing Henderson's equation. The total daily moisture evaporated is summed and printed along with the hourly results. This is repeated for every day, and the grand total evaporated moisture for the time period studied, is summed.

The procedure for calculating the life cycle cost is identical for the conventional and solar energy systems. After the evaporated moisture is estimated, the program determines the years over which mortgage payments contribute to the analysis. This is the minimum of the term of the loan and equipment lifetime. If the term of the loan is less than the equipment lifetime, all payments will contribute to the analysis. This method was used to choose N_{min} for this study. But if the equipment life is chosen to be less than the term of the loan, then the term depends on the rationale behind that choice. If the discounted cash flow is calculated over the equipment lifetime without regard for costs outside of that time period, N_{min} equals the term of the equipment lifetime. If all payments are expected to continue past the equipment lifetime, N_{min} equals the term of the loan. If the equipment lifetime is chosen as the time of sale of the facility, then N_{min} would equal the equipment lifetime, the remaining loan principal would be repaid at that time, and the principal balance would be deducted from resale value.

This same argument is used to determine the minimum years over which depreciation deductions contribute to the analysis. For this study, the depreciation life is chosen to be less than the equipment lifetime.

Next, the effective tax rate, $\bar{t}$, is calculated as given by equation 4.5. This accounts for state income taxes being deductible from income for federal tax purposes, but federal taxes are not deductible for state tax purposes.

The present worth factors included in calculating P_1 and P_2 utilize a Fortran statement function. These statement functions, PWF and PWFP, define the functions given by equation 4.3, using one statement and dummy variables. After calculating values for present worth factors, all the terms for P_1 and P_2 are calculated. P_1 and P_2 for the solar energy system are calculated first, followed by P_1 and P_2 for the conventional system.

Life cycle costs can then be calculated, depending on the load. The base load is set at the moisture that the silica gel dehumidifier alone can evaporate. Increasing the load by addition of a conventional heater varies the fraction of energy supplied by solar energy. This Economic Analysis program accompanied by a sample of the output is listed in Appendix D.

CHAPTER V

APPLICATIONS

The sorption dehumidification system finds applications wherever process air is utilized for dehumidification or humidity control. Besides a variety of agricultural and food processing applications, pharmaceutical and chemical manufacturing utilizes dehumidified air to reduce caking and lumping of powdered products. Paper manufacturing and lumber drying also require dehumidified air. Humidity control in marine environments is required to reduce rot, mildew and corrosion in storage areas. Humidity control also finds an application in the area of human comfort. This chapter discusses some of these areas, and is provided as a springboard for further study. Many other applications for this system are left to the reader and his imagination.

GRAIN AND OILSEEDS

Safe storage of cereal grains and oilseeds depends on the equilibrium relative humidity (E.R.H.) and the length of time stored. Grain and oilseeds are susceptible to mold growth and insect infestation if the equilibrium relative humidity exceeds 70%. The equilibrium relative humidity, temperature, history, condition and type of commodity all have an effect on the moisture content. Weather conditions occasionally force the farmer to harvest grain before it is at a moisture content suitable for storage and some grains give higher yields when harvested at higher moisture contents. Grain drying is then necessary.

The moisture content of grain will be in equilibrium with the relative humidity of the surrounding air as described by isotherms on an equilibrium moisture curve for a particular commodity. Equilibrium moisture curves also depend on the direction of moisture movement. Grain undergoing desorption has a higher moisture content for a given relative humidity than grain undergoing adsorption, as shown in Figure 12. Figures 13, 14 and 15 show several isotherms for desorption of corn, soybeans and peanuts (1). With a given relative humidity, the moisture content will vary for different commodities due to structural and chemical compositional differences. For example, at 75% relative humidity and 30°C, the moisture content of corn is 14%, of soybeans is 13% and of peanuts is 8%.

Figure 16 shows that the allowable storage time for corn decreases as the grain temperature increases and as the moisture content increases (23). For a temperature of 60°F, the difference in storage time is twice as long for 18% moisture content as for corn with 20% moisture content. Likewise, at 20% moisture content, the allowable storage time at 70°F is 20 days, whereas at 50°F, it is 60 days. For minimum spoilage, drying should start immediately after the grain is harvested.

Table 6 lists the safe maximum moisture contents for storage for one and five years for the eight major grains produced in the United States. Some grains such as wheat and soybeans rarely require extra drying. However, corn is an example which requires drying more frequently. It can be seen in Figure 17 that the states with high corn production also required large amounts of energy to dry crops in 1974. In order to dry corn at 28% moisture content to a safe storage level of 12%, 11.9 pounds of water must be removed per bushel (7). Present figures estimate that 2000 BTU are required to evaporate one pound of water from grain (22).

Caution should be exercised when drying so that the grain is not overheated. High grain temperatures can reduce grain quality for many uses through: killing the germ, thereby decreasing germination or malting qualities; changing the nature of the chemical constituents - gelatinize the starch of grain with

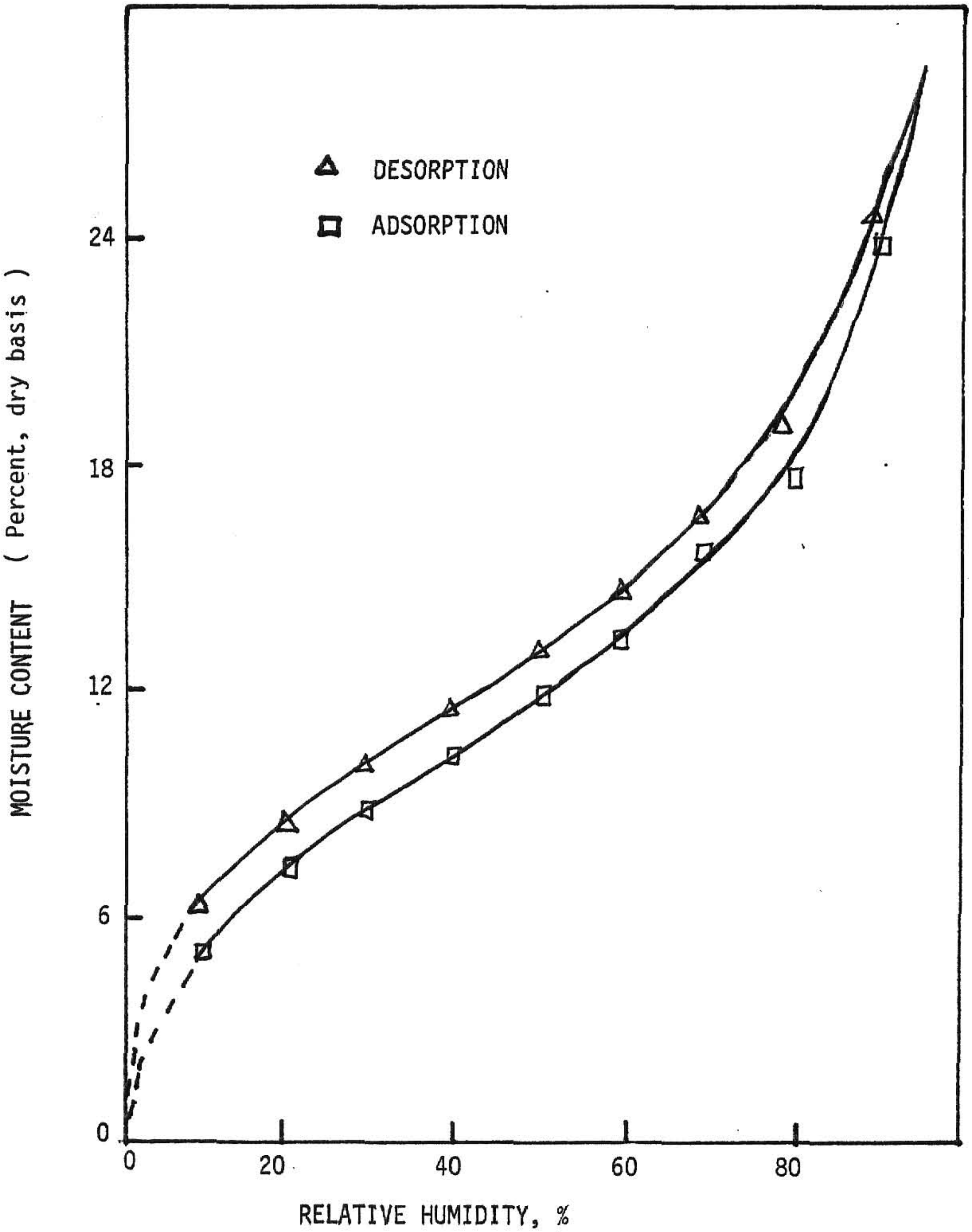


FIGURE 12. Adsorption - desorption isotherms of corn at 22° C. Chung (1966).

FIGURE 13

EQUILIBRIUM MOISTURE CURVES
YELLOW DENT CORN

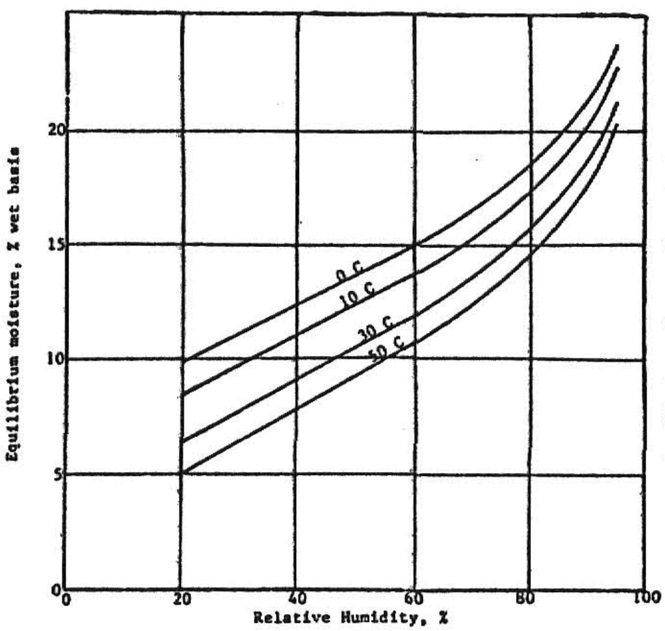


FIGURE 14

EQUILIBRIUM MOISTURE CURVES
SOYBEANS

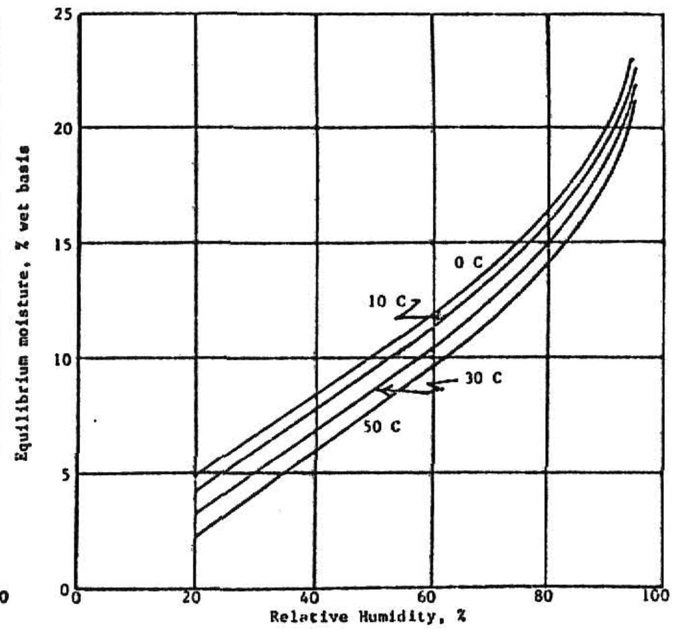


FIGURE 15

EQUILIBRIUM MOISTURE CURVES
PEANUT KERNEL

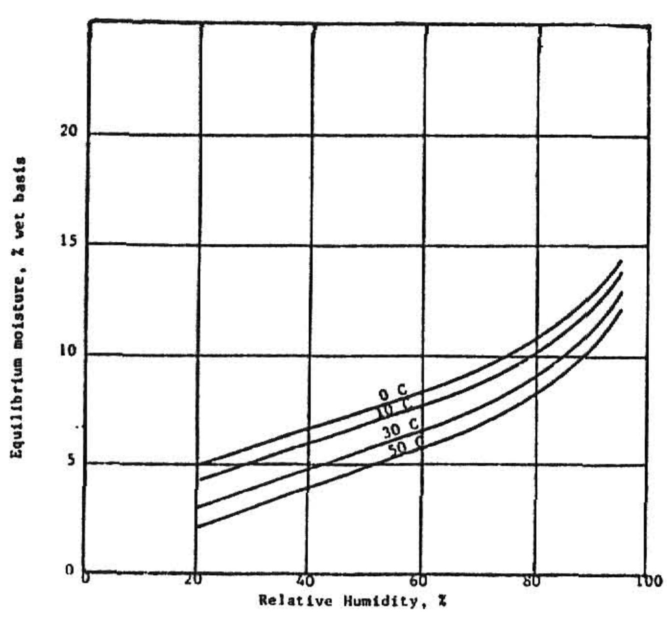


FIGURE 16

ALLOWABLE STORAGE TIME FOR CORN

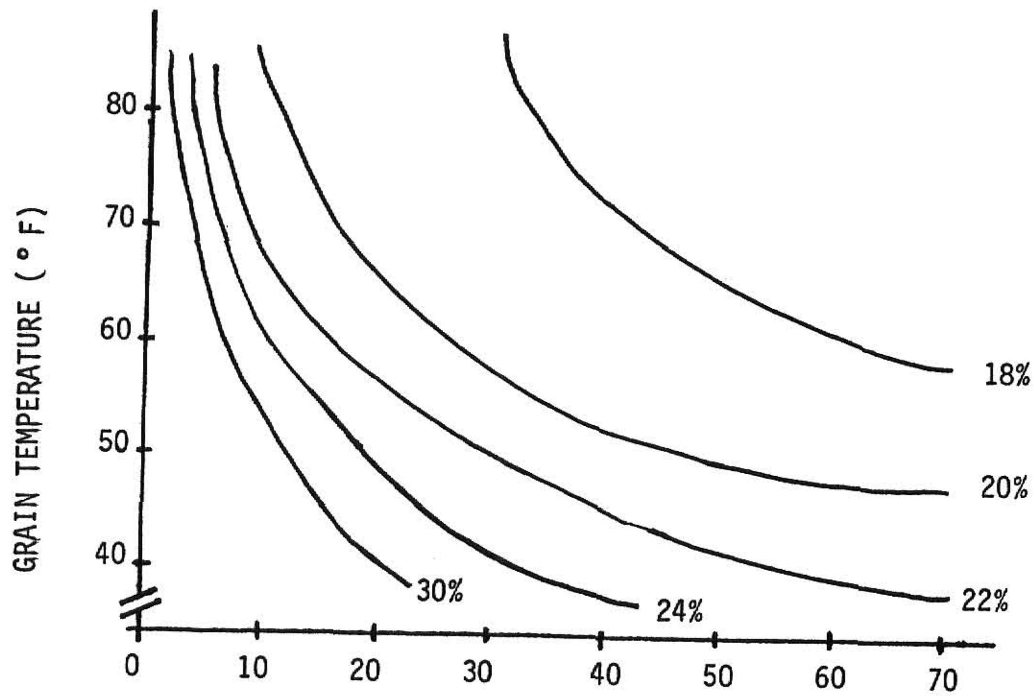


TABLE 6

MOISTURE CONTENT (%) OF VARIOUS GRAINS

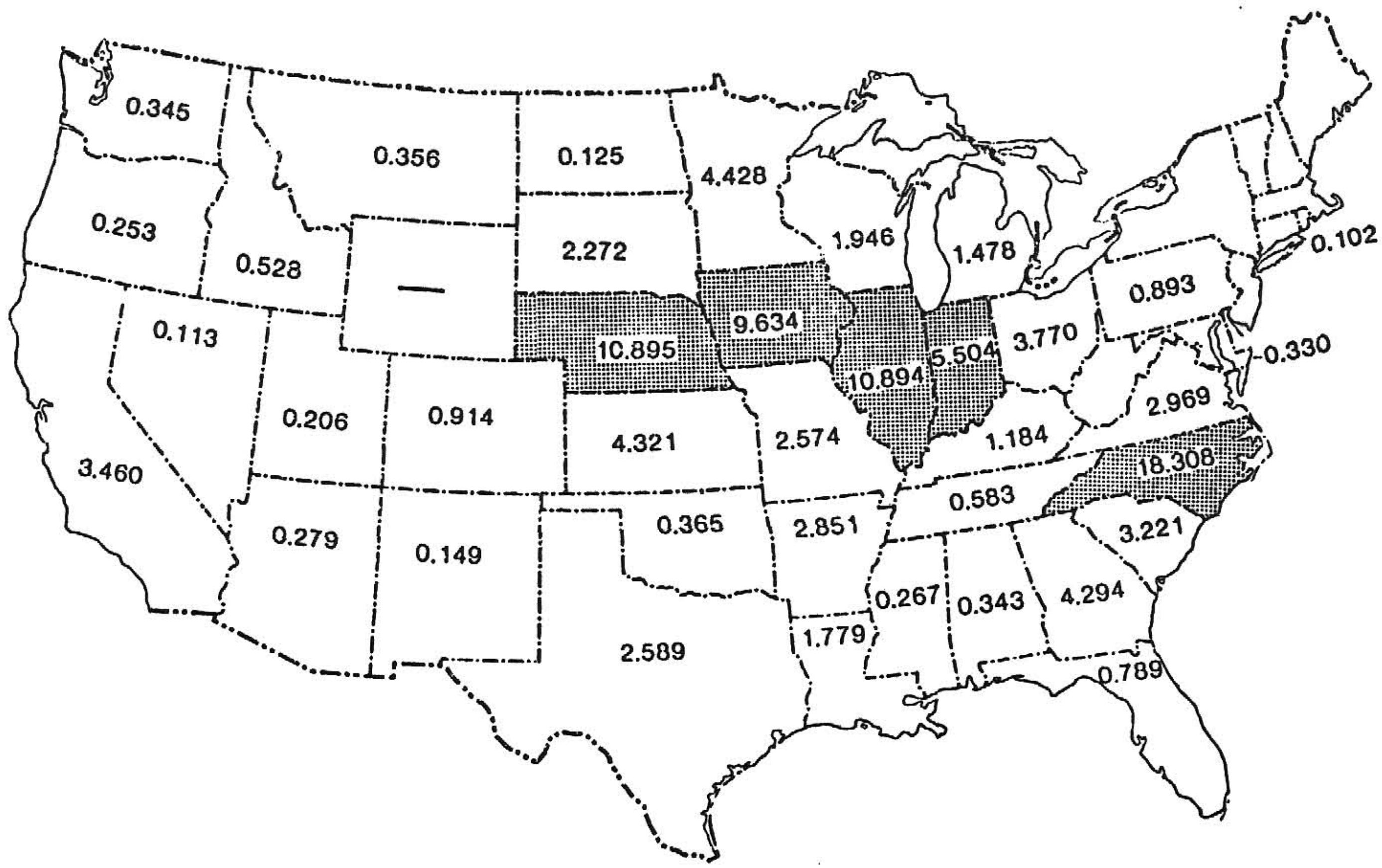
CEREAL	BEST AT HARVEST	USUAL AT HARVEST	1 YEAR STORAGE	5 YEAR STORAGE
BARLEY	18-20	10-18	13	11
CORN	28-32	14-30	13	10-11
OATS	15-20	10-18	14	11
RICE	25-271	16-25	12-14	10-12
RYE	16-20	12-18	13	11
SORGHUM	30-35	10-20	12-13	10-11
SOYBEAMS		12-13	11	10
WHEAT	18-20	9-17	13-14	11-12

FIGURE 17

ENERGY CONSUMED FOR CROP AND GRAIN DRYING - 1974

(10^{12} BTU/YEAR)

Shaded Areas Represent 50% of Total Consumption



high moisture content, increase fat acidity, denature the protein, etc.; and through cracking the endosperm. These stress cracks result when a porous body is dried due to thermal expansion through temperature gradients and contraction caused by moisture losses (18). Thus, high temperatures or quick moisture removal lead to grain fissuring. The moisture removal rate can be explained by the diffusion of moisture from the center of the commodity. Drying occurs through water vaporization from the grain surface when the water vapor pressure exceeds the partial pressure in the surrounding air. Diffusion of water takes place from the center to the surface, with the rate depending on the nature of the commodity. Once the seed coat is broken, the grain becomes much more susceptible to mold and insect invasion. Table 7 lists temperatures safe for various commodities and their uses.

High temperatures can cause fissures in grain, but so can extremes of relative humidity. White (41) reports fissuring in soybeans caused by air with low relative humidities, whereas Kunze and Prasad (28) found that high relative humidity air causes rice to fissure. Use of the heat exchanger in the sorption dehumidification system allows control of the air temperature and relative humidity so that high temperatures and extreme relative humidities may be avoided.

Conventional grain dryers heat air with propane or natural gas to high temperatures and blow the hot air through the grain, but vary in configuration. Continuous flow dryers convey grain either with a horizontal belt, or vertically by gravity. Since continuous, they can handle large amounts of grain with relatively uniform moisture contents, but have low thermal efficiencies. Batch drying can be done either in a bin or with a portable batch dryer. As the name implies, a batch of grain is dried at one time, then transferred to another container for storage. This method is restricted to smaller quantities

TABLE 7

AIR TEMPERATURES UTILIZED TO DRY CEREAL GRAINS AND OILSEEDS

GRAIN	PURPOSE	MAXIMUM SAFE TEMPERATURE - °F
CORN	DISTILLING	140
	FEED	280
	MILLING-DRY	120
	MILLING-WET	130-140
	SEED	100-110
OILSEEDS		115
RICE		120-130
SORGHUM		140-150
WHEAT	FLOUR	160
	SEED	100-110
OTHER CEREAL GRAINS	SEED	100-110

of grain, yet operates with a higher thermal efficiency than a continuous dryer. Dryeration is yet another method employed to dry grain. It operates in two stages, drying grain from 20-30% moisture content to 16-18% with air temperatures ranging from 90-115 °C in the first bin. The grain is then transferred to a second bin, allowed to set for 4-8 hours, and cooled with ambient air which simultaneously removes an additional 2 percent moisture. The advantages of dryeration are a high thermal efficiency, slower moisture removal, reduced grain breakage and a higher dryer capacity.

