
DETERMINATION OF THE FEASIBILITY OF USING
SOLAR ENERGY IN A FOOD PROCESSING PLANT

BY

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UNIVERSITY OF WISCONSIN-MADISON

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MASTER OF SCIENCE

(CHEMICAL ENGINEERING)

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TABLE OF CONTENTS

Acknowledgements	i
Table of Contents	ii
Abstract	iv
List of Figures	vi
List of Tables	viii
Nomenclature	ix
1.0 Introduction	1
2.0 Analysis of Plant Energy Demand	5
2.1 Processing Energy Demand	5
2.1.1 General Considerations	5
2.1.2 Canning Plant Processing Energy Demand	5
2.2 Space Heating Energy Demand	26
2.2.1 General Considerations	26
2.2.2 Canning Plant Space Heating Energy Demand	27
3.0 The Solar Energy Collection System	34
3.1 General System Description	34
3.2 Design Parameters	36
3.3 Determination of Solar System Performance	40
3.4 Performance of Canning Plant Solar System	44
3.4.1 Canning Plant Solar Process Energy	45

3.4.2	Canning Plant Solar Space Heating	55
3.4.3	Canning Plant Yearly Solar Fraction	57
4.0	Solar Energy Economics	62
4.1	Life Cycle Cost Analysis	62
4.1.1	General Considerations	62
4.1.2	Application to Solar Energy System	63
4.2	Feasibility of Canning Plant Solar System	65
5.0	Conclusion	76
	Appendix A	79
	Appendix B	81
	Appendix C	82
	Bibliography	84

ABSTRACT

This study outlines a method by which the feasibility of using solar energy in a food processing plant can be determined. To demonstrate the procedure a vegetable canning plant located near Madison, Wisconsin is analyzed.

The canning plant processes approximately 47,000 kilograms (ca. 3.5 tons) of peas per hr. and 80,000 kilograms (ca. 22 tons unhusked) of corn per hr. each for a seven week period. The total canning season begins about the second week in June and ends about the third week in September. For each of the two canning seasons, those unit operations requiring hot water at or below 100° C (212° F) were considered and energy rates were determined. Production records were used to find hourly, daily and seasonal variation in these rates. This energy represented about 35% of the total processing energy demand.

Plant buildings must be maintained at or above 12.8° C (55° F) to protect the warehoused product. The energy required to meet this space heating demand was estimated from the plant's natural gas meter readings and heating efficiency using the degree-day method.

The combined energy required for space heating and for processing water below 100°C was found to be about 50% of the total plant energy demand.

The solar energy collection systems considered in this study are forced circulation liquid systems with flat-plate collectors and water tank to store sensible heat. The fraction of the plant's energy demand supplied by solar systems of various sizes were determined using computer programs developed by the Solar Energy Laboratory of the University of Wisconsin-Madison.

The economic feasibility of installing a solar energy system in the plant was investigated by conducting 20 year life cycle cost studies of estimated plant energy costs with and without a solar energy system. Optimum solar system collector sizes are determined for various system costs, backup energy costs and projected fuel inflation rates.

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1 Canning plant unit operations	7
2 Time variation of pea canning boiler feed water	11
3 Time variation of pea canning blancher water	12
4 Time variation of pea canning flume water	13
5 Time variation of pea canning topper water	14
6 Time variation of pea canning clean-up water	15
7 Time variation of corn canning boiler feed water	16
8 Time variation of corn canning topper water	17
9 Time variation of corn canning flume water	18
10 Time variation of corn canning clean-up water	19
11 Time variation of total hot water demand for pea canning	20
12 Time variation of total hot water demand for corn canning	21
13 Dimensions of canning plant buildings	28
14 Schematic of retrofit solar energy system	37
15 Variation of solar collection efficiency with collector area for dedicated and integrated solar systems	51
16 Variation of storage tank temperature with collector area	54
17 Percent of canning plant solar compatible energy demand supplied by solar as a function of collector area.	61

18	Present worth of solar savings as a function of fuel cost and collector area with optimistic solar parameters	68
19	Present worth of solar savings as a function of fuel cost and collector area with pessimistic solar parameters	70
20	Variation of optimum collector area with fuel cost and inflation rate	71
21	Variation of present worth of solar savings with fuel cost and inflation rate	72
22	Canning plant economic break-even curves	74

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Time schedule for the canning plant	10
2	Total energy demand of the canning plant	23
3	Break-down of canning plant energy demand by season and unit operation	24
4	Percent of canning plant energy demand compatible with solar energy	25
5	Calculation of energy used to heat canning plant buildings	30
6	Determination of UA for canning plant buildings	32
7	Determination of design space heating load for canning plant buildings	33
8	Specifications of a two glass cover flat-plate collector solar system	46
9	Results of TRNSYS simulations of solar systems used exclusively for each unit operation in pea canning	49
10	Results of TRNSYS simulation of a solar system used to service all canning plant unit operations	50
11	Results of FCHART analysis of canning plant solar space heating percent	56
12	Calculation of percent of solar compatible plant energy demand supplied by solar	58
13	Comparison of calculated % solar with results of f-chart model	59
14	Parameters used for FCHART economic analysis for the canning plant	66