Natural air drying has found increased interest since the advent of higher fuel prices. Ambient air, that is 10 ° F lower than the grain temperature, is blown through a bed of grain. This method is effective only if the air relative humidity is lower than 62% (29). This method requires good weather conditions and long periods of time to dry completely. Supplementing the natural air dryers with solar preheating has been found to reduce the drying time (32).

Due to the long drying time with natural air dryers, even with solar preheating, researchers have studied alternative methods to dry grain. Rodda and Rode (34) studied the use of a desiccant dehumidifier with an air conditioner to dry grain and found the energy efficiency comparable to that of heated air dryers. Danziger, et al (14) studied the effect of drying field corn with air dehumidified with silica gel and also with the corn mixed directly with silica gel. They report an increase of quality when drying corn with silica gel at room temperature. Aldis, et al (2) compared corn and milo dried with natural air to corn and milo dried with air dehumidified by silica gel. Drying time was considerably shorter using the dehumidified air than with the natural air. Mold growth also decreased with use of the dehumidified air. No differences were found in energy requirements or susceptibility to breakage. Silica gel has also been studied as a method to dry and maintain a dry moisture content of grain in humid climates. Hsiao (24) placed bags of silica gel in grain bins and determined the ratios of silica gel and grain required with different initial grain moisture contents, and the frequency of regeneration necessary for the silica gel.

ALFALFA

Alfalfa meal is fed to cattle, swine, sheep and poultry. Fresh cut alfalfa ranges in moisture content from 65-85% and should be dried immediately to 6-8% for pelleted feed (26). Currently, alfalfa is dried in rotary type drums, either in single or multiple drums at a high rate, removing 6000 pounds of water per hour at temperatures around 800-1000°C. However, research shows that alfalfa dehydrated at 180 °C, compared to 130° C, reduced digestibility, nitrogen retention and growth of sheep (19). Krause and Klopfenstein (27) studied the effect of freeze dried, sun cured and oven dried alfalfa, and of soybean meal on steer and lamb production. They report a desirable low ammonia concentration in in alfalfa dehydrated with temperatures of 80-120° C. Therefore, a sorption dehumidification system would produce a better quality of air for dehydration. Table 8 lists the geographical areas and number of dehydrating drums in operation in 1981. Alfalfa is cut approximately four times during a season at 30 day intervals beginning in early June (38).

MISCELLANEOUS AGRICULTURAL PRODUCTS

Distillers grain, occasionally fed to cattle and swine, is another area where drying improves allowable storage time (13), and could be dried with a sorption dehumidification process. Distillers grain is the byproduct of fermentation in the production of alcohol which ranges in moisture content from 85-95%. It has been found that 16-18 pounds of distillers grain is recoverable

TABLE 8

ALFALFA DEHYDRATING DRUMS IN OPERATION IN 1981

STATES	NUMBER OF DRUMS
NEBRASKA	99
KANSAS	41
IOWA, MINNESOTA, WISCONSIN, NORTH DAKOTA, SOUTH DAKOTA	31
MARYLAND, PENNSYLVANIA, OHIO, MICHIGAN	30
CALIFORNIA, NEVADA, ARIZONA, WASHINGTON, OREGON	15
COLORADO, UTAH, MONTANA, IDAHO	14
ARKANSAS, TENNESSEE, ALABAMA	6
ILLINOIS, MISSOURI, INDIANA, KENTUCKY	5
TEXAS, OKLAHOMA, NEW MEXICO	4

from a 56 pound bushel of grain. The net energy values for dry distillers grain and corn do not differ, and most alcohol fuel byproducts contain 28-30% protein, about three times that found in corn.

The citrus industry utilizes several drying operations. Miller (31) reports that surface moisture removal from fresh citrus fruit ranks as the principal consumption of energy on the packinghouse line, requiring 6.59 kW per 40.8 kilogram box of fruit. The production of juice leaves citrus pulp and peel as byproducts (6). When dried to 10% moisture, it is almost equivalent to the nutritional value of corn for livestock feed.

Grapes are sun-dried on racks or on the vine, or dehydrated in tunnel dryers for raisin production in California. Raisins produced by artificial dehydration vary in flavor and color from sun-dried fruit and are less desirable. But weather conditions in California's Central Valley during the fall do not always cooperate with the sun-dried operation. Studer and Olmo (39) report that a combination of partial drying on the vine completed by artificial dehydration would produce a fruit similar to the sun-dried raisin while diminishing the risk of bad weather.

Approximately 57% of the potato crop undergoes processing, with 22% of that being dehydrated (37). Dehydrated potatoes take forms of granules, flakes, flakelets and diced. Washington and Idaho are the major producers of processed potatoes, followed with high production in Maine, North Dakota, Minnesota, Oregon and Michigan.

Other agricultural crops that require some degree of drying are:

Apricots	Onions
Apples	Parsley
Bananas	Peaches
Carioca	Pineapple
Carrots	Plums
Cassava	Yams
Figs	

In drying fruit, careful consideration must be given to the sensitivity of the crop to temperature, ultraviolet light and bacterial action (29). Some of the applications listed above may be a sort of novelty, nevertheless, they are presently dried with conventional systems.

One application reported by Farmer, et al (17) is in solar drying of paunch contents. In the processing of meat, the rumen of a mature, slaughtered animal contains 25-30 kilogram of partially digested feed with high moisture contents. If dried, paunch contents can be used as animal feed. They developed an enclosed dryer utilizing direct solar energy. Use of a sorption dehumidification system could insure continuous operation for this application.

PAPER AND PAPERBOARD

Another industry which uses large quantities of fossil fuels for drying process heat is in the manufacture of paper and paperboard. Following chemical, refinery and primary metal production, the paper industry is the fourth leading energy consumer in the manufacturing industry and the leading consumer of fuel oils (10). Wood is pulped by either mechanical grinding or by chemical reduction, and the pulp is combined with water to form the correct consistancy (25). The pulp fibers are fed onto a fast moving wire mesh to form a sheet of paper. At this point, the paper contains substantial amounts of water, with a ratio of 200:1 of water to fiber. The major portion of this water falls through the wire due to gravity as the mesh moves, and a suction section placed near the end of the mesh removes an additional amount of moisture. The paper then passes through a series of presses, reducing the moisture content from about four to two kilograms of water per kilogram of fiber. The presses can only reduce the moisture content to a minimum of 55-60 percent moisture, otherwise the fibers would be crushed and the paper quality reduced. Heat must then be added to reduce the finished paper moisture content to 8 percent.

The actual drying process requires from 7.6 to 14.5 x 10^6 Joules per kilogram of the finished product. Water must be removed from the paper itself, but the felt presses also require drying to some degree. Higher temperatures ranging from 300 to 450° C may be used.

LUMBER

Lumber drying is still another area where a dehumidification process may be quite feasible. Dehumidification drying of spruce studs studied by Cech and Pfaff (8) was found to consume less energy than the conventional steam dried kiln (Figure 18). A refrigerant system was used to condense air vapor and produce dry, hot air. It was found that the three dehumidification charges consumed 46-68 percent less energy than the conventional kiln dried sample with no appreciable quality difference. However, some means to provide stress relieving of the studs must be made, generally some additional humidification system. A lower temperature was used in the dehumidification process, 93 ° F instead of 150-180 ° F used for kiln drying. This lower temperature is well suited to temperatures produced by flat plate collectors. However, the lower temperature lengthens the drying time, as shown in Figure 19. One solution to decrease the drying time would be to combine the two processes, first using a dehumidification process, then at about 25% moisture content, finish drying with a conventional kiln. This could simultaneously provide stress relief for the lumber. Areas of major lumber production are the Pacific West, South Atlantic and Rocky Mountain states.

AIR CONDITIONING

The area of air conditioning has been studied by Rush and Macriss (35)

FIGURE 18

ENERGY CONSUMPTION FOR DRYING SPRUCE STUDS

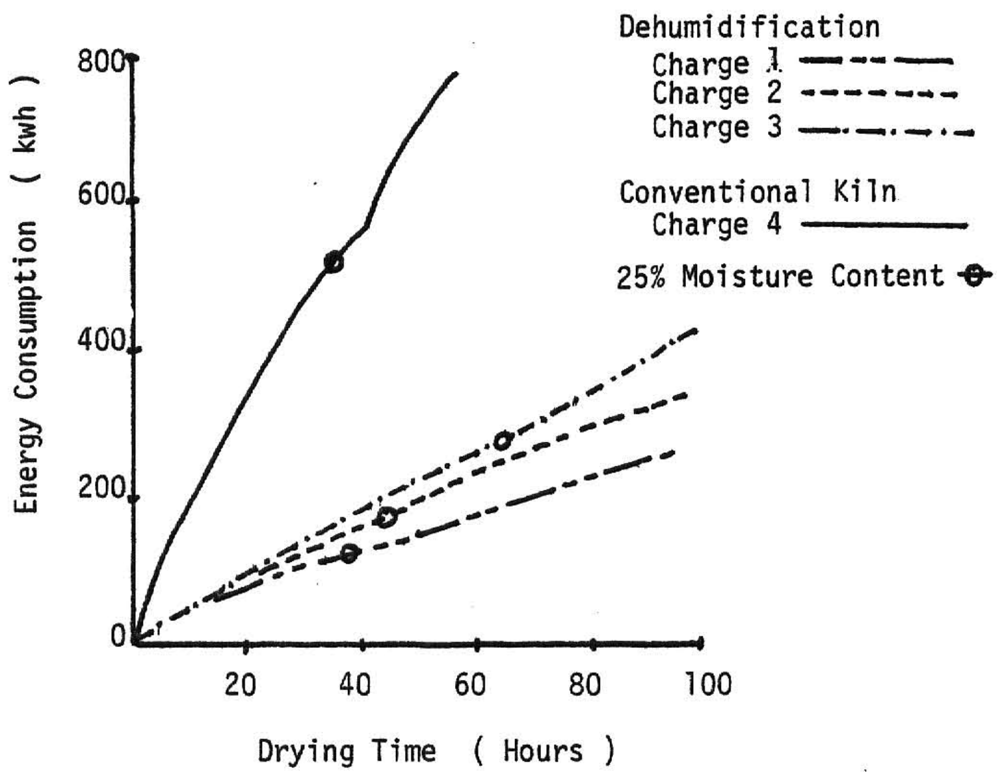
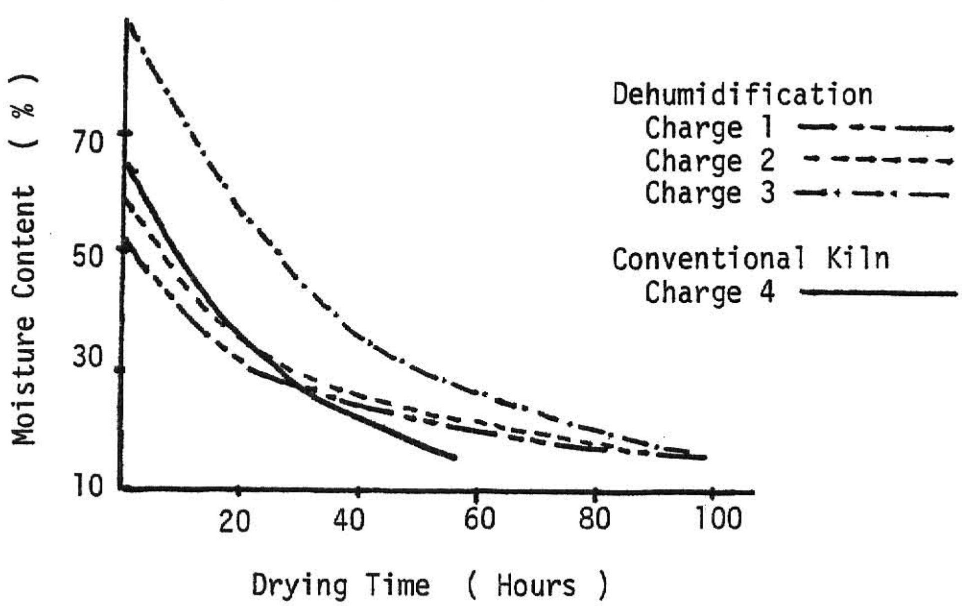


FIGURE 19

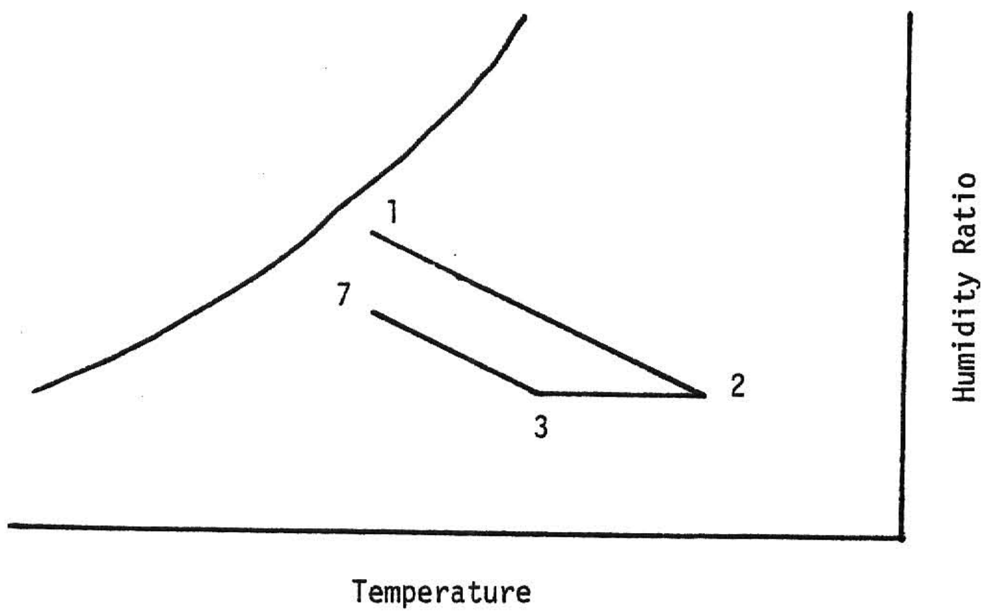
DRYING CURVES FOR SPRUCE STUDS



using asbestoes wheels for the rotating desiccant bed and heat exchanger, and by Dunkle (16) using a solar powered sorption system. The addition of a humidifier on the sorption system takes advantage of evaporative cooling, which then delivers cool, moist air to a building. The humidifying process takes place from 3 to 7 in Figure 20 on a psychrometric chart.

FIGURE 20

PSYCHROMETRIC PLOT OF
DESICCANT AIR CONDITIONING



CHAPTER VI

RESULTS AND DISCUSSION

The purpose of this chapter is to investigate the Economic Analysis model. Choosing one application at one location, the dependency of the life cycle costs can be examined as the dehydration and economic parameters vary. A good application for this system is drying grain, principally corn, throughout the midwest United States. The TMY station at Omaha, Nebraska lies right in the heart of large corn production where harvest takes place in October.

The Weather Data program described in Chapter III was run for the month of October, to locate five consecutive clear days. Clear weather occured October 20-24, so the entire program - the combination of the Weather Data, Subroutine System and the Economic Analysis - was run for twenty four hours a day during that interval. This provided the dehumidifier process outlet air conditions and atmospheric pressure data required by the Economic Analysis program. With these data, the dependency of life cycle costs on the various economic and dehydration parameters can be studied by running only the Economic Analysis program (Appendix D).

Since the fraction of energy supplied by solar can be written as

$$F = \frac{Q_s}{L}$$

the third term for the life cycle cost of the fuel in equation 4.2 can be simplified to:

$$P_{1s}C_f\, L(\,1 - F\,) = P_{1s}C_f\, L\,(1 - \frac{Q_s}{L})$$

$$= P_{1s}C_f\,(\,L - Q_s\,)$$

Equations 4.1 and 4.2 are then recognizable as linear equations of the form $y = b + ax$, where:

	CONVENTIONAL	SOLAR
y =	LCC_c	LCC_s
x =	L	L
a =	$P_{1c}C_f$	$P_{1s}C_f$
b =	$P_{2c}C_{Ec}$	$P_{2s}(C_A A + C_{Es}) + P_{2c}C_{Ec} - P_{1s}C_f Q_s$

The dehydration parameters vary the load which the system can handle, while the economic analysis parameters vary the P_1's and P_2's. All other parameters (C_{Ec}, A, Q_s, . . .) remain constant for this study. Of the noteworthy dehumidification parameters, the inlet dryer wet bulb temperature and initial moisture content of the grain can be varied. The economic analysis parameters that most affect P_1 and P_2 are the Federal Tax Credit, Mortgage Interest Rate, Downpayment, Depreciation, Fuel Inflation Rate, Term of the Economic Analysis and the Market Discount Rate.

DEHYDRATION PARAMETERS

DRYER INLET WET BULB TEMPERATURE: As the set dryer inlet wet bulb temperatures of the air more nearly equal the air temperatures exiting the dehumidifier, the additional heat required decreases, so that the fraction of energy supplied by solar increases. For the solar energy system, Figure 21 shows how the life cycle cost varies with the fraction of solar energy as the inlet wet bulb temperature varies from 15 to 25°C. Note that when the origins for each curve are aligned, the curves lie along the same line. The wet bulb temperature has no effect on the life cycle cost, except indirectly through the fraction of energy supplied by solar as can be seen from Figure 22. This plot of life cycle cost versus the load has the same intercept and slope for each inlet wet bulb temperature, hence, the same line. A higher inlet wet bulb

FIGURE 21

EFFECT OF THE DRYER INLET WET BULB TEMPERATURE ON THE SOLAR FRACTION

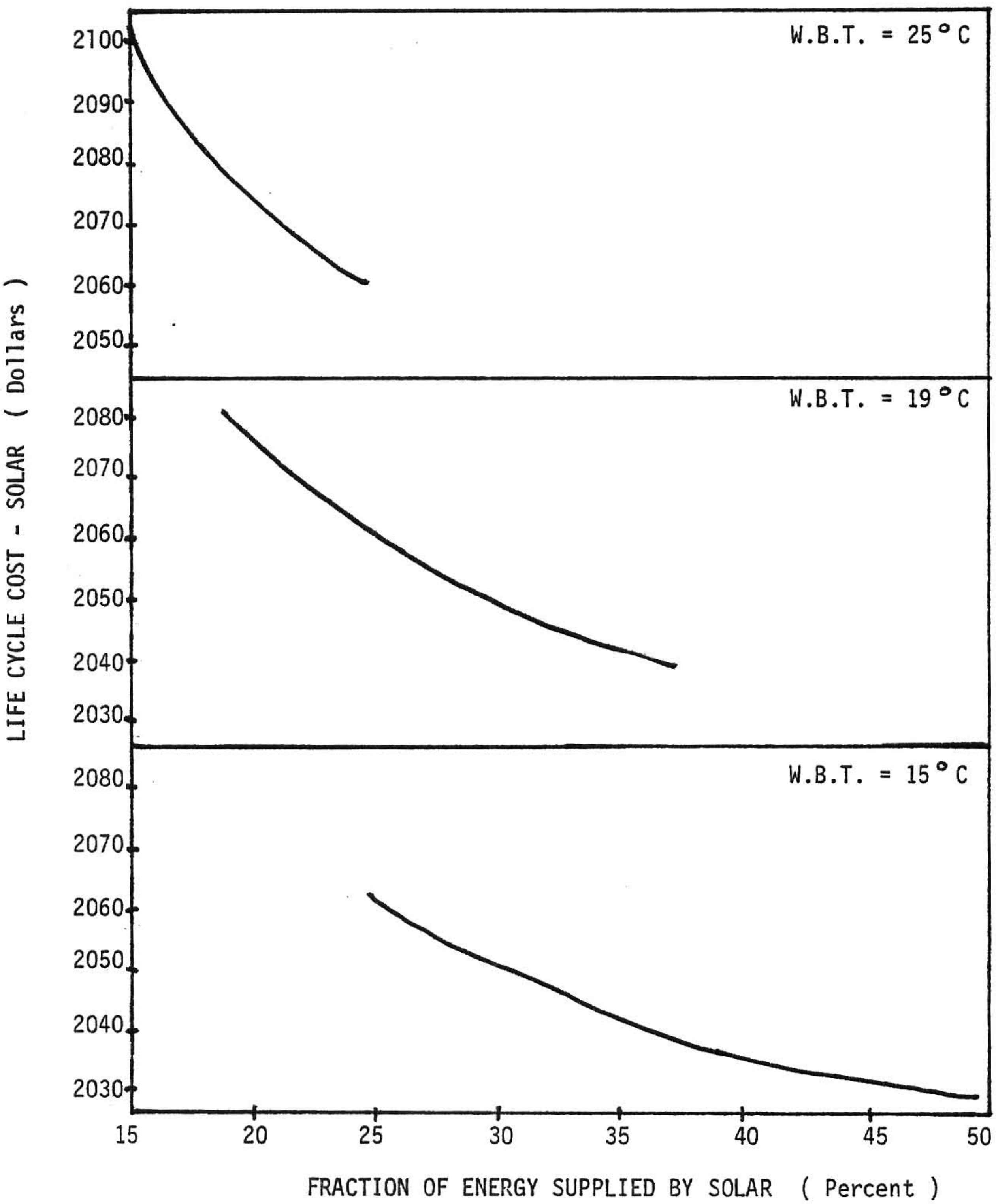
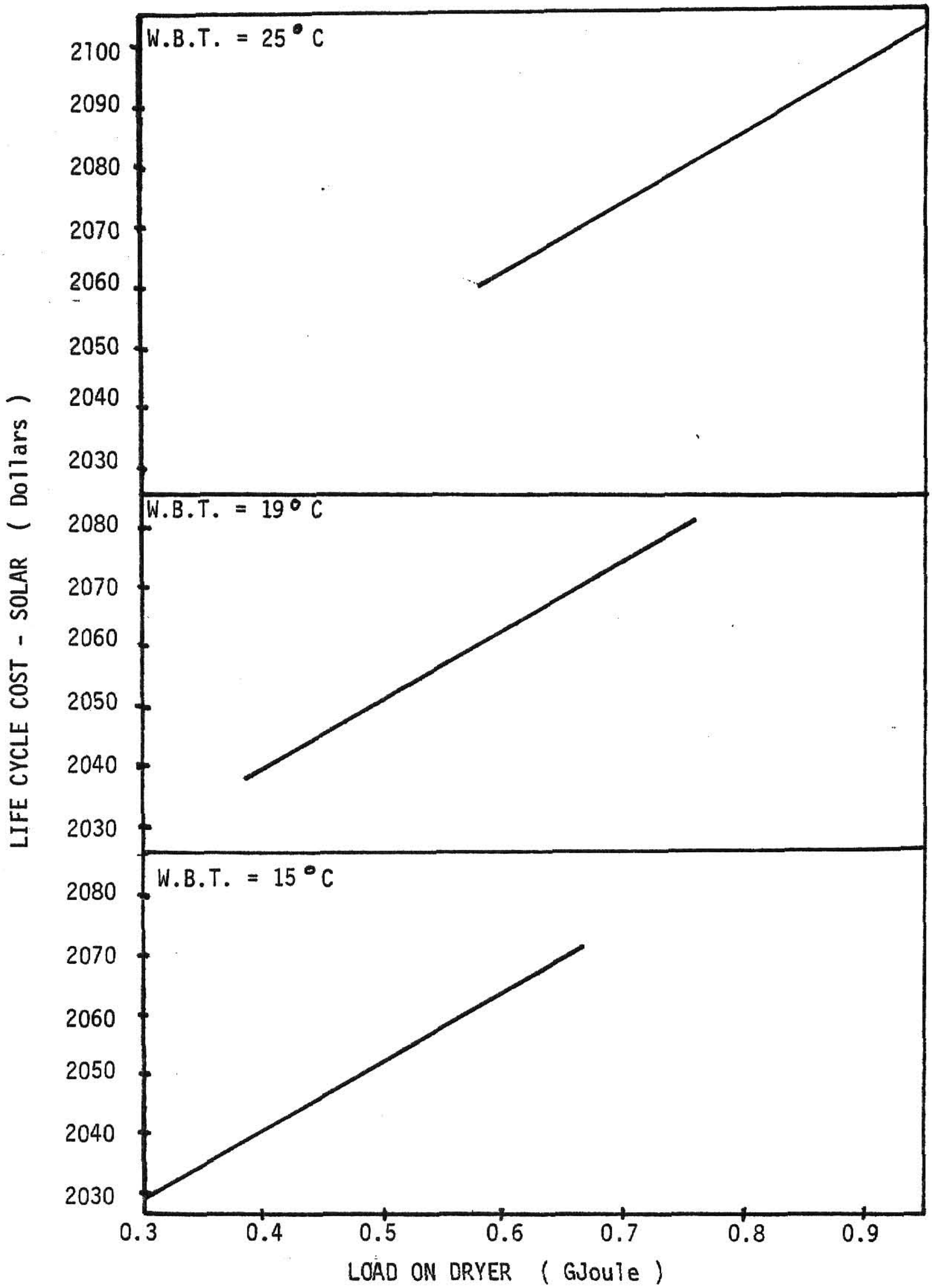


FIGURE 22

EFFECT OF THE DRYER INLET WET BULB TEMPERATURE ON THE LOAD



temperature evaporates more moisture, thereby increasing the load on the dryer. Since the solar heat gain remains constant, the intercept, b, remains constant and only the load varies. The life cycle cost decreases as the fraction of energy supplied by solar increases.

INITIAL MOISTURE CONTENT: This also affects the life cycle cost only indirectly by varying the load, hence, the fraction of energy supplied by solar. Figure 23 is the plot of life cycle cost versus the load for moisture contents of 33.33 and 25 percent dry basis. The higher moisture content of the commodity imposes a higher load on the dryer, but does not directly influence the life cycle cost.

With these results, any reasonable dryer inlet wet bulb temperature and initial moisture content could be chosen as operating conditions, in order to vary the economic analysis parameters. An initial moisture content of 25% (corresponding to 20% wet basis), and an intermediate wet bulb temperature equal to 19 °C were chosen.

ECONOMIC PARAMETERS

From equations 4.4 and 4.6, the economic parameters affect P_1 and P_2 differently. The Federal Tax Credit (FTC), Mortgage Interest Rate (m), Down-payment (D) and Depreciation (DEP) vary only P_2, which in turn affects the intercept of the life cycle cost equation. The Fuel Inflation Rate (i_f) varies only P_1, thereby changing the slope of the life cycle cost equation. The Term of the Economic Analysis (N_e) and Market Discount Rate (d) appear in both terms for P_1 and P_2. These parameters were varied individually, while the others remained at base values listed on page 122 in Appendix D.

FEDERAL TAX CREDIT : The effect of the federal tax credit can be seen in Figure 24. Since the tax credit applies only to a solar system, P_{2c} remains

FIGURE 23

EFFECT OF EQUILIBRIUM MOISTURE CONTENT ON THE LOAD

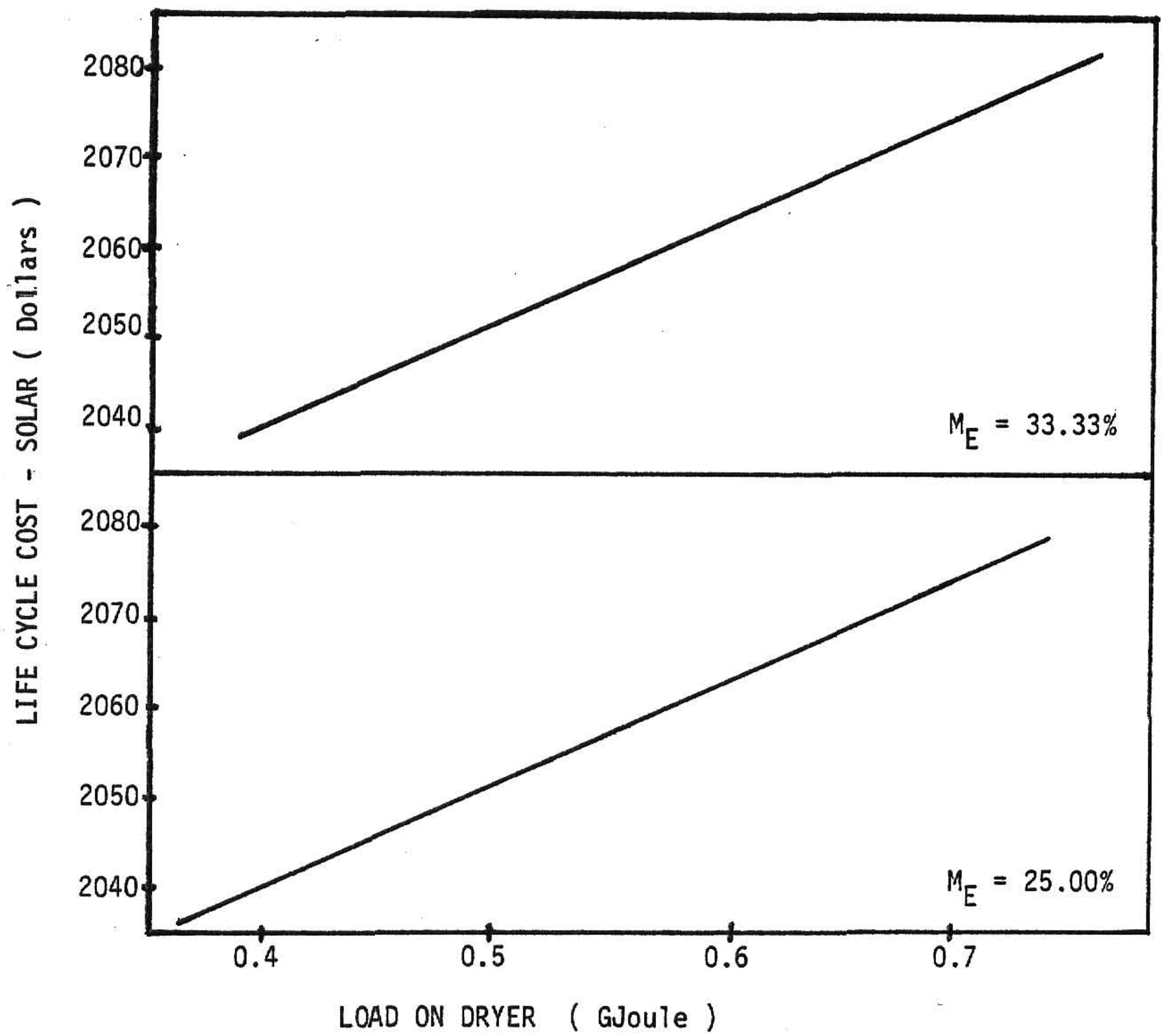
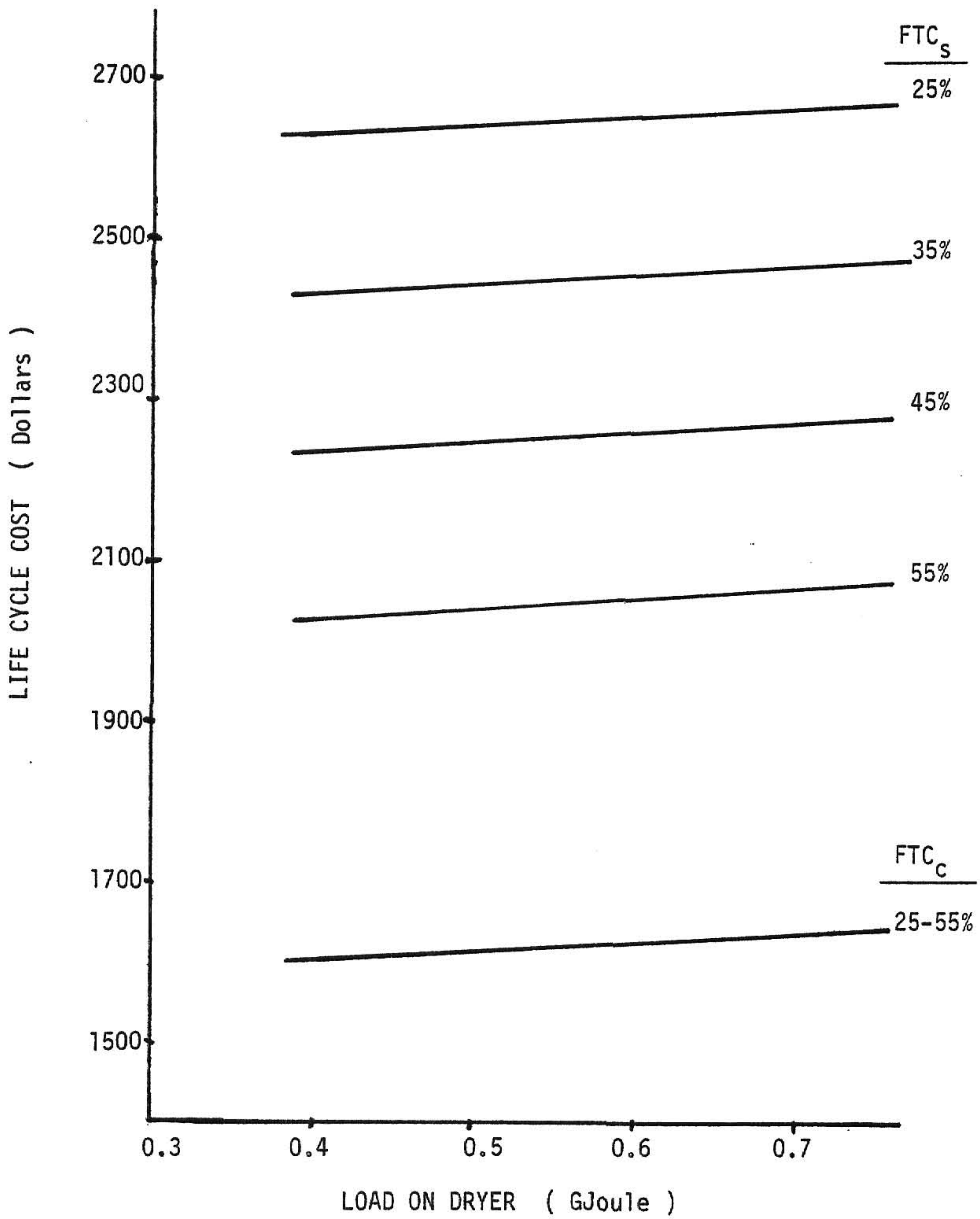


FIGURE 24

EFFECT OF FEDERAL TAX CREDIT
ON LIFE CYCLE COST



constant while P_{2s} changes. The life cycle cost decreases as the federal tax credit increases.

MARKET INTEREST RATE: The relationship between the Market Interest Rate and the life cycle cost is shown in Figure 25. As the mortgage interest rates decline, the life cycle costs decrease, as one would expect. The life cycle cost for the solar energy system at 14 and 16 percent differ by a larger amount than for the conventional system at 14 and 16 percent. This is due to a larger equipment cost for the solar energy system which includes both solar and conventional equipment. For the 2% intervals between 8-10-12-14-16 percent, P_{2s} differs by the same amount as P_{2c}.

DOWNPAYMENT: The downpayment varies linearly with P_2 as shown in Figure 26. Because of this, Figure 27 shows that as the downpayment increases, the life cycle cost increases. Again, the larger equipment cost for the solar energy system causes a proportionally larger change in the solar life cycle cost.

DEPRECIATION: The most favorable method of depreciation is accelerated cost recovery. Since the depreciation affects only P_2, the slope of the life cycle cost versus the load is the same for the different methods. Figure 28 illustrates the advantage of the accelerated cost recovery depreciation over no depreciation for the systems.

FUEL INFLATION RATE: This parameter affects only P_1 and varies the slope of the life cycle cost equation. The slope increases as the fuel inflation rate increases (Figure 29). Note also that at one value of load, the life cycle cost for the conventional system varies with the fuel inflation rate more than the life cycle cost for the solar energy system. This can be attributed to the fraction of energy supplied by solar which reduces the amount of fuel required at a particular load.

TERM OF ECONOMIC ANALYSIS: The program was run with terms of 5 and 15 years

FIGURE 25

EFFECT OF MORTGAGE INTEREST RATE ON LIFE CYCLE COST

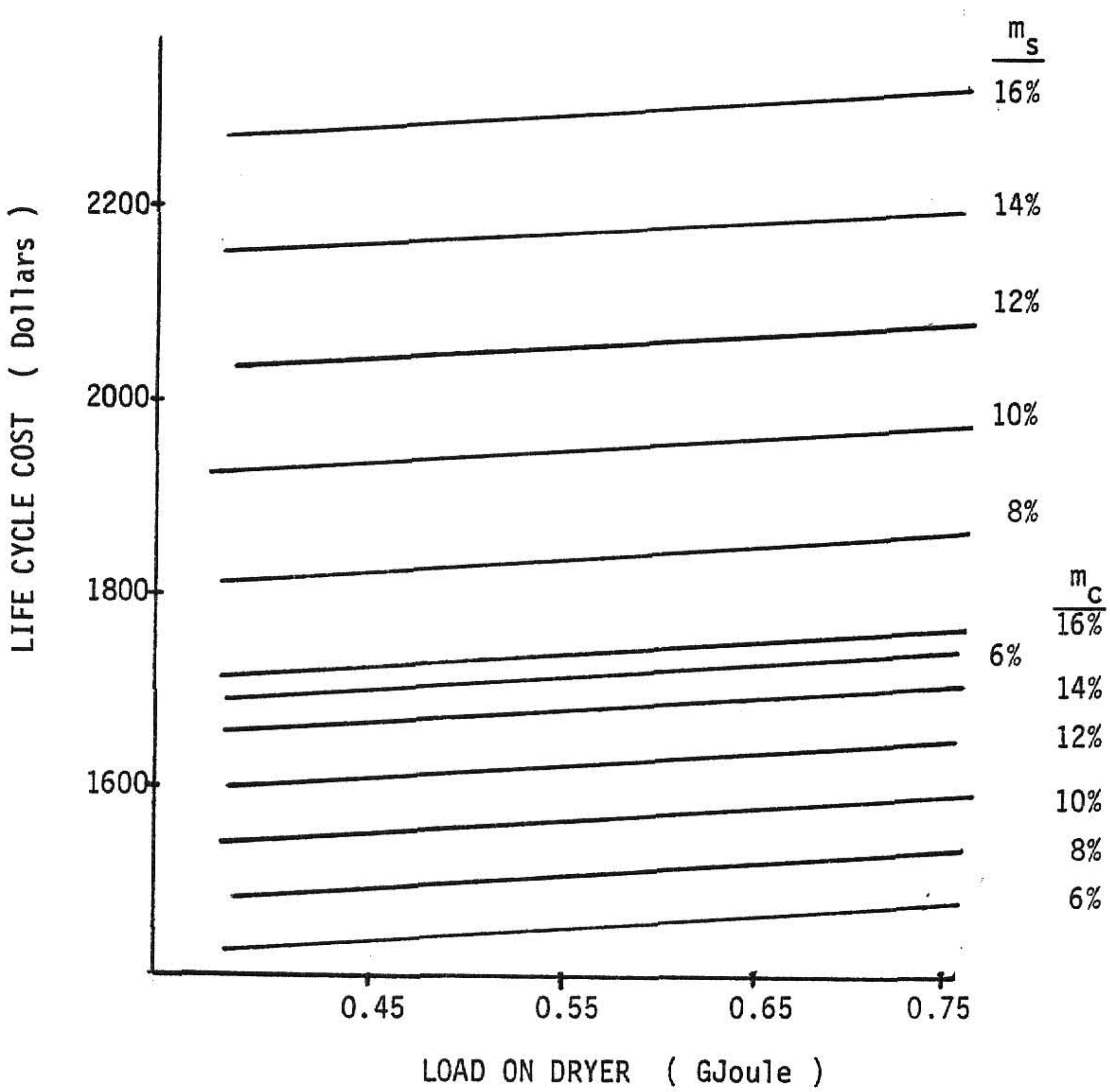


FIGURE 26

EFFECT OF DOWNPAYMENT OF P_2

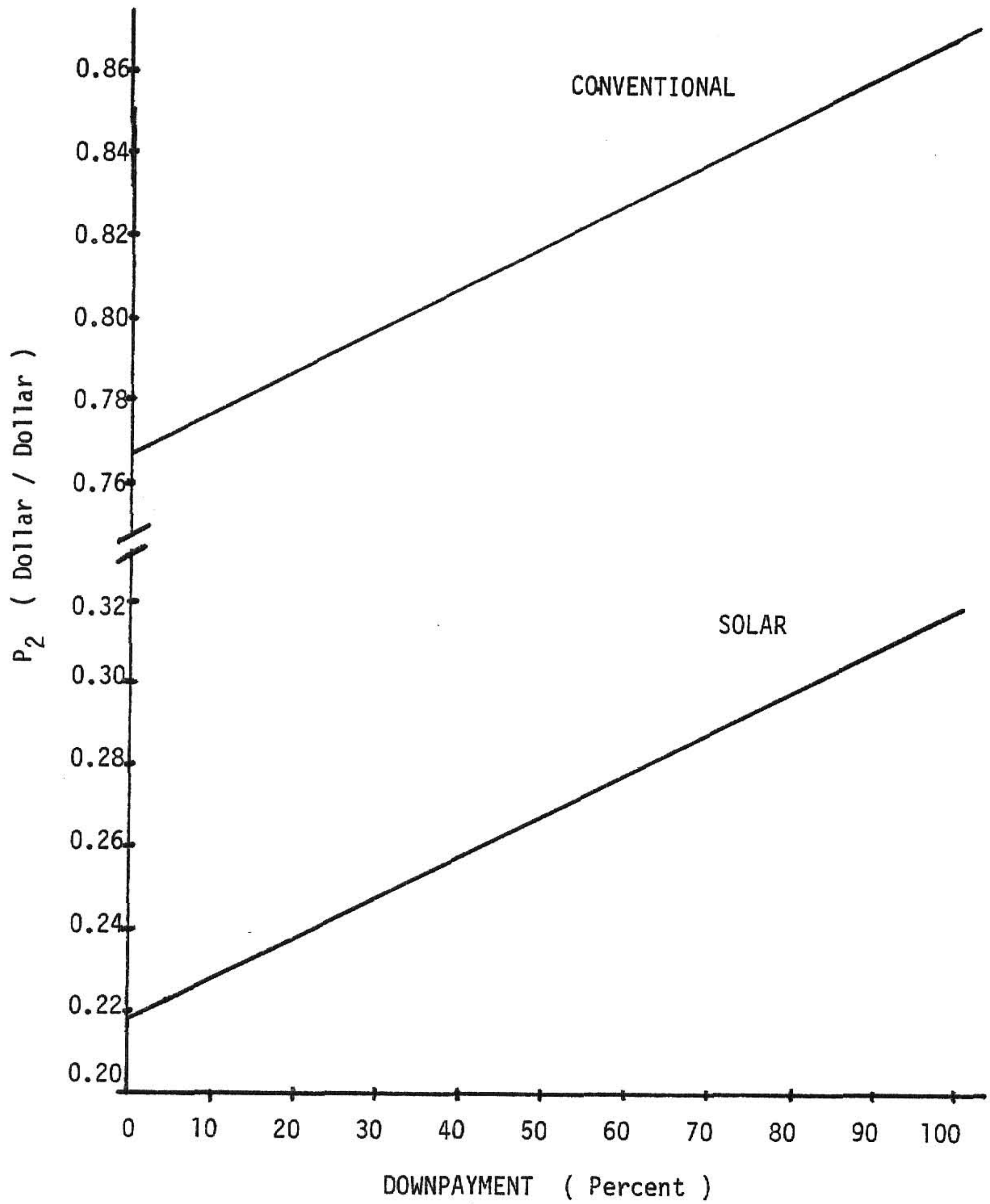


FIGURE 27

EFFECT ON DOWNPAYMENT
ON LIFE CYCLE COST

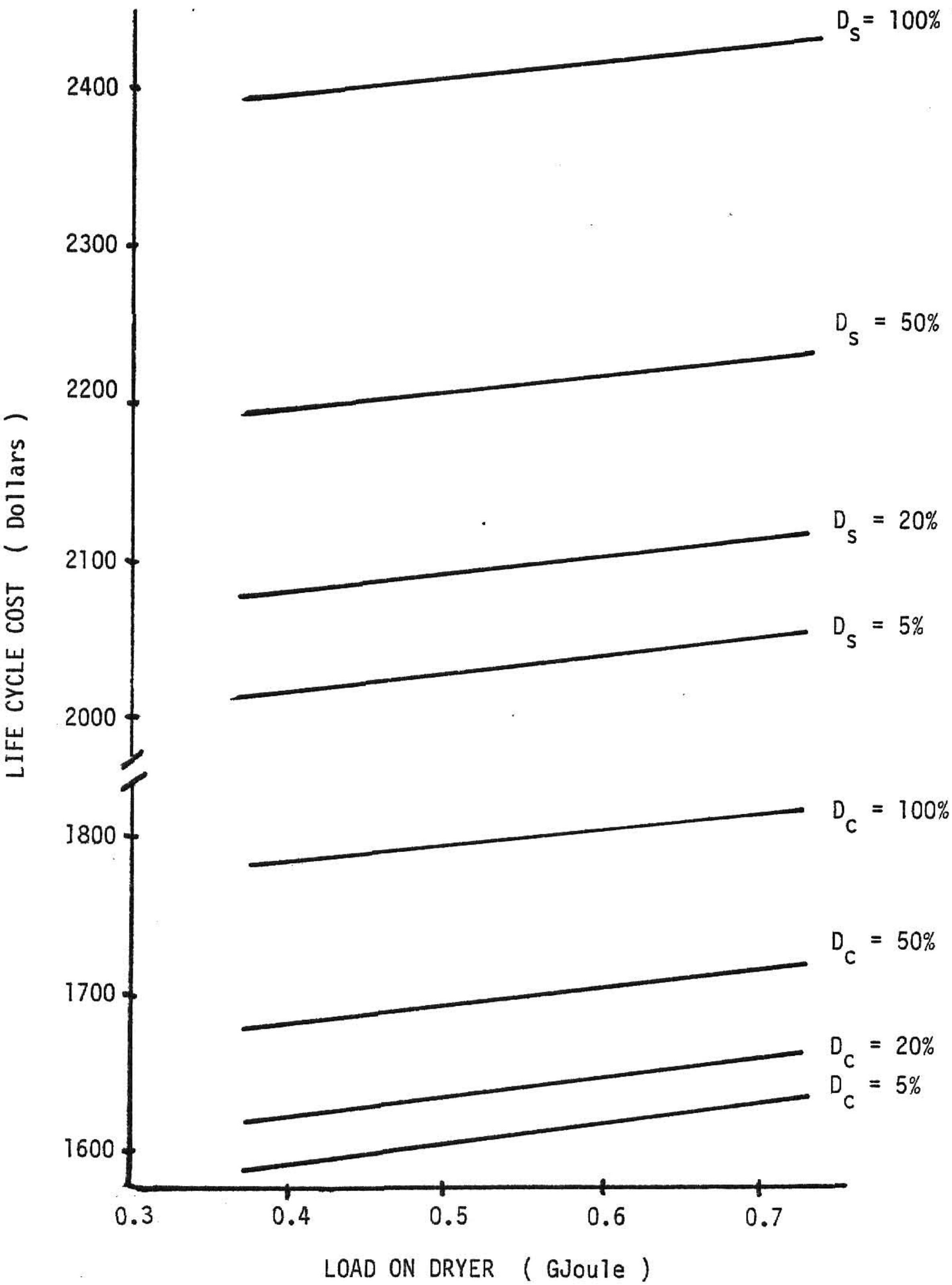


FIGURE 28

EFFECT OF DEPRECIATION ON LIFE CYCLE COST

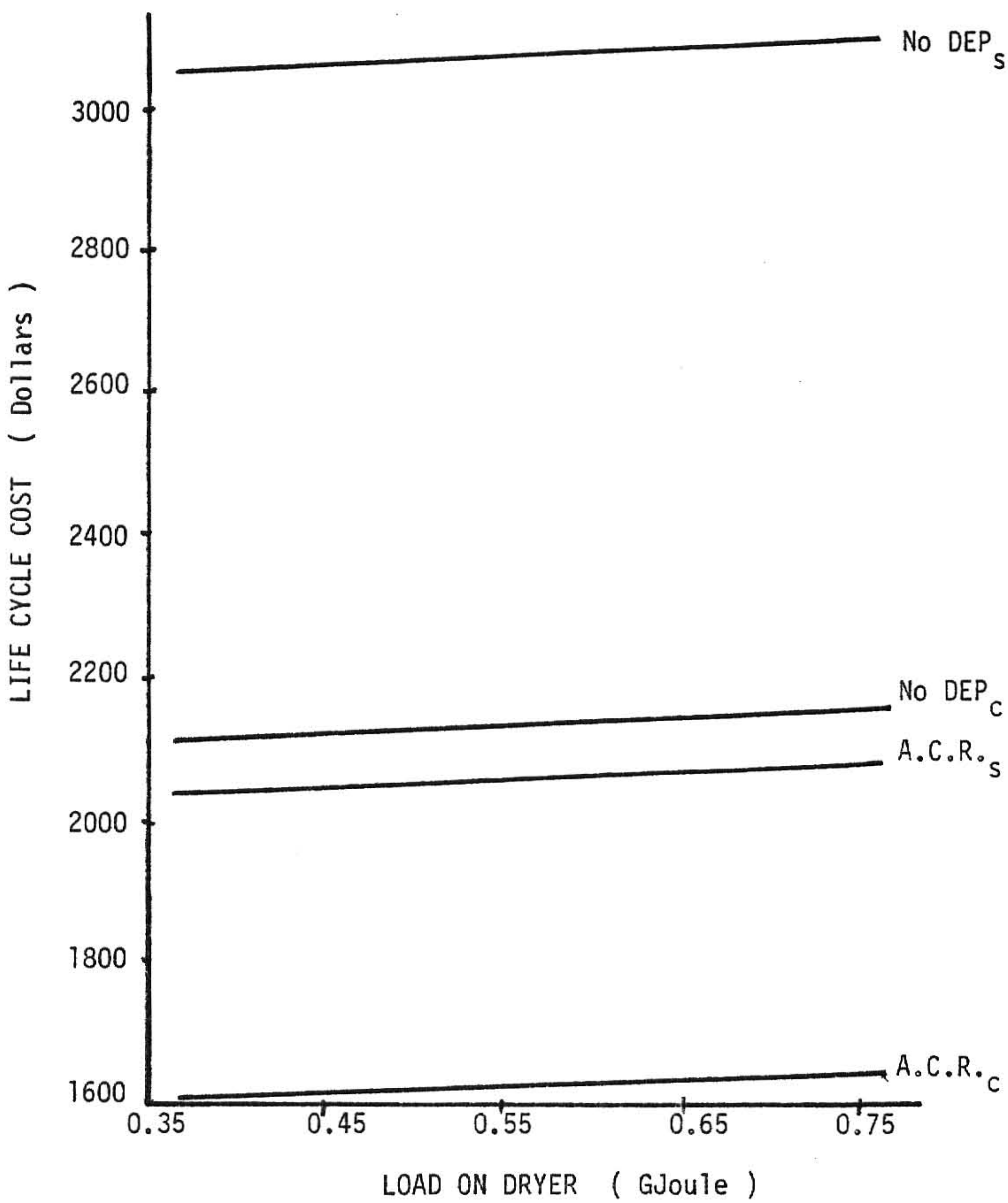
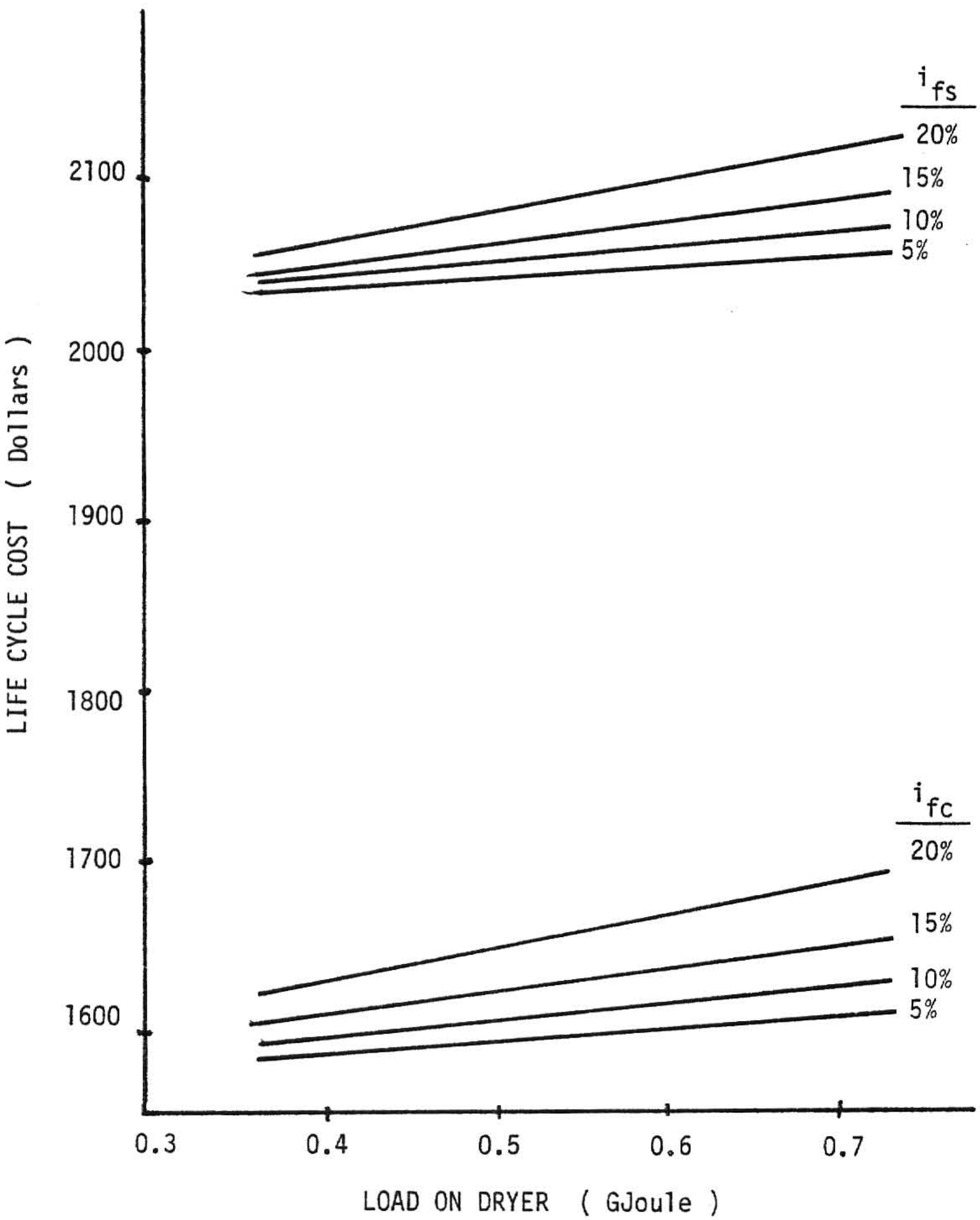


FIGURE 29

EFFECT OF FUEL INFLATION RATE ON LIFE CYCLE COST



to illustrate the basic effect of N_e on the life cycle cost. The life cycle cost increased both in value and in rate of increase with the change in load, when the length of the economic analysis increased as shown in Figure 30. This makes sense, since the present day (life cycle) cost of operating the system would increase if operated for a longer period of time. However, the annual cost of the system decreases, as the system lifetime increases as shown in Figure 31.

MARKET DISCOUNT RATE: Lower investment rates of return cause both P_1 and P_2 to increase so that the life cycle cost increases, and the rate of change in life cycle cost, increase with the load as shown in Figure 32.

FIGURE 30

EFFECT OF ECONOMIC ANALYSIS TERM
ON LIFE CYCLE COST

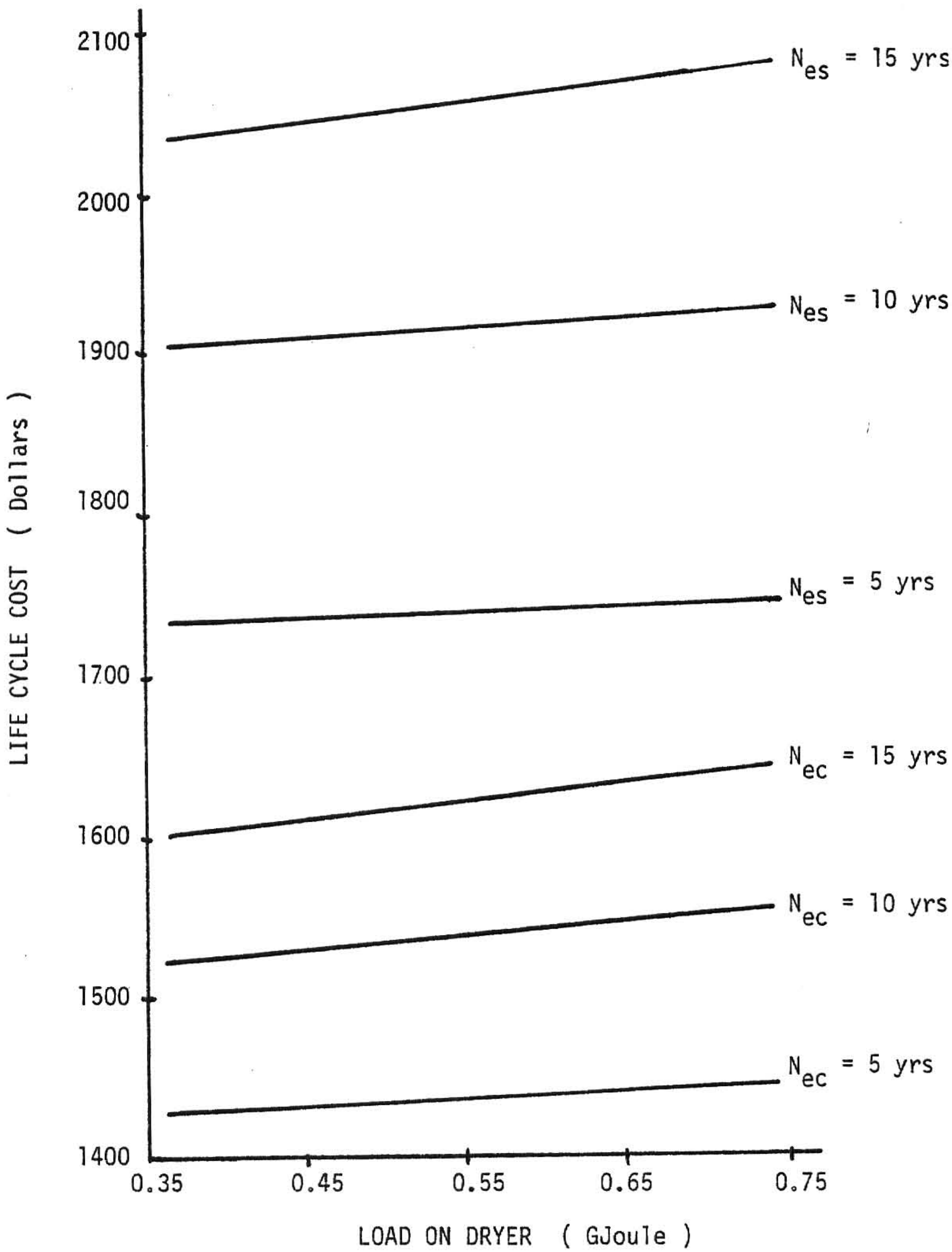


FIGURE 31

ANNUAL COST AFFECTED BY ECONOMIC ANALYSIS TERM

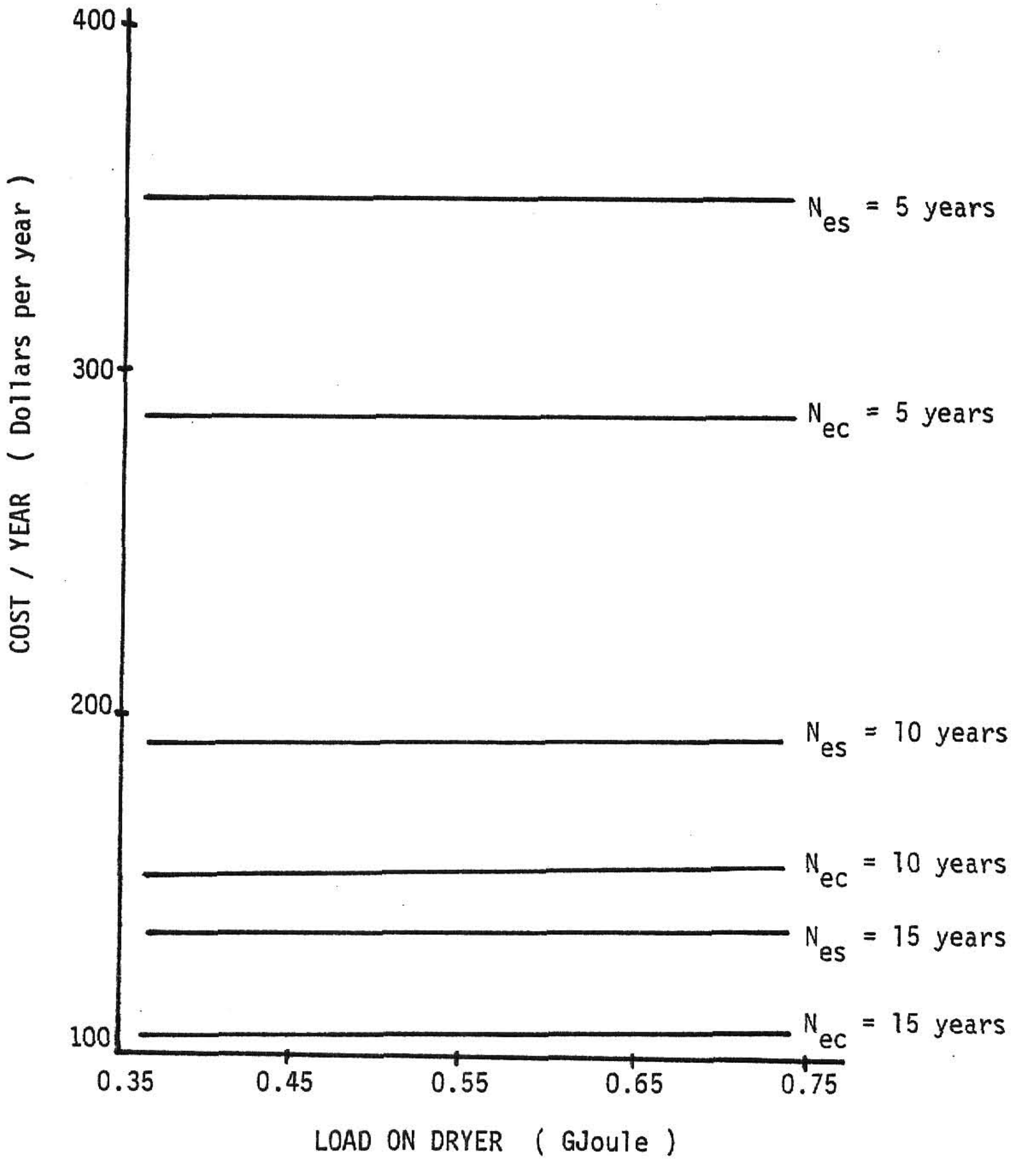
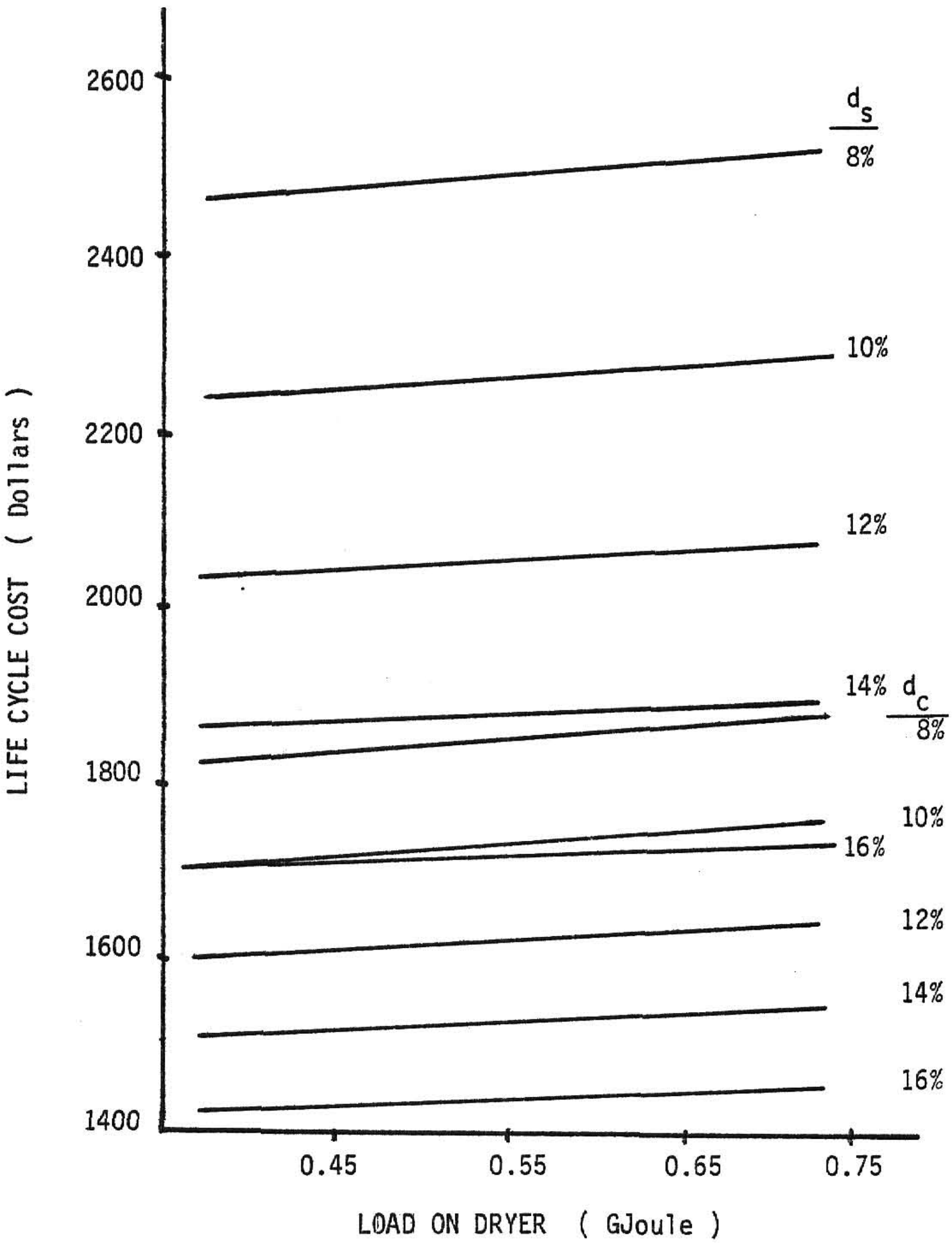


FIGURE 32

EFFECT OF MARKET DISCOUNT RATE
ON LIFE CYCLE COST



CHAPTER VII

SUMMARY AND CONCLUSIONS

The computer model developed incorporates:

1. Hourly solar radiation and meteorological data from the Typical Meteorological Year computer tape.
2. A computer model developed previously by other graduate students which predicts the hourly performance of a solar energy powered sorption dehumidification system.
3. An economic analysis for the operation of the system for several days.

Since the performance of the system depends on the location and time of year, and the economic analysis depends on the particular use of the system, a survey of several potential applications is given.

The Economic Analysis computer model predicts that favorable economic conditions for the Solar Energy Powered Sorption Dehumidification System include a healthy federal tax credit, low market interest rate, low mortgage downpayment, depreciation with the accelerated cost recovery method, longer term for the economic analysis and a high market discount rate.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

There are enough recommendations for future research to keep many a graduate student busy. Among them are:

1. Incorporate a desiccant storage system as an option into the present economic analysis model, as described on page 42.
2. Study the effect of various dehumidifier operating conditions on the life cycle cost of the solar energy system, i.e. air mass flow rate, solar collector size, etc.
3. Search out the potentially feasible life cycle costs for different applications in different locations with typical economic analysis parameters.
4. Develop an accurate method to predict the amount of moisture removed from a commodity in the dryer, as described on page 38.
5. Build a pilot plant combining the dehumidification and drying systems to obtain experimental verification of the model.
6. Develop a design computer model to size the Solar Energy Powered Sorption Dehumidification System.

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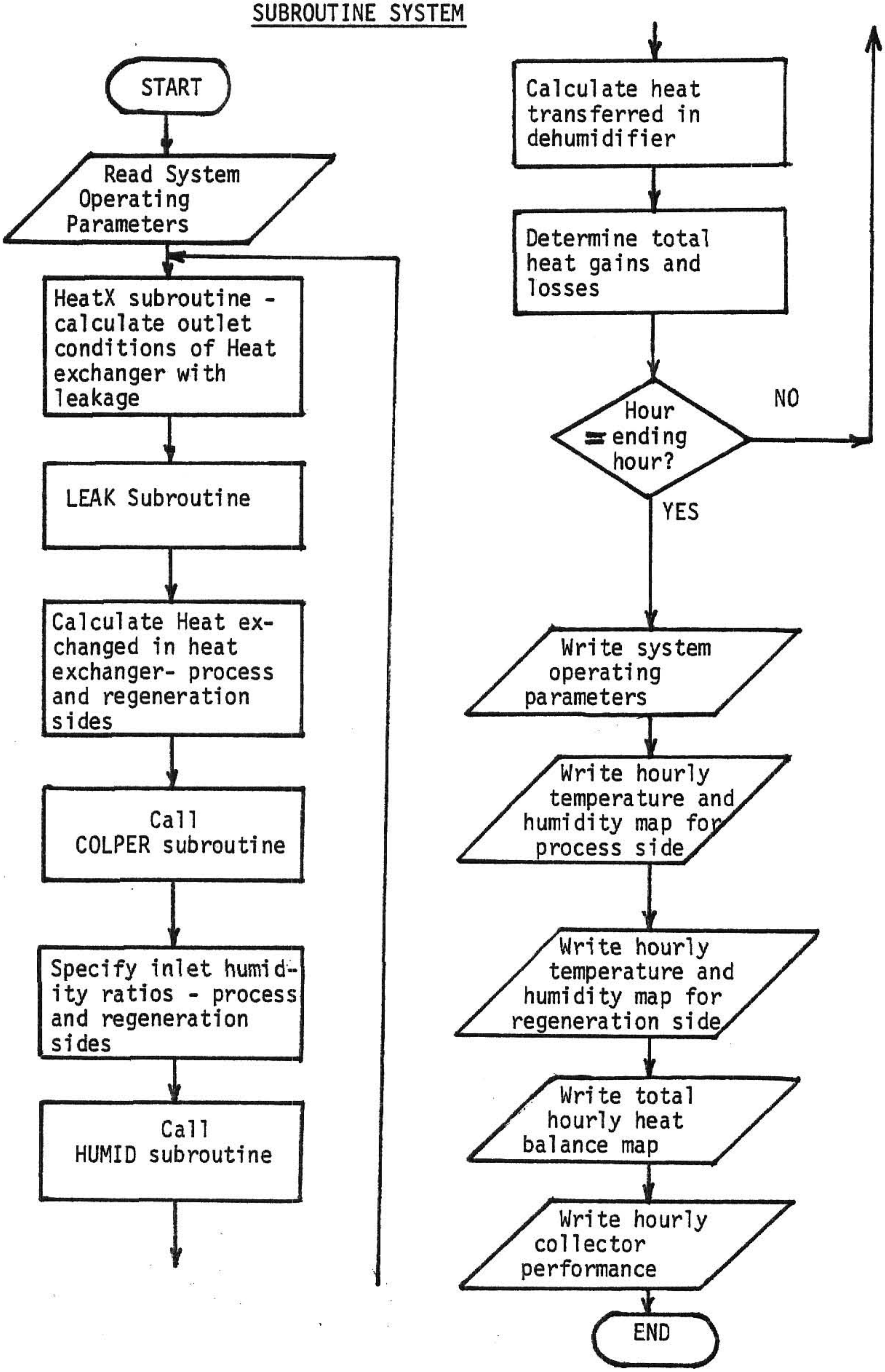
APPENDIX A

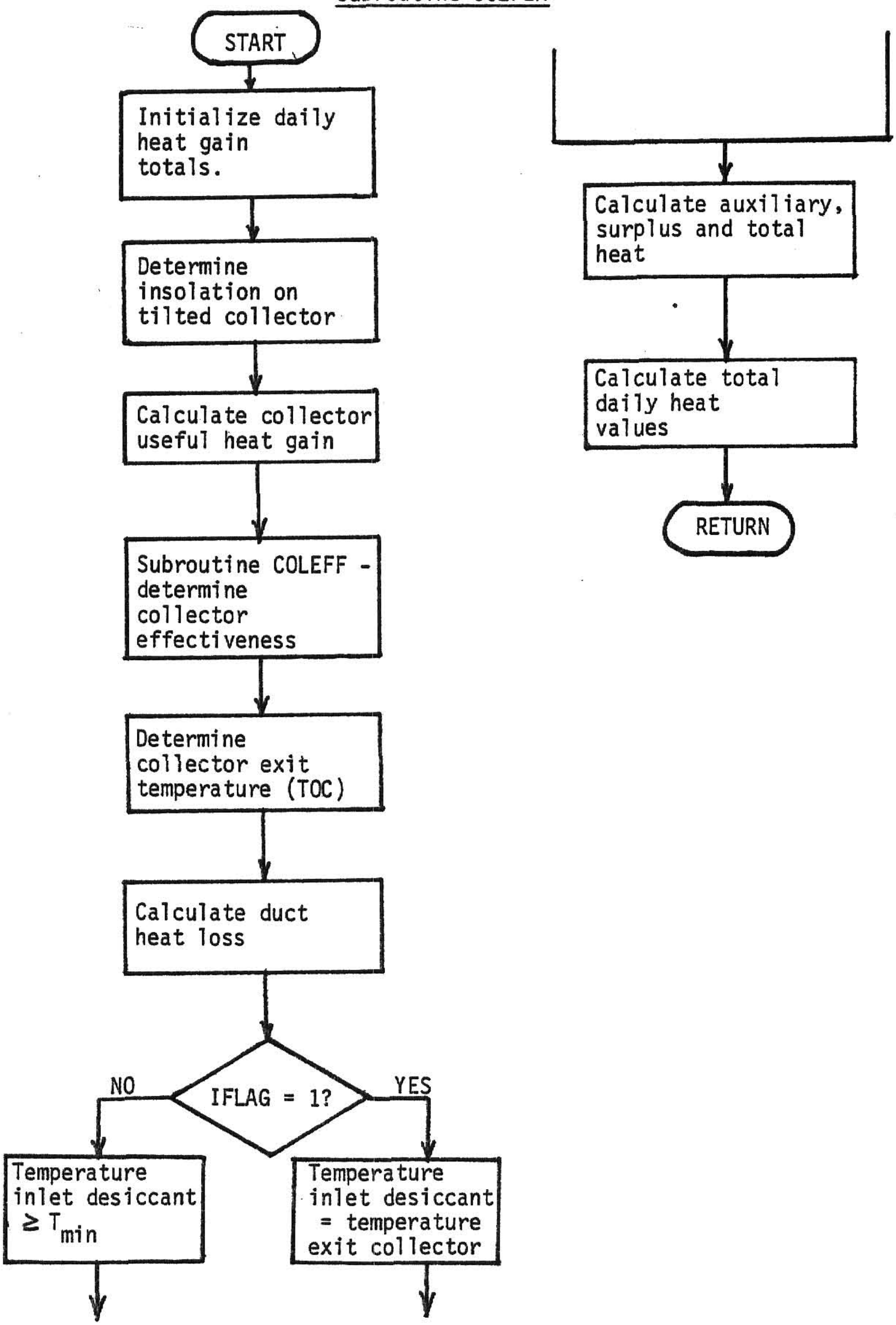
SUBROUTINE SYSTEM FLOWCHART

This appendix contains the flowchart for the SYSTEM subroutine, and supporting subroutines COLPER, HUMID, EGV and ALFAV. This is the modified version of the computer model developed by Singer and enhanced by Ananth.

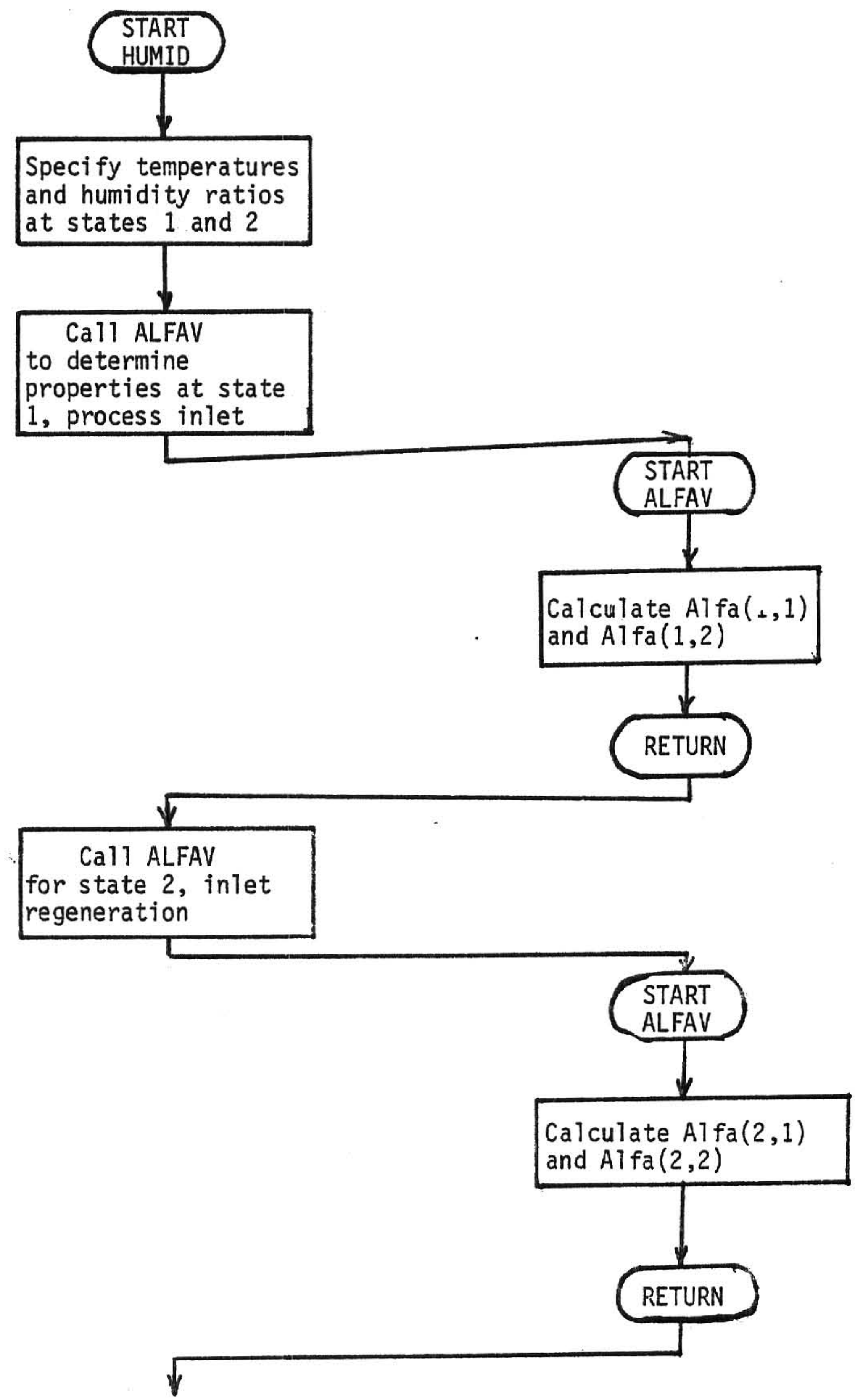
SUBROUTINE SYSTEM

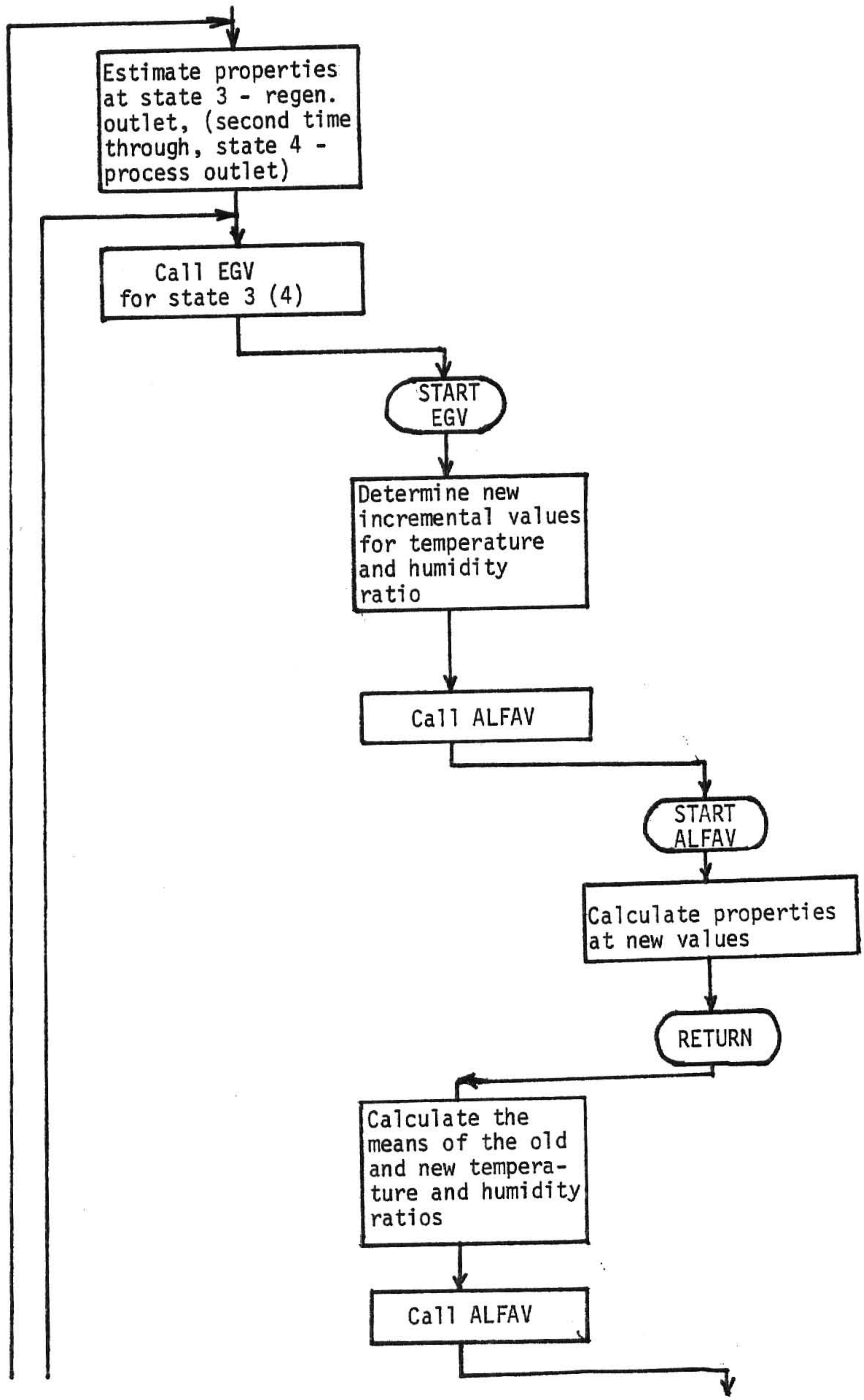


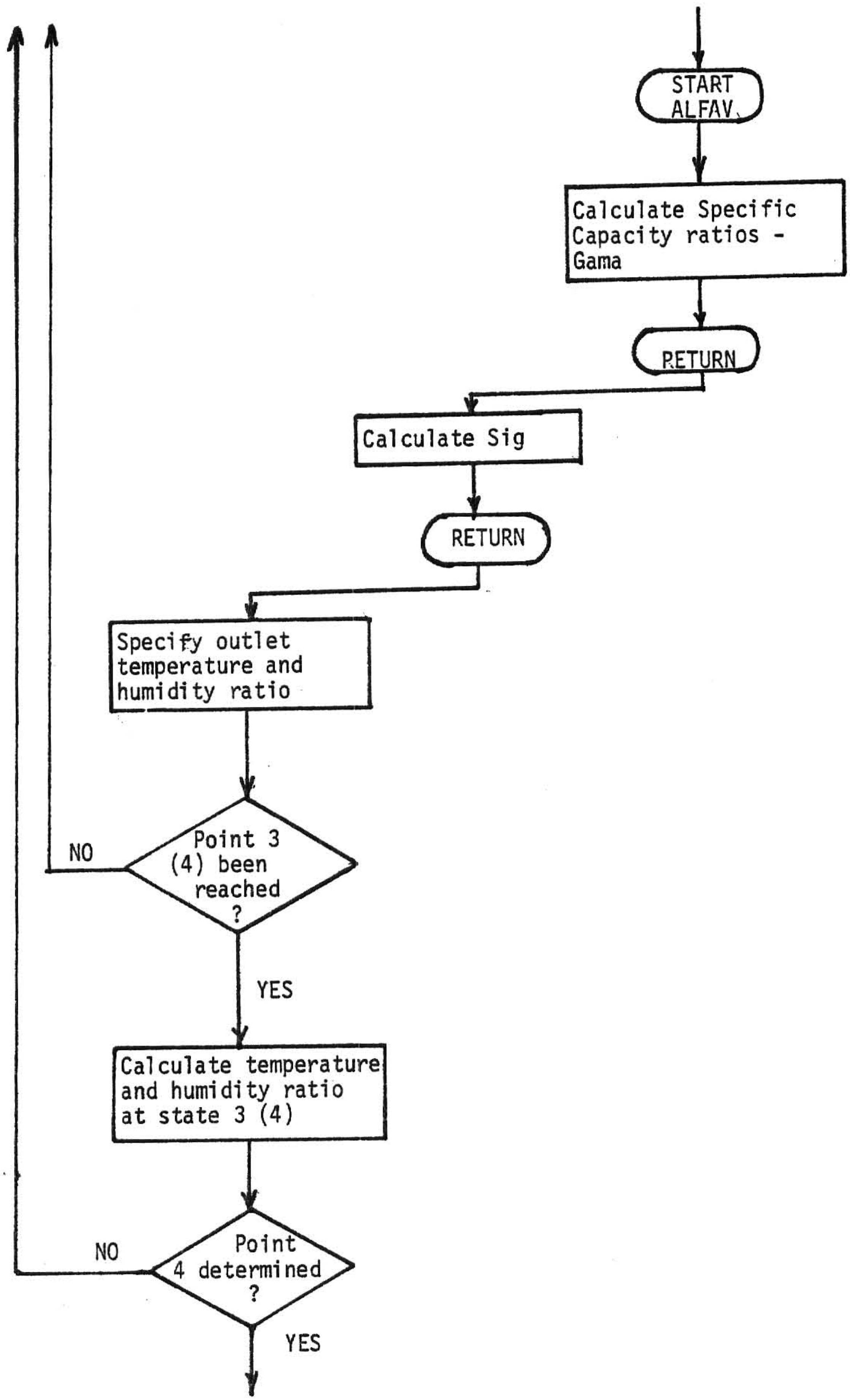
Subroutine COLPER

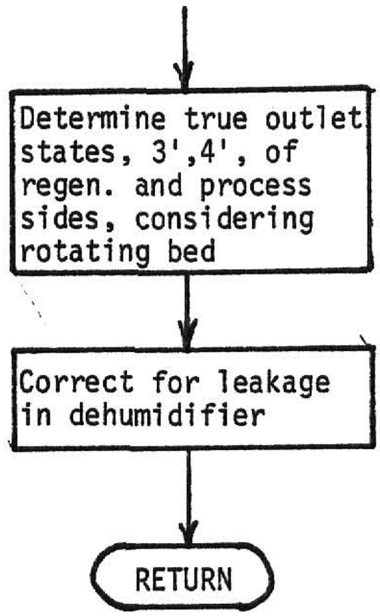


Subroutines HUMID, EGV and ALFAV




Estimate properties at state 3 - regen. outlet, (second time through, state 4 - process outlet)
Call EGV for state 3 (4)
START EGV
Determine new incremental values for temperature and humidity ratio
Call ALFAV
START ALFAV
Calculate properties at new values
RETURN
Calculate the means of the old and new temperature and humidity ratios
Call ALFAV

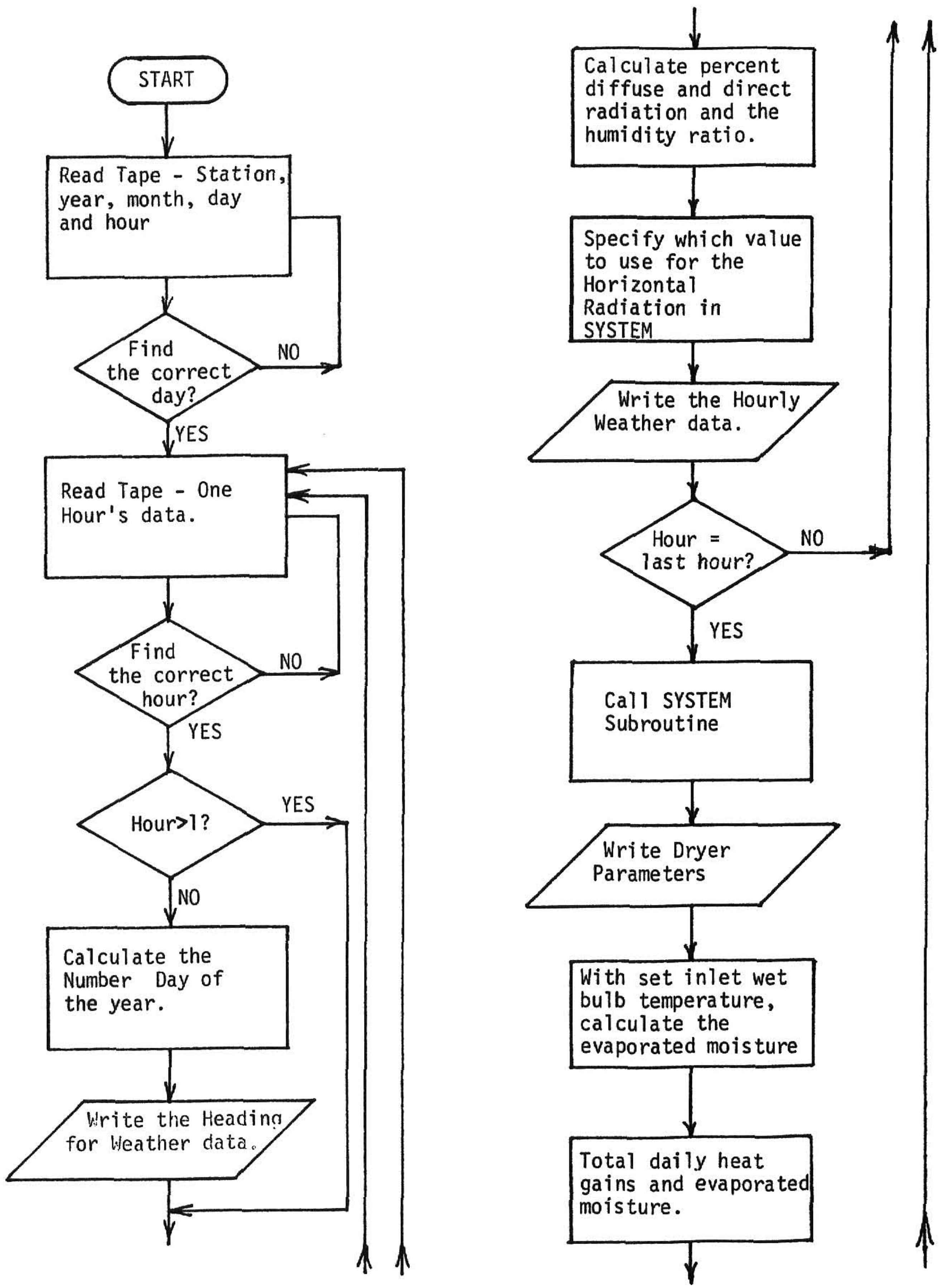

START
ALFAV
Calculate Specific
Capacity ratios -
Gama
RETURN
Calculate Sig
RETURN
Specify outlet
temperature and
humidity ratio
Point 3
(4) been
reached
?
NO
YES
Calculate temperature
and humidity ratio
at state 3 (4)
Point
4 determined
?
NO
YES

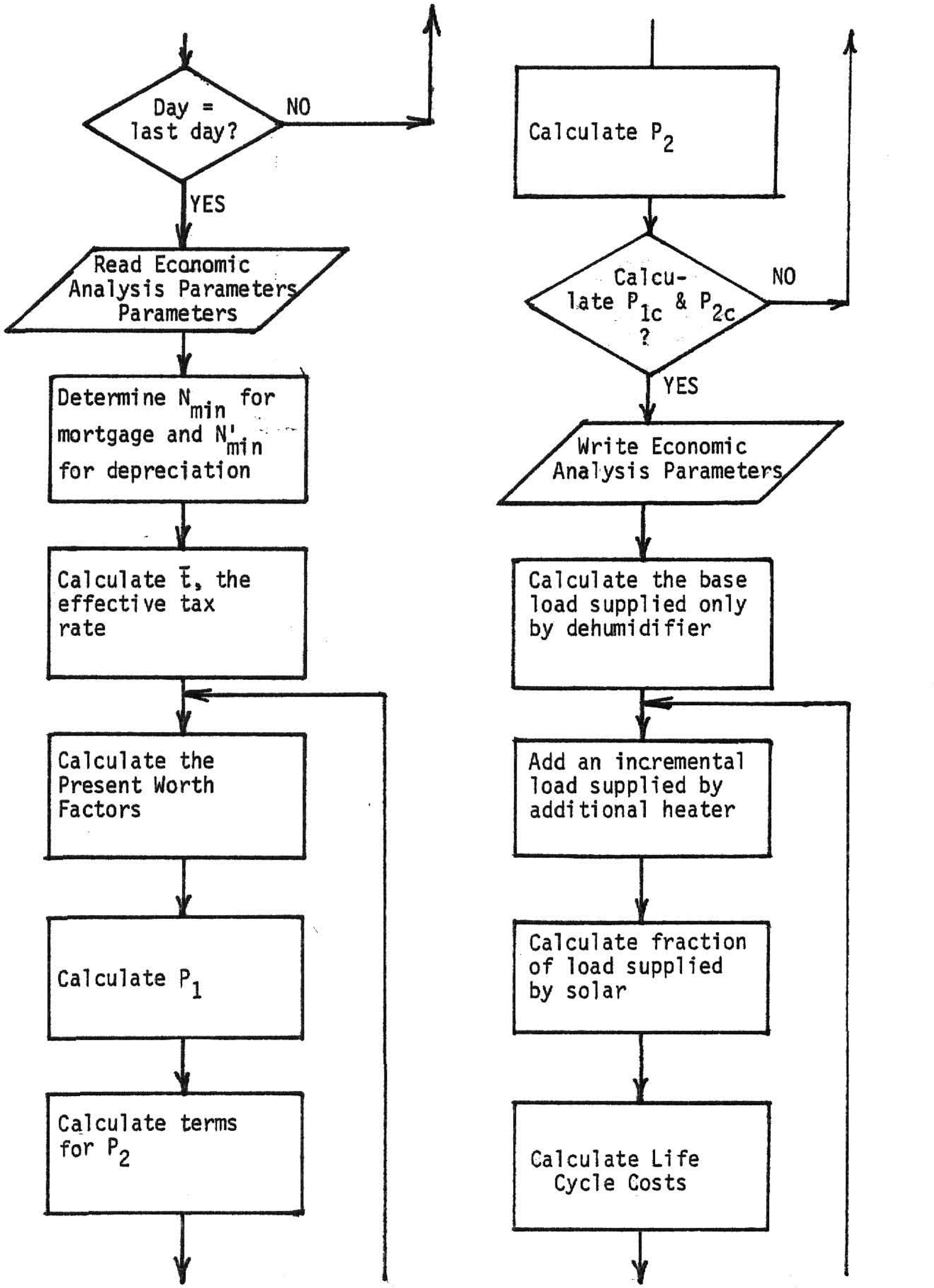

Determine true outlet states, 3',4', of regen. and process sides, considering rotating bed
Correct for leakage in dehumidifier
RETURN

APPENDIX B

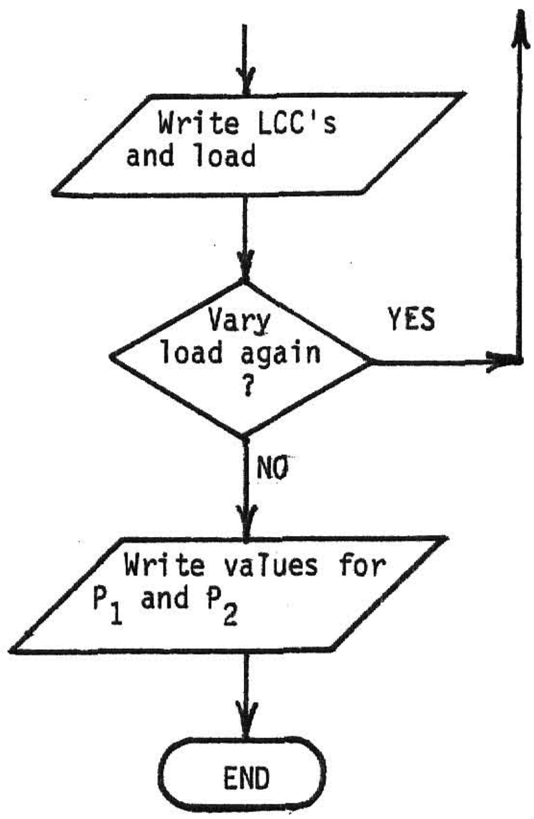
ENTIRE COMPUTER MODEL FLOWCHART

The flowchart listed here is the integrated version of the Weather Data and Economic Analysis computer models, which calls subroutine SYSTEM. To conserve space, two lines are placed side by side on each page of this appendix.


START
Read Tape - Station, year, month, day and hour
Find the correct day?
NO
YES
Read Tape - One Hour's data.
Find the correct hour?
NO
YES
Hour>1?
YES
NO
Calculate the Number Day of the year.
Write the Heading for Weather data.
Calculate percent diffuse and direct radiation and the humidity ratio.
Specify which value to use for the Horizontal Radiation in SYSTEM
Write the Hourly Weather data.
Hour = last hour?
NO
YES
Call SYSTEM Subroutine
Write Dryer Parameters
With set inlet wet bulb temperature, calculate the evaporated moisture
Total daily heat gains and evaporated moisture.



Day = last day?
NO
YES
Read Economic Analysis Parameters Parameters
Determine N_{min} for mortgage and N'_{min} for depreciation
Calculate $\bar{t}$, the effective tax rate
Calculate the Present Worth Factors
Calculate P_1
Calculate terms for P_2
Calculate P_2
Calculate P_{1c} & P_{2c} ?
NO
YES
Write Economic Analysis Parameters
Calculate the base load supplied only by dehumidifier
Add an incremental load supplied by additional heater
Calculate fraction of load supplied by solar
Calculate Life Cycle Costs


Write LCC's and load
Vary load again ?
YES
NO
Write values for P_1 and P_2
END

APPENDIX C

WEATHER DATA COMPUTER PROGRAM AND TYPICAL RESULTS

This appendix lists the program which reads the TMY weather data tape and calculates the ambient humidity ratio for Omaha, Nebraska during the month of October. The arrays allow storage for thirty days with 24 hours per day. The JCL required for execution in Fortran is given. Two days during that time period of typical output are listed.

```
/*ROUTE  PRINT VM___
/*TAPE9
// EXEC FORTQCLG,PARM=NOMAP
//FORT.SYSIN DD *
C          NOMENCLATURE FOR THE WEATHER PORTION OF PRCGRAM FOLLOWS
C        CLK=CLOCK HOUR UNDER CONSIDERATION
C        DAY=DAY UNDER CCNSIDERATICN
C        DAYB=BEGINNING DESIRED DAY OF STUDY
C        DAYP=PRCGRAM AID TO CONTROL READING THE TAPE.  AFTER ONE DAY IS
C          READ FOR THE DESIRED NUMBER OF HOURS, THE NEXT READING IS FOR
C          THE NEXT CAY.
C        DBT=DRY BULB TEMPERATURE
C        DEND=DESIRED ENDING DAY OF STUDY
C        DIFR=DIFFUSE RACIATION
C        DIRR=DIRECT RADIATION
C        DPT=DEW POINT TEMPERATURE
C        ENCR=ENGINEERING CORRECTEC RADIATION
C        EXTR=EXTRATERRESTRIAL RADIATION
C        HRB=DESIRED BEGINNING HOUR OF STUDY
C        HREND=DESIRED ENDING HOUR OF STUDY
C        I=DAY UNDER CALCULATION
C        IDATE=NUMBER DAY OF THE YEAR
C        IHR=SOLAR HOUR UNDER CONSIDERATION
C        ILEAP=PROGRAM AID TO DETERMINE THE NUMBER CAY OF THE YEAR
C        J=HOUR UNDER CALCULATION
C        KT=HOURLY CLEARNESS INDEX
C        MEND=DESIRED ENDING MONTH OF STUDY
C        MINS=MINUTES OF SUNSHINE
C        MO=MONTH UNDER CONSIDERATION
C        MOB=DESIRED BEGINNING MONTH OF  STUDY
C        MOTEST=PROGRAM AID TO DETERMINE THE NUMBER DAY OF THE YEAR
C        ND=NUMBER OF DAYS INCLUDED IN STUDY
C        NDAY=NUMBER CAY OF THE YEAR
C        NH=NUMBER OF HOURS INCLUDED IN STUDY
C        OBSR=OBSERVEC RADIATION
C        PERB=PERCENTAGE OF BEAM RADIATION BASED ON EXTRATERRESTRIAL
C          RADIATION
```

```
C        PERD=PERCENTAGE OF DIFFUSE RADIATION BASED ON EXTRATERRESTRIAL
C          RADIATION
C        PSEA=ATMOSPHERIC PRESSURE AT SEA LEVEL
C        PSTN=ATMOSPHERIC PRESSURE AT THE STATION
C        SKY=SKY CONDITIONS, TYPE AND EXTENT OF CLOUD COVER
C        SNOW=INDICATOR OF SNOW GROUND COVERAGE
C        STDYR=STANDARD YEAR RADIATION
C        STN=STATION NUMBER UNDER CONSIDERATION
C        WEAT=WEATHER CONDITIONS, SNOW, RAIN, MONSOON, ETC.
C        WDIR=WIND DIRECTION
C        WVEL=WIND VELOCITY
C        YR=YEAR UNDER CONSIDERATION
C          MAIN PROGRAM STARTS HERE
       DIMENSION DBT(30,24),DPT(30,24),IHR(30,24),H(30,24),IDATE(30),
      XPERB(30,24),PERD(30,24),REFLEC(30,24),WDIR(30,24),WVEL(30,24)
      X,WAM(30,24),PSTN(30,24),PSEA(30,24),OBSR(30,24),EXTR(30,24),
      XSTDYR(30,24),BETA(30,24),BETAF(30,24),PWV(30,24),ENCR(30,24)
      X,PSTNC(30,24)
C          THE FOLLOWING 4 STATEMENTS DECLARE VARIABLES FOR THE WEATHER
C          DATA PORTION OF THE PROGRAM
       INTEGER DAYB,DEND,HRB,HREND,DAYF
       INTEGER STN,YR,DAY,CLK(30,24),DIRR(30,24),WDIR,WVEL,DIFR(30,24),
      X WEAT(30,24),            SKY(30,24),SNOW(30,24),MINS(30,24)
       REAL KT(30,24)
   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(6I5)
```

```
    1 FORMAT(I5,I2,I2,I2,I2)                                          WEA00760
    2 FORMAT(I5,I2,I2,I2,I2,2X,I4,F4.0,1X,I4,I5,10X,F5.0,F5.0,        WEA00770
     XF5.0,10X,I2,6X,I5,4X,I8,2F5.2,2F4.1,I3,I4,4X,I1)                WEA00780
C        SPECIFY THE DAYS, MONTH AND HOURS DESIRED BY USER            WEA00790
      READ (5,20) MOB,DAYB,MEND,DEND,HRB,HREND                        WEA00800
      ND=DEND-DAYB+1                                                  WEA00810
      NH=(HREND-HRB)+1                                                WEA00820
      DAYP=DAYB                                                       WEA00830
      DAYF=DAYB-1                                                     WEA00840
      IZ=24                                                           WEA00850
C        TAPE IS READ BEGINNING JAN 1 UNTIL THE DESIRED DATES ARE FOUND.WEA00860
   50 READ (3,1)STN,YR,MO,DAY,MHR                                     WEA00870
      IF(MO.LT.MOB) GO TO 50                                          WEA00880
      IF(DAY.LT.DAYF) GO TO 50                                        WEA00890
      IF(MHR.LT.IZ) GO TO 50                                          WEA00900
      DO 80 I=1,ND                                                    WEA00910
C        THE SET OF DATA IS READ FOR EACH HOUR AT ONE WHOOSH, HOUR    WEA00920
C        CONTROL IS REQUIRED.                                         WEA00930
      DO 81 J=1,NH                                                    WEA00940
   40 READ (3,2)STN,YR,MO,DAY,IHR(I,J),CLK(I,J),EXTR(I,J),DIRR(I,J),DIFRWEA00950
     X(I,J),OBSR(I,J),ENCR(I,J),STDYR(I,J),MINS(I,J),SKY(I,J),WEAT(I,J),WEA00960
     XPSEA(I,J),PSTN(I,J),DBT(I,J),DPT(I,J),WDIR(I,J),WVEL(I,J),      WEA00970
     XSNOW(I,J)                                                       WEA00980
   70 IF (IHR(I,J).LT.HRB) GO TO 40                                   WEA00990
      IF (DAY.LT.DAYP) GO TO 40                                       WEA01000
      IF (J.GT.1) GO TO 61                                            WEA01010
C        CALCULATE THE NUMBER DAY OF THE YEAR, ALLOWING FOR LEAP YEARS WEA01020
C        ILEAP AND MOTEST ARE JUST TO AID IN THE PROGRAM MECHANISM    WEA01030
      ILEAP=YR-48                                                     WEA01040
      IF (ILEAP/4*4.NE.ILEAP) GO TO 913                               WEA01050
      MOTEST=MO-2                                                     WEA01060
      IF (MOTEST) 913,913,930                                         WEA01070
  930 NDAY=DAY+1                                                      WEA01080
      GO TO 914                                                       WEA01090
  913 NDAY=DAY                                                        WEA01100
  914 GO TO (901,902,903,904,905,906,907,908,909,910,911,912),MO      WEA01110
  901 IDATE(I)=NDAY                                                   WEA01120
      GO TO 960                                                       WEA01130
```

```
  902 IDATE(I)=NDAY+31                                                  WEA01140
      GO TO 960                                                         WEA01150
  903 IDATE(I)=NDAY+59                                                  WEA01160
      GO TO 960                                                         WEA01170
  904 IDATE(I)=NDAY+90                                                  WEA01180
      GO TO 960                                                         WEA01190
  905 IDATE(I)=NDAY+120                                                 WEA01200
      GO TO 960                                                         WEA01210
  906 IDATE(I)=NDAY+151                                                 WEA01220
      GO TO 960                                                         WEA01230
  907 IDATE(I)=NDAY+181                                                 WEA01240
      GO TO 960                                                         WEA01250
  908 IDATE(I)=NDAY+212                                                 WEA01260
      GO TO 960                                                         WEA01270
  909 IDATE(I)=NDAY+243                                                 WEA01280
      GO TO 960                                                         WEA01290
  910 IDATE(I)=NDAY+273                                                 WEA01300
      GO TO 960                                                         WEA01310
  911 IDATE(I)=NDAY+304                                                 WEA01320
      GO TO 960                                                         WEA01330
  912 IDATE(I)=NDAY+334                                                 WEA01340
  960 CONTINUE                                                          WEA01350
      WRITE (6,10)                                                      WEA01360
      WRITE (6,11) MO,DAY,YR,STN                                        WEA01370
      WRITE (6,12) IDATE(I)                                             WEA01380
      WRITE (6,13)                                                      WEA01390
      WRITE (6,14)                                                      WEA01400
      WRITE (6,17)                                                      WEA01410
   61 CONTINUE                                                          WEA01420
C       THE TAPE STORES A '9' IF THE DATA WAS NOT RECORDED OR IF THE    WEA01430
C       VALUE IS ZERO. THE FOLLOWING 'IF' STATEMENTS MAKES PRETTY OUTPUTWEA01440
      IF (EXTR(I,J).EQ.9999) EXTR(I,J)=0                                WEA01450
      IF (DIRR(I,J).EQ.99999) DIRR(I,J)=0                               WEA01460
      IF (DIFR(I,J).EQ.99999) DIFR(I,J)=0                               WEA01470
      IF (OBSR(I,J).EQ.99999) OBSR(I,J)=0                               WEA01480
      IF (ENCR(I,J).EQ.99999) ENCR(I,J)=0                               WEA01490
      IF (STDYR(I,J).EQ.99999) STDYR(I,J)=0                             WEA01500
      IF (MINS(I,J).EQ.99) MINS(I,J)=0                                  WEA01510
```

```
      IF (SKY(I,J).EQ.99999) SKY(I,J)=0                                 WEA01520
      IF (WEAT(I,J).EQ.99999999) WEAT(I,J)=0                            WEA01530
      IF (SNOW(I,J).EQ.1) REFLEC(I,J)=0.7                               WEA01540
      IF (SNOW(I,J).EQ.0) REFLEC(I,J)=0.2                               WEA01550
      IF (SNOW(I,J).NE.9) GO TC 62                                      WEA01560
      SNOW(I,J)=0                                                       WEA01570
      REFLEC(I,J)=0.0                                                   WEA01580
   62 CONTINUE                                                          WEA01590
      IF (EXTR(I,J).EQ.0) GO TO 44                                      WEA01600
      KT(I,J)=ENCR(I,J)/EXTR(I,J)                                       WEA01610
      IF (KT(I,J).LE.0.35)  PERD(I,J)=1.0-0.249*KT(I,J)                 WEA01620
      IF (KT(I,J).GE.0.75)  PERD(I,J)=0.117                             WEA01630
      IF ((KT(I,J).GT.0.35).AND.(KT(I,J).LT.0.75)) PERD(I,J)=1.557-1.84*WEA01640
     XKT(I,J)                                                           WEA01650
      PERB(I,J)=1.C-PERD(I,J)                                           WEA01660
      GO TO 45                                                          WEA01670
   44 PERB(I,J)=0.0                                                     WEA01680
      PERD(I,J)=0.0                                                     WEA01690
   45 CONTINUE                                                          WEA01700
C        CALCULATE AMBIENT HUMIDITY FROM DRY BULB AND STATICN           WEA01710
C        ATMOSPHERIC PRESSURE DATA USING ASHRAE METHOD                  WEA01720
      BETA(I,J)  =374.12-DBT(I,J)                                       WEA01730
      BETAF(I,J)=BETA(I,J)/100.                                         WEA01740
      PWV(I,J)=218.167*10**(-BETA(I,J)/(DPT(I,J)+273.15)*(3.2437814+.586WEA01750
     X826*BETAF(I,J)+0.011702379*BETAF(I,J)**3)/(1.+.2187846*BETAF(I,J))WEA01760
     X)                                                                 WEA01770
      PSTNC(I,J)=PSTN(I,J)*.0098692                                     WEA01780
      WAM(I,J)=(.62198*PWV(I,J))/(PSTNC(I,J)-PWV(I,J))                  WEA01790
      WRITE (6,15) IHR(I,J),CLK(I,J),EXTR(I,J),ENCR(I,J),PERB(I,J),PERD WEA01800
     X(I,J),SKY(I,J),WEAT(I,J),PSEA(I,J),PSTN(I,J),CBT(I,J),DPT(I,J),   WEA01810
     XWAM(I,J),WDIR(I,J),WVEL(I,J),SNOW(I,J)                            WEA01820
   81 CONTINUE                                                          WEA01830
C        DAYP IS JUST A CONTROL FOR  READING THE TAPE.  AFTER CNE DAY ISWEA01840
C        READ FOR THE DESIRED NUMBER OF HOURS, THE NEXT READING IS FOR  WEA01850
C        THE NEXT CAY.                                                  WEA01860
      DAYP=DAY+1                                                        WEA01870
   80 CONTINUE                                                          WEA01880
      STOP                                                              WEA01890
```

```
      END                                                                WEA01900
//GO.FT03F001  DD DSN=TMY,UNIT=TAPE1600,VOL=SER=9TMY03,LABEL=(26,,,IN),   WEA01910
// DCB=(RECFM=FB,LRECL=132,BLKSIZE=3168)                                  WEA01920
//GO.SYSIN DD *                                                           WEA01930
   10     1    10    3C     7    17                                       WEA01940
```

***** TMY WEATHER DATA FCR CMAHA, NEBRASKA *****

10/ 5/68

STATION NC.94918

NUMBER DAY OF THE YEAR =279

TIME			RADIATION			SKY		PRESSURE		TEMPERATURE			WIND		SNOW
SOLAR	CLOCK	EXT-T	ENG-C	BEAM	DIFFUSE	COND	WEATHER	SEA-L	STN	D.B.	DEW	HUMIDITY	DIR	VEL	COVER
700	712	263.	8.	0.0076	0.9924	0	0	101.35	97.81	10.9	7.0	0.00732	160	57	0
800	812	1168.	56.	0.0119	0.9881	0	0	101.37	97.82	10.2	8.0	0.00741	160	51	0
900	912	2005.	169.	0.0210	0.9790	4600	1000010	101.38	97.83	9.4	8.9	0.00745	160	46	0
1000	1012	2689.	226.	0.0209	0.9791	0	0	101.34	97.80	9.8	9.3	0.00766	163	44	0
1100	1112	3172.	246.	0.0193	0.9807	0	0	101.31	97.76	10.2	9.6	C.00785	167	43	0
1200	1212	3423.	230.	0.0167	0.9833	6000	1000010	101.27	97.73	10.6	10.0	0.00807	170	41	0
1300	1312	3423.	199.	0.0145	0.9855	0	0	101.20	97.66	10.4	9.8	0.00796	170	46	0
1400	1412	3172.	187.	0.0147	0.9853	0	0	101.12	97.60	10.2	9.6	C.00786	170	52	0
1500	1512	2689.	143.	0.0132	0.9868	6000	1000010	101.05	97.53	10.0	9.4	C.00776	170	57	0
1600	1612	2005.	112.	0.0139	0.9861	0	0	101.04	97.52	9.8	9.2	0.00766	167	48	0
1700	1712	1168.	30.	0.0064	0.9936	0	0	101.02	97.50	9.6	9.1	0.00758	163	40	0

***** TMY WEATHER DATA FOR OMAHA, NEBRASKA *****

10/ 6/68 STATION NO.94918

NUMBER DAY OF THE YEAR =280

TIME		RADIATION				SKY		PRESSURE		TEMPERATURE			WIND		SNOW
SOLAR	CLOCK	EXT-T	ENG-C	BEAM	DIFFUSE	COND	WEATHER	SEA-L	STN	D.B.	DEW	HUMIDITY	DIR	VEL	COVER
700	711	247.	139.	0.4785	0.5215	0	0	101.12	97.57	8.7	7.4	C.00692	323	31	0
800	811	1145.	754.	0.6547	0.3453	0	0	101.16	97.62	10.2	7.6	0.00732	327	36	0
900	911	1983.	1492.	0.8830	0.1170	0	0	101.21	97.66	11.7	7.8	0.00775	330	41	0
1000	1011	2667.	2124.	0.8830	0.1170	0	0	101.20	97.65	13.7	7.2	0.00810	323	48	0
1100	1111	3150.	2518.	0.8830	0.1170	0	0	101.18	97.64	15.8	6.7	C.00853	317	55	0
1200	1211	3401.	2697.	0.8830	0.1170	0	0	101.17	97.63	17.8	6.1	C.00892	310	62	0
1300	1311	3401.	2664.	0.8830	0.1170	0	0	101.11	97.58	18.3	5.5	C.00888	307	50	0
1400	1411	3150.	2448.	0.8830	0.1170	0	0	101.06	97.54	18.9	5.0	C.00890	303	38	0
1500	1511	2667.	2014.	0.8830	0.1170	0	0	101.00	97.49	19.4	4.4	0.00886	300	26	0
1600	1611	1983.	1370.	0.7142	0.2858	0	0	100.98	97.47	17.4	5.7	C.00869	247	24	0
1700	1711	1145.	571.	0.3606	0.6394	0	0	100.96	97.45	15.3	7.0	0.00849	193	23	0

APPENDIX D

ECONOMIC ANALYSIS COMPUTER PROGRAM AND TYPICAL RESULTS

The computer program listed here determines the life cycle costs for a conventional dryer and a dryer utilizing the Solar Energy Powered Sorption Dehumidification System. The equipment costs were estimated at $2000 for a conventional dryer, $1000 for the Sorption system and $300 per square meter for the collector. The price of fuel estimated propane at $0.85 per gallon with an efficiency of 85%, which results in a delivered price of approximately $12.00 per GJoule. One day of hourly station atmospheric pressures and dehumidifier outlet humidity ratio data are included with this example. Typical output include the commodity dryer parameters, one day of hourly dryer inlet and outlet conditions, the economic analysis parameters and the life cycle costs as they vary with the load.

```
C          NOMENCLATURE LIST BEGINS HERE                                   EA 00010
C        AMASSP=AIR MASS FLOW RATE THROUGH DEHUMIDIFIER - PROCESS SIDE     EA 00020
C        CA=UNIT COST VARYING WITH SIZE OF SOLAR ENERGY SYSTEM             EA 00030
C        CEC=EQUIPMENT COST - CONVENTIONAL                                 EA 00040
C        CES=EQUIPMENT COST - SOLAR                                        EA 00050
C        CF=COST OF FUEL, DOLLARS                                          EA 00060
C        CFLAG=PROGRAMING FLAG TO DESIGNATE THE DIFFERENCE BETWEEN INCOME  EA 00070
C              PRODUCING AND NON-INCOME PRODUCING SOLAR SYSTEMS            EA 00080
C        CMC=MISCELLANEOUS COST - CONVENTIONAL                             EA 00090
C        CMIR= ANNUAL MORTGAGE INTEREST RATE - CONVENTIONAL                EA 00100
C        DC=DOWNPAYMENT - CONVENTIONAL                                     EA 00110
C        DEPC=DEPRECIATION TAX DEDUCTION - CONVENTIONAL                    EA 00120
C        DEPS=DEPRECIATION TAX DEDUCTION - SOLAR                           EA 00130
C        DIC=DEPRECIATION INFLATION RATE- USED FOR DECLINING BALANCE       EA 00140
C             - CONVENTIONAL                                               EA 00150
C        DIS=DEPRECIATION INFLATION RATE- USED FOR DECLINING BALANCE       EA 00160
C             -SOLAR                                                       EA 00170
C        DMCC=DISCOUNTED VALUE OF MISC. COSTS - SOLAR  (INSURANCE,ETC.)    EA 00180
C             -CONVENTIONAL                                                EA 00190
C        DMCS=DISCOUNTED VALUE OF MISC. COSTS - SOLAR  (INSURANCE,ETC.)    EA 00200
C             -SOLAR                                                       EA 00210
C        DOPC=FLAG INDICATING WHICH DEPRECIATION SCHEDULE IS UTILIZED -    EA 00220
C              CONVENTIONAL                                                EA 00230
C        DOPS=FLAG INDICATING WHICH DEPRECIATION SCHEDULE IS UTILIZED -    EA 00240
C              SOLAR                                                       EA 00250
C        DRC=D, MARKET DISCOUNT RATE - CONVENTIONAL                        EA 00260
C        DRS=D, MARKET DISCOUNT RATE - SOLAR                               EA 00270
C        DRVC=DISCOUNTED RESALE VALUE - CONVENTIONAL                       EA 00280
C        DRVS=DISCOUNTED RESALE VALUE - SOLAR                              EA 00290
C        DS= DOWNPAYMENT - SOLAR                                           EA 00300
C        EMCD= EQUILIBRIUM MOISTURE CONTENT OF WET GRAIN, DRY BASIS        EA 00310
C        F=FRACTION OF HEAT SUPPLIED BY SOLAR, WITH RESPECT TO THE TOTAL   EA 00320
C              HEAT SUPPLIED (1-F IS THE PERCENT AUXILIARY AND ADDITIONALEA 00330
C              HEAT SUPPLIED)                                              EA 00340
C        FI=FUEL INFLATION RATE                                            EA 00350
C        FTR=FEDERAL TAX RATE                                              EA 00360
C        GC= GRAIN CONSTANT C                                              EA 00370
C        GEMT=GRAND TOTAL EVAPORATED MOISTURE                              EA 00380
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C       GI=GENERAL INFLATION RATE                                          EA 00390
C       GN=GRAIN CONSTANT N                                                EA 00400
C       GTQAUX=GRAND TOTAL AUXILIARY HEAT SUPPLIED TO THE DEHUMIDIFIER     EA 00410
C       GTQU=GRAND TOTAL OF SOLAR HEAT GAIN                                EA 00420
C       HID=SET ENTHALPY RATIO OF INLET AIR TO DRIER                       EA 00430
C       LADD=ADDITIONAL LOAD VARIED TO DETERMINE OPTIMUM LIFE CYCLE COST  EA 00440
C       LCCC=LIFE CYCLE COSTS - CONVENTIONAL                               EA 00450
C       LCCS=LIFE CYCLE COSTS - SOLAR                                      EA 00460
C       LP=LOAD DRIED BY DEHUMIDIFIER                                      EA 00470
C       LPP=LOAD DRIED BY DEHUMIDIFIER AND SUPPLEMENTAL SOURCE             EA 00480
C       MPIC=DISCOUNTING MORTGAGE, PRINCIPAL AND INTEREST - CONVENTIONAL  EA 00490
C       MPIS=DISCOUNTING MORTGAGE, PRINCIPAL AND INTEREST - SOLAR          EA 00500
C       ND=NUMBER OF DAYS TO BE ANALYZED                                   EA 00510
C       NDEPC=TERM OF DEPRECIATION - CONVENTIONAL                          EA 00520
C       NDEPS=TERM OF DEPRECIATION - SOLAR                                 EA 00530
C       NDEPPC=TERM OF DEPRECIATION, USED FOR D.B. AND S.O.D.-CONVENTION  EA 00540
C       NDEPPS=TERM OF DEPRECIATION, USED FOR D.B. AND S.O.D.-SOLAR       EA 00550
C       NEA=TERM OF THE ECONOMIC ANALYSIS                                  EA 00560
C       NH=NUMBER OF HOURS TO BE ANALYZED                                  EA 00570
C       NLS=TERM OF THE LOAN - SOLAR                                       EA 00580
C       NLC=TERM OF THE LOAN - CONVENTIONAL                                EA 00590
C       NMINC=YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS -    EA 00600
C               CONVENTIONAL                                               EA 00610
C       NMINPC= YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS    EA 00620
C               FOR THE EQUIPMENT - CONVENTIONAL                           EA 00630
C       NMINS=YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS -    EA 00640
C               SOLAR                                                      EA 00650
C       NMINPS= YEARS THE MORTGAGE PAYMENTS CONTRIBUTE TO THE ANALYSIS    EA 00660
C               FOR THE EQUIPMENT - SOLAR                                  EA 00670
C       POD=PARTIAL WATER VAPOR PRESSURE EXITING DRIER                     EA 00680
C       PONES=RATIO OF LIFE CYCLE FUEL COSTS TO FIRST YEAR FUEL COSTS     EA 00690
C             - SOLAR                                                      EA 00700
C       PSTN=STATION ATMOSPHERIC PRESSURE - KILOPASCALS                    EA 00710
C       PSTNC=STATION ATMOSPHERIC PRESSURE - ATMOSPHERES                   EA 00720
C       PTCC=DISCOUNTED PROPERTY TAX COSTS - CONVENTIONAL                  EA 00730
C       PTCS=DISCOUNTED PROPERTY TAX COSTS - SOLAR                         EA 00740
C       PTWOS=LIFE CYCLE COSTS OF ADDITIONAL CAPITOL INVESTMENT TO         EA 00750
C             INITIAL INVESTMENT - SOLAR                                   EA 00760
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C       PW_C=PRESENT WORTH FACTOR FOR CALCULATING TERMS IN PCNE OR PTWO  EA 00770
C              - CONVENTIONAL                                            EA 00780
C       PW_S=PRESENT WORTH FACTOR FOR CALCULATING TERMS IN PCNE OR PTWO  EA 00790
C              - SCLAR                                                   EA 00800
C       PWF=PRESENT WORTH FACTOR IF I NOT = D                            EA 00810
C       PWFP=PRESENT WORTH FACTOR IF I=D                                 EA 00820
C       RH=RELATIVE HUMIDITY OF AIR EXITING DRIER                        EA 00830
C       RVS=RATIO OF RESALE VALUE AT END OF PERIOD OF ANALYSIS TO INITIALEA 00840
C              INVESTMENT - SOLAR                                        EA C0850
C       RVC=RATIO OF RESALE VALUE AT END OF PERICD CF ANALYSIS TC INITIALEA 00860
C              INVESTMENT - CCNVENTIONAL                                 EA C0870
C       SMC=SOLAR RATIO OF MISC. COSTS TO INITIAL INVESTMENT             EA 00880
C       SMIR=ANNUAL MORTGAGE INTEREST RATE - SOLAR                       EA 00890
C       STR=STATE TAX RATE                                               EA 00900
C       TAC=TOTAL COLLECTOR AREA                                         EA 00910
C       TAVS=PROPERTY TAX RATE BASED ON ASSESSED VALUE                   EA 00920
C       TBAR=EFFECTIVE TAX RATE                                          EA 00930
C       TCR=TAX CREDIT RATE                                              EA 00940
C       TDIC=DISCOUNTED VALUE OF INCOME TAX DEDUCTICNS ON THE INTEREST   EA 00950
C              - CONVENTIONAL                                            EA 00960
C       TDIS=DISCOUNTED VALUE OF INCOME TAX DEDUCTICNS ON THE INTEREST   EA 00970
C              - SOLAR                                                   EA 00980
C       TIDD-INLET TEMPERATURE TO DRYER, DRY BULB                        EA C0990
C       TIDW-INLET TEMPERATURE TO DRYER, WET BULB                        EA 01000
C       VC=RATIO OF ASSESSED VALUATION OF THE SYSTEM IN FIRST YEAR TO    EA 01010
C            THE INITIAL INVESTMENT OF THE SYSTEM - CONVENTICNA          EA 01020
C       VS=RATIO OF ASSESSED VALUATION OF THE SYSTEM IN FIRST YEAR TO    EA 01030
C            THE INITIAL INVESTMENT OF THE SYSTEM - SOLAR                EA 01040
C       WOD=HUMIDITY RATIO EXITING DRIER                                 EA 01050
C       WOXP=HUMIDITY RATIO EXITING DEHUMIDIFIER - PROCESS AIR           EA 01060
      REAL MPIS,LP,MPIC,LCCS,LCCC,LADD,LPP                               EA 01070
      INTEGER DOPS,DOPC,CFLAG                                            EA 01080
      DIMENSION EM(10,24),EMT(10),POD(10,24),PSTN(10,24),PSTNC(10,24),   EA 01090
     XRH(10,24),TIDD(10,24),TIDDR(10,24),WOXP(10,24),WOD(10,24)          EA 01100
     X,IHR(10,24)                                                        EA 01110
      PWF(KK,Y,Z)=(1.-((1.+Y)/(1.+Z))**KK)/(Z-Y)                         EA 01120
      PWFP(KKP,YP,ZP)=KKP/(1.+YP)                                        EA 01130
C       THE ECCNCMIC ANALYSIS BEGINS HERE                                EA 01140
```

```
C        READ INFLATION AND TAX RATES
      READ (5,90) FI,GI,FTR,STR
C        READ TERM CF ECONCMIC ANALYSIS, DISCOUNT RATES AND FUEL COSTS
      READ (5,91) NEA,DRS,DRC,CF,CFLAG
C        READ SOLAR MORTGAGE CATA
      READ (5,92) NLS,DS,SMIR,TCR
C        READ SOLAR DEPRECIATION DATA
      READ (5,93) DCPS,NDEPS
C        READ SOLAR COST AND VALUE DATA
      READ (5,94) CA,CES,TAVS,VS,RVS,SMC
C        READ CONVENTICNAL MORTGAGE DATA
      READ (5,95) NLC,DC,CMIR
C        READ CONVENTICNAL DEPRECIATION DATA
      READ (5,96) DCPC,NDEPC
C        READ CCNVENTICNAL CCST AND VALUE DATA
      READ (5,97) CEC,TAVC,VC,RVC,CMC
C        READ SYSTEM OPERATING DATA
      READ (5,98) AMASSP,GTQU,ND,NH,TAC
C        READ PROCESS COMMODITY DATA
      READ (5,18) EMCD,GC,GN,TIDW,HID
      BETAD=374.12-TIDW
      BETAFD=BETAD/100.
      PSAT=218.167*10**(-BETAD/(TIDW+273.15)*(3.2437814+
     X.586826*BETAFD+0.011702379*BETAFD**3)/(1.+.2187846*BETAFD))
C        WRITE DRYER PARAMETERS
      WRITE(6,170)
      WRITE(6,171) AMASSP
      WRITE(6,172) ND
      WRITE(6,173) NH
      WRITE(6,174) GTQU
      WRITE(6,175) TAC
      WRITE(6,176) EMCD,GC,GN
      WRITE(6,177) TIDW
      WRITE(6,178) HID
  170 FORMAT ('1'///,T6,'******  COMMODITY DRYER PARAMETERS  ******')
  171 FORMAT('-'/T8,'AIR FLOW RATE',T40,'= ',F8.5,' KG/S')
  172 FORMAT('0',T8,'NUMBER OF DAYS ANALYZED',T40,'= ',I3)
  173 FORMAT('0',T8,'NUMBER OF HOURS PER DAY',T40,'= ',I3)
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  174 FORMAT('0',T8,'TOTAL HEAT SUPPLIED BY SOLAR',T40,'= ',F10.6,' GJOU
     XLE')
  175 FORMAT('0',T8,'TOTAL COLLECTOR AREA',T40,'= ',F6.3,'  M**2')
  176 FORMAT('0',T8,'CCMMODITY  INITIAL MOISTURE',T40,'= ',F6.2,' PERCEN
     XT DRY BASIS'/T19,'CONTENT'/T19,'CONSTANT "C"',T40,'= ',F10.6/T19,
     X'CONSTANT "N"',T40,'= ',F5.2)
  177 FORMAT('0',T8,'SET INLET WET BULB',T40,'= ',F6.2/T8,'TEMPERATURE')
  178 FORMAT('0',T8,'SET INLET ENTHALPY',T40,'= ',F6.2,' KJ/KG DRY AIR')
      DO 10 I=1,ND
      DO 11 J=1,NH
C        READ HCURLY DATA FROM SYSTEM
      READ (5,99) IHR(I,J),WOXP(I,J),PSTN(I,J)
C        CALCULATE THE EVAPORATEC MOISTURE, IN KILOGRAMS MOISTURE PER
C        HOUR
C        HEAT INLET DRYER AIR TO TIDW
      TIDD(I,J)=(HID-2501.*WOXP(I,J))/(1.+1.805*WCXP(I,J))
C        TIDDR=TIDD IN DEGREES RANKINE
      TIDDR(I,J)=1.8*TIDC(I,J)+492.
      RH(I,J)=1.-EXP(-GC*TIDDR(I,J)*(EMCD**GN))
      POD(I,J)=PSAT*RH(I,J)
      PSTNC(I,J)=PSTN(I,J)*0.0098692
      WOD(I,J)=.62198*POD(I,J)/(PSTNC(I,J)-POD(I,J))
      EM(I,J)=AMASSP*(WOD(I,J)-WOXP(I,J))*3600.
C        NEED TO INITIALIZE DAILY TOTAL EVAPORATED MOISTURE
      IF (J.EQ.1) EMT(I)=0.0
      EMT(I)=EMT(I)+EM(I,J)
   11 CONTINUE
C        WRITE HOURLY TEMPERATURE AND HUMIDITY MAP FOR THE DRYER
      WRITE (6,160) I
      WRITE (6,163)
      WRITE (6,164)
      WRITE (6,165)
      DC 167 J=1,NH
      RHP=RH(I,J)*100.
      WRITE(6,166) IHR(I,J),TIDD(I,J),WOXP(I,J),RHP,WOD(I,J),EM(I,J)
  167 CONTINUE
      WRITE (6,168) EMT(I)
  160 FORMAT('1'//T6,'****   HOURLY TEMPERATURE AND HUMIDITY MAP   ****'
```

```
     X,T100,'****    DRYER    ****'//T102,'DAY ',I3)
 163 FORMAT('0',T25,'INLET',T50,'OUTLET'//T8,'HOUR',T44,'RELATIVE',T70,
     X'MOISTURE')
 164 FORMAT('0',T7,'ENDING',T20,'TEMP',T29,'HUMIDITY',T44,'HUMIDITY',T5
     X4,'HUMIDITY',T69,'EVAPCRATED')
 165 FORMAT('0',T6,8('-'),T19,18('-'),T43,18('-'),T68,12('-'))
 166 FORMAT(' ',T6,I5,T20,F5.1,T30,F6.4,T45,F5.1,T55,F6.4,T70,F5.2)
 168 FORMAT('-',//T12,'DAILY TOTAL MOISTURE EVAPCRATED = ',F6.2)
      IF (I.EQ.1) GEMT=0.0
      GEMT=GEMT+EMT(I)
  10 CONTINUE
  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)
  98 FORMAT (F10.5,F10.6,I3,I2,F6.3)
  99 FORMAT (I6,F6.4,F6.2)
  18 FORMAT (F6.2,F10.8,F5.3,F5.1,F10.4)
      ZERO=0.0
C        NMINPS 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        NDEPS 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
```

```
      CIC=-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*(PWCS*(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)
      GC TO 800
  804 DEPS=(0.2*PWKS+0.32*PWLS+0.24*PWKS*PWLS+0.16*PWLS*PWLS+0.08*PWKS*
     X*PWLS*PWLS)*TEAR
  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+DMCS+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 ANC 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,CRC)
      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,ZERC)
```

```
      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
      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) DSF,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)
      GO TO 123
  127 WRITE (6,128)
  123 CONTINUE
      GO TO (130,131,132,137),DOPC
  130 WRITE (6,134)
      GO TO 133
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131 WRITE (6,135)                                                          EA 03810
    GO TO 133                                                              EA 03820
132 WRITE (6,136)                                                          EA 03830
    GO TO 133                                                              EA 03840
137 WRITE (6,138)                                                          EA 03850
133 CONTINUE                                                               EA 03860
    ICFLAG=CFLAG+1                                                         EA 03870
    GO TO (142,143),ICFLAG                                                 EA 03880
142 WRITE (6,140)                                                          EA 03890
    GO TO 144                                                              EA 03900
143 WRITE (6,141)                                                          EA 03910
144 CONTINUE                                                               EA 03920
100 FORMAT ('1'//T6,'******  ECONOMIC ANALYSIS PARAMETERS  ******')        EA 03930
101 FORMAT('-',T45,'SOLAR ENERGY',T65,'CCNVENTICNAL'/T45,'DEHUMIDIFIEREA 03940
   X',T65,'DEHUMICIFIER'/T44,14('_'),T64,14('_'))                          EA 03950
102 FORMAT('-',T5,'MARKET DISCCUNT RATE - PERCENT',T48,F5.1,T68,F5.1) EA 03960
103 FORMAT('0',T5,'TERM OF MORTGAGE - YEARS',T46,I5,T66,I5)                EA 03970
104 FORMAT('0',T5,'DOWNPAYMENT - PERCENT',T48,F5.1,T68,F5.1)               EA 03980
105 FORMAT('0',T5,'MORTGAGE INTEREST RATE - PERCENT',T48,F5.1,T68,F5.1EA 03990
   X)                                                                      EA 04000
106 FORMAT('0',T5,'TERM OF DEPRECIATION - YEARS',T46,I5,T66,I5)            EA 04010
107 FORMAT('0',T5,'PROPERTY TAX - DOLLARS',T43,F10.2,T63,F10.2)            EA 04020
108 FORMAT('0',T5,'ASSESSED VALUATION - DOLLARS',T43,F1C.2,T63,F10.2) EA 04030
109 FORMAT('C',T5,'RESALE VALUE - DCLLARS',T43,F10.2,T63,F10.2)            EA 04040
110 FORMAT('0',T5,'MISCELLANEOUS COSTS - PERCENT',T48,F5.1,T68,F5.1)       EA 04050
111 FORMAT('0',T5,'FIXED COST CF EQUIPMENT',T44,F10.0,T64,F10.0)           EA 04060
112 FORMAT('0',T5,'COST PER COLLECTOR AREA',T48,F5.0,T69,5('-'))           EA 04070
113 FORMAT('0',T5,'FEDERAL TAX CREDIT - PERCENT',T48,F5.1,T69,5('-')) EA 04080
114 FORMAT('-',T25,'FUEL INFLATION RATE',T54,'= ',F5.1,'  PERCENT')        EA 04090
115 FORMAT('0',T25,'GENERAL INFLATION RATE',T54,'= ',F5.1,'  PERCENT')EA 04100
116 FORMAT('0',T25,'FEDERAL TAX RATE',T54,'= ',F5.1,'  PERCENT')           EA 04110
117 FORMAT('0',T25,'STATE TAX RATE',T54,'= ',F5.1,'  PERCENT')             EA 04120
118 FORMAT('0',T25,'FUEL PRICE',T54,'= ',F5.2,'  DOLLAR/GJOULE')           EA 04130
119 FORMAT('0',T25,'TERM OF ECCNOMIC ANALYSIS',T54,'= ',I5,'  YEARS') EA 04140
124 FORMAT('-',T25,'STRAIGHT LINE DEPRECIATION - SOLAR')                   EA 04150
125 FORMAT('-',T25,'DECLINING BALANCE DEPRECIATION - SOLAR')               EA 04160
126 FORMAT('-',T25,'SUM OF DIGITS DEPRECIATION - SOLAR')                   EA 04170
128 FORMAT('-',T25,'ACCELERATEC COST RECOVERY DEPRECIATION - SOLAR')  EA 04180
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  134 FORMAT('0',T25,'STRAIGHT LINE DEPRECIATICN - CONVENTICNAL')        EA 04190
  135 FORMAT('0',T25,'DECLINING BALANCE DEPRECIATION - CONVENTIONAL')    EA 04200
  136 FORMAT('0',T25,'SUM OF DIGITS DEPRECIATICN - CONVENTICNAL')        EA 04210
  138 FORMAT('0',T25,'ACCELERATED COST RECOVERY DEPRECIATION - CONVENTIOEA 04220
     XNAL')                                                              EA 04230
  140 FORMAT('0',T25,'NON-INCOME PRODUCING SYSTEM')                      EA 04240
  141 FORMAT('0',T25,'INCOME PRODUCING SYSTEM')                          EA 04250
      WRITE (6,151)                                                      EA 04260
      WRITE (6,152)                                                      EA 04270
      WRITE (6,153)                                                      EA 04280
      LADD=0.                                                            EA 04290
C        LATENT HEAT OF VAPORIZATION IS 0.00240 GJCULE PER KILOGRAM      EA 04300
      DO 150 KOUNT=1,16                                                  EA 04310
      LP=GEMT*0.00240                                                    EA 04320
      LPP=LP+LADD                                                        EA 04330
      F=GTQU/LPP                                                         EA 04340
      FF=F*100.                                                          EA 04350
      EF=1./(1.-F)                                                       EA 04360
C       LPP IS IN GJOULE                                                 EA 04370
      LCCS=PTWOS*(CA*TAC+CES)+PTWOC*CEC+PONES*CF*LPP*(1.-F)              EA 04380
      LCCC=PTWOC*(CEC)+PONEC*CF*LPP                                      EA 04390
      WRITE (6,154) LP,LADD,LPP,FF,LCCS,LCCC,EF                          EA 04400
      LADD=LADD+0.025                                                    EA 04410
  150 CONTINUE                                                           EA 04420
      WRITE (6,155) PONES,PONEC                                          EA 04430
      WRITE (6,156) PTWOS,PTWCC                                          EA 04440
      WRITE (6,157)                                                      EA 04450
      WRITE (6,158)                                                      EA 04460
  151 FCRMAT ('1'////T6,'******  ECONOMIC ANALYSIS  ******')             EA 04470
  152 FORMAT ('-',T53,'SOLAR ENERGY',T87,'CCNVENTICNAL'//T14,'LOAD SUPPLEA 04480
     XIED BY'/T45,'FRACTION OF'/T15,'SUPPLEMENTARY',T44,'LOAD SUPPLIED'/EA 04490
     XT2,'DEHUMIDIFIER',T19,'HEATER',T32,'TOTAL',T47,'BY SOLAR',T60,'LIFEA 04500
     XE CYCLE COST',T85,'LIFE CYCLE COST',T106,'DRYER EFFICIENCY')       EA 04510
  153 FORMAT (' ',T2,12('-'),T15,13('-'),T31,7('-'),T44,13('-'),T59,17('EA 04520
     X-'),T84,17('-'),T105,16('-'))                                      EA 04530
  154 FORMAT ('0',T2,F10.3,T14,F10.3,T28,F10.4,T48,F5.1,T60,F10.2,T86,F1EA 04540
     X0.2,T109,F1C.4)                                                    EA 04550
  155 FCRMAT ('-'///T53,'P-ONE = ',F8.4,T84,'P-ONE = ',F8.4)             EA 04560
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  156 FORMAT ('-',T53,'P-TWO = ',F8.4,T84,'P-TWO = ',F8.4)            EA 04570
  157 FORMAT ('-',T6,'MOISTURE EVAPORATED IN KILOGRAMS'/T6,'LOAD IN GJOUEA 04580
     XLE '/T6,'SOLAR FRACTION IN PERCENT'/T6,'LIFE CYCLE COSTS IN DOLLAREA 04590
     XS')                                                                EA 04600
  158 FORMAT ('1')                                                       EA 04610
      STOP                                                               EA 04620
      END                                                                EA 04630

$ENTRY
 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
  02836     143420  524  3272
2500  00001100 19    190      54216
    1  0052  9837
    2  0000  9841
    3  0002  9844
    4  0000  9845
    5  0000  9847
    6  0000  9848
    7  0000  9851
    8  0000  9855
    9  0005  9858
   10  0005  9852
   11  0008  9847
   12  0018  9841
   13  0024  9830
   14  0024  9818
   15  0029  9807
   16  0032  9805
   17  0024  9802
   18  0022  9800
```

19	0015	9800
20	0012	9800
21	0009	9800
22	0008	9794
23	0010	9789
24	0005	9783

```
******  COMMODITY DRYER PARAMETERS  ******

  AIR FLOW RATE                        =  0.02836 KG/S

  NUMBER OF DAYS ANALYZED              =   5

  NUMBER OF HOURS PER DAY              =  24

  TOTAL HEAT SUPPLIED BY SOLAR         =   0.143420 GJOULE

  TOTAL COLLECTOR AREA                 =  3.272  M**2

  COMMODITY  INITIAL MOISTURE          =  25.00 PERCENT DRY BASIS
             CONTENT
             CONSTANT "C"              =   0.000011
             CONSTANT "N"              =  1.90

  SET INLET WET BULB                   =  19.00
  TEMPERATURE

  SET INLET ENTHALPY                   =  54.22 KJ/KG DRY AIR
```

**** HOURLY TEMPERATURE AND HUMIDITY MAP ****

**** DRYER ****

DAY 1

HOUR ENDING	INLET TEMP	INLET HUMIDITY	OUTLET RELATIVE HUMIDITY	OUTLET HUMIDITY	MOISTURE EVAPORATED
1	40.8	0.0052	94.0	0.0133	0.82
2	54.2	0.0	94.7	0.0134	1.37
3	53.7	0.0002	94.7	0.0134	1.35
4	54.2	0.0	94.7	0.0134	1.37
5	54.2	0.0	94.7	0.0134	1.37
6	54.2	0.0	94.7	0.0134	1.37
7	54.2	0.0	94.7	0.0134	1.37
8	54.2	0.0	94.7	0.0134	1.37
9	52.9	0.0005	94.6	0.0134	1.32
10	52.9	0.0005	94.6	0.0134	1.32
11	52.1	0.0008	94.6	0.0134	1.29
12	49.6	0.0018	94.5	0.0134	1.18
13	48.0	0.0024	94.4	0.0134	1.12
14	48.0	0.0024	94.4	0.0134	1.12
15	46.7	0.0029	94.3	0.0134	1.07
16	45.9	0.0032	94.3	0.0134	1.04
17	48.0	0.0024	94.4	0.0134	1.13
18	48.5	0.0022	94.4	0.0134	1.15
19	50.3	0.0015	94.5	0.0135	1.22
20	51.1	0.0012	94.6	0.0135	1.25
21	51.9	0.0009	94.6	0.0135	1.28
22	52.1	0.0008	94.6	0.0135	1.29
23	51.6	0.0010	94.6	0.0135	1.27
24	52.9	0.0005	94.6	0.0135	1.33

DAILY TOTAL MOISTURE EVAPORATED = 29.79

****** ECONOMIC ANALYSIS PARAMETERS ******

	SOLAR ENERGY DEHUMIDIFIER	CONVENTIONAL DEHUMIDIFIER
MARKET DISCOUNT RATE - PERCENT	12.0	12.0
TERM OF MORTGAGE - YEARS	5	5
DOWNPAYMENT - PERCENT	10.0	10.0
MORTGAGE INTEREST RATE - PERCENT	12.0	12.0
TERM OF DEPRECIATION - YEARS	5	5
PROPERTY TAX - DOLLARS	0.0	0.0
ASSESSED VALUATION - DOLLARS	0.0	0.0
RESALE VALUE - DOLLARS	0.0	0.0
MISCELLANEOUS COSTS - PERCENT	2.0	2.0
FIXED COST OF EQUIPMENT	1000.	2000.
COST PER COLLECTOR AREA	300.	-----
FEDERAL TAX CREDIT - PERCENT	55.0	-----

FUEL INFLATION RATE	= 13.0	PERCENT
GENERAL INFLATION RATE	= 6.0	PERCENT
FEDERAL TAX RATE	= 30.0	PERCENT
STATE TAX RATE	= 5.0	PERCENT
FUEL PRICE	= 12.00	DOLLAR/GJOULE
TERM OF ECONOMIC ANALYSIS	= 15	YEARS

ACCELERATED COST RECOVERY DEPRECIATION - SOLAR

ACCELERATED COST RECOVERY DEPRECIATION - CONVENTIONAL

INCOME PRODUCING SYSTEM

****** ECONOMIC ANALYSIS ******

LOAD SUPPLIED BY			SOLAR ENERGY		CONVENTIONAL	
DEHUMIDIFIER	SUPPLEMENTARY HEATER	TOTAL	FRACTION OF LOAD SUPPLIED BY SOLAR	LIFE CYCLE COST	LIFE CYCLE COST	DRYER EFFICIENCY
0.365	0.0	0.3654	39.3	2251.22	1707.16	1.6462
0.365	0.025	0.3904	36.7	2254.07	1710.01	1.5807
0.365	0.050	0.4154	34.5	2256.91	1712.85	1.5274
0.365	0.075	0.4404	32.6	2259.76	1715.70	1.4830
0.365	0.100	0.4654	30.8	2262.60	1718.54	1.4455
0.365	0.125	0.4904	29.2	2265.45	1721.39	1.4134
0.365	0.150	0.5154	27.8	2268.29	1724.23	1.3856
0.365	0.175	0.5404	26.5	2271.14	1727.08	1.3613
0.365	0.200	0.5654	25.4	2273.98	1729.92	1.3399
0.365	0.225	0.5904	24.3	2276.83	1732.77	1.3209
0.365	0.250	0.6154	23.3	2279.67	1735.61	1.3039
0.365	0.275	0.6404	22.4	2282.52	1738.46	1.2886
0.365	0.300	0.6654	21.6	2285.36	1741.30	1.2748
0.365	0.325	0.6904	20.8	2288.21	1744.15	1.2622
0.365	0.350	0.7154	20.0	2291.05	1746.99	1.2508
0.365	0.375	0.7404	19.4	2293.90	1749.84	1.2403

P-ONE = 9.4832   P-ONE = 9.4832

P-TWO = 0.2828   P-TWO = 0.8328

MOISTURE EVAPORATED IN KILOGRAMS
LOAD IN GJOULE
SOLAR FRACTION IN PERCENT

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Finally, this thesis is for my father, who taught me how to build my Yellow Brick Road, to my mother, who taught me the determination and love to start building it, and to my brothers and sisters, who have never ceased to give me the motivation to dream about it.

VITA

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MASTERS OF SCIENCE

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FEASIBILITY STUDY OF A SOLAR ENERGY POWERED SORPTION DEHUMIDIFICATION SYSTEM

by

ANN FERN ATKINSON

B.S., Kansas State University, 1981

ABSTRACT OF A MASTER'S THESIS

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KANSAS STATE UNIVERSITY
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ABSTRACT

A computer model was developed that combined TMY-SOLMET weather data with a computer model of an air dehumidifier utilizing a rotating bed of silica gel regenerated by solar energy, and includes an economic analysis of the entire apparatus. The computer model describing the dehumidifier performance was previously found to acceptably predict the performance of an experimental solar dehumidifier, but required hourly insolation and corresponding meteorological data. The TMY-SOLMET weather computer tape readily supplies credible data at a variety of United States Weather stations. Once the performance of the solar dehumidifier is determined at a particular location, time of year and length of operation, the economic analysis can be done. The economic analysis calculates the life cycle cost of a conventional dehumidifier and a solar dehumidifier augmented with a conventional dehumidifier serving as a backup, and includes the cost of fuel and all costs associated with the equipment. For a fifteen year study of a small corn dryer in Omaha, Nebraska for five days during October, it was found that the life cycle cost of the solar dehumidifier system is about $500 higher than that of the conventional system alone.