NOMENCLATURE

BF	Solar backup fuel
C_{min}	minimum fluid capacitance rate for space heating load heat exchanger
D.D.	degree-day
e_L	effectiveness of space heating load heat exchanger
GJ	giga joule = 10^9 joule = 9.48×10^8 BTU
H	instantaneous total solar radiation on a horizontal surface
H_T	instantaneous total solar radiation on a tilted surface
Kg	kilogram = 2.20 pound
KJ	kilo joule = 10^3 joule = .948 BTU
l	liter = .264 gallon
L_s	monthly space heating load
M	meter = 3.28 feet
\dot{M}_L	flowrate of fluid to load and from mains
T	storage tank temperature
T_a	instantaneous ambient temperature
\bar{T}_{amb}	daily average ambient temperature
T_{env}	temperature to which storage tank energy losses occur
T_L	temperature of fluid entering storage tank
\dot{Q}_{env}	rate of energy loss from the tank to the surroundings
\dot{Q}_{tank}	rate of energy delivery from the tank to the load

x

\dot{Q}_u rate at which energy is transferred to the
storage tank

UA overall building energy loss coefficient-
area product

W wall = 1 joule · sec

ΔE net change in internal energy of the storage
tank fluid

1.0 INTRODUCTION

Approximately 17% of the total U.S. energy consumption is attributed to the food systems (1). This figure includes energy used for production through processing, distribution, and preparation. Energy in processing food products accounts for approximately 30% of the total energy used in the food system and estimates of energy sources show that nearly 50% of the energy is obtained from natural gas with about 30% purchased as electricity (2). Due to the ever increasing cost of fossil fuels and the depletion of their supplies, other forms or sources of energy for the food processing sector must be considered. A particularly attractive alternative energy source is solar energy (3).

Presently solar energy is being used directly in food processing for producing sun-dried fruits and vegetables. Since this process alters product characteristics significantly it cannot be viewed as a preservation method of great importance. There are however several unit operations in which solar energy could be used. These include: (1) heating water for cleaning, precooking and feed to boilers, (2) heat for pasteurization of fruit juice and milk, and (3) heat for temperature control in warehousing processed (primarily canned) foods.

Proctor and Morse (4) studied the energy demand in a Coca-Cola plant in Australia to provide data on the level and rate of energy demand. They found that over 40% of the total heat required was in the form of process water at 60-80 °C.

A study of the type conducted by Proctor and Morse is necessary in order to determine the apparent compatibility of solar energy systems with a particular food processing plant. This is due to the intermittent supply of solar energy and the variation of energy use, both seasonal and hourly, of a plant. However, the necessary hourly assessment of the unit operations of food processing plants can not be found in the literature.

The FEA target goals for the energy reduction in the food and kindred products (SIC) division (5) identified specific areas in which each processing system could significantly improve its energy utilization. However, generally these guidelines included only gross energy figures rather than the specific information necessary to generate an hourly energy demand model typical of the industry. Likewise, the literature dealing with production waste streams indicated areas of energy waste, but was too general to be of help in generating the energy demand model. Since much of the necessary

data are missing and since there is no convenient way to retrieve the information, it is necessary to acquire the data through measurements on a particular plant.

The purpose of this investigation is to outline the procedure necessary to evaluate the compatibility of solar energy with a particular food processing plant. First, the decision making and data generation process for determining the energy demand model for a plant is outlined. And then, after a discussion of the particulars of a solar energy collection system, the manner of determination of the performance (both thermal and economic) of such a system is detailed.

To demonstrate the procedure, a vegetable canning plant is analyzed as to its energy requirement and the feasibility of retrofit with a solar energy collection system. The plant is located near Madison, Wisconsin and produces canned and frozen peas and corn. An attempt was made to isolate the energy requirement that was due solely to the canning operation. It was felt that separation of the freezing operation from the canning would result in an analysis applicable to a larger number of plants since most vegetable processing plants do not have both freezing and canning operations. The task was made easier by the simultaneous overall energy analysis which was being conducted by

another research team on the same plant (6).

2.0 ANALYSIS OF ENERGY DEMAND

A food processing plant has two basic demands for energy. It requires hot water streams of various temperatures to service the unit operations involved in processing raw foodstuffs. Energy is also needed to space heat plant buildings during the winter season.

2.1 PROCESSING ENERGY DEMAND

2.1.1 GENERAL CONSIDERATIONS

The processing energy demand can be characterized in terms of hourly water flowrate and temperature required for each unit operation and the time it is required. Daily variations in this demand must then be determined from production records. To simplify the computer simulations to be done in this study it is necessary to develop a convenient repeating unit containing model days determined from these records. These model days include start and stop times for each unit operation and the mass flowrate and temperature of water required. As most industries have either a five or six day work week, an appropriate repeating unit would be a model week with one or two model days having zero mass flowrate of water.

2.1.2 CANNING PLANT PROCESSING ENERGY DEMAND

The unit operations necessary in the canning process

are outlined in Figure 1. The product arrives at the plant from the fields via truck whereupon it is washed with cold water. It is then fed into a blancher which is a tank maintained at approximately 87° C by direct injection of steam and through which the product is moved by a chain conveyor. In the blancher, air is eliminated from the tissues and enzymes are deactivated. High overflow rates and hence a large make-up of hot water is required to avoid the development of off flavors.

From the blancher the product is transported to the filler by means of the flume transport system. This system is maintained at a temperature of approximately 71° C and also has a high overflow and makeup rate for the same reasons outlined for the blancher. The blancher and flume system are also drained, rinsed and refilled several times during the course of a day.

After leaving the flume system the product is de-watered and placed in a can. The can topper then fills the can with fresh hot water from a steam heated tank at approximately 71° C, salt water is added, and the can is sealed.

Next the can travels via conveyor through a continuous retort. Here the contents of the cans are thermally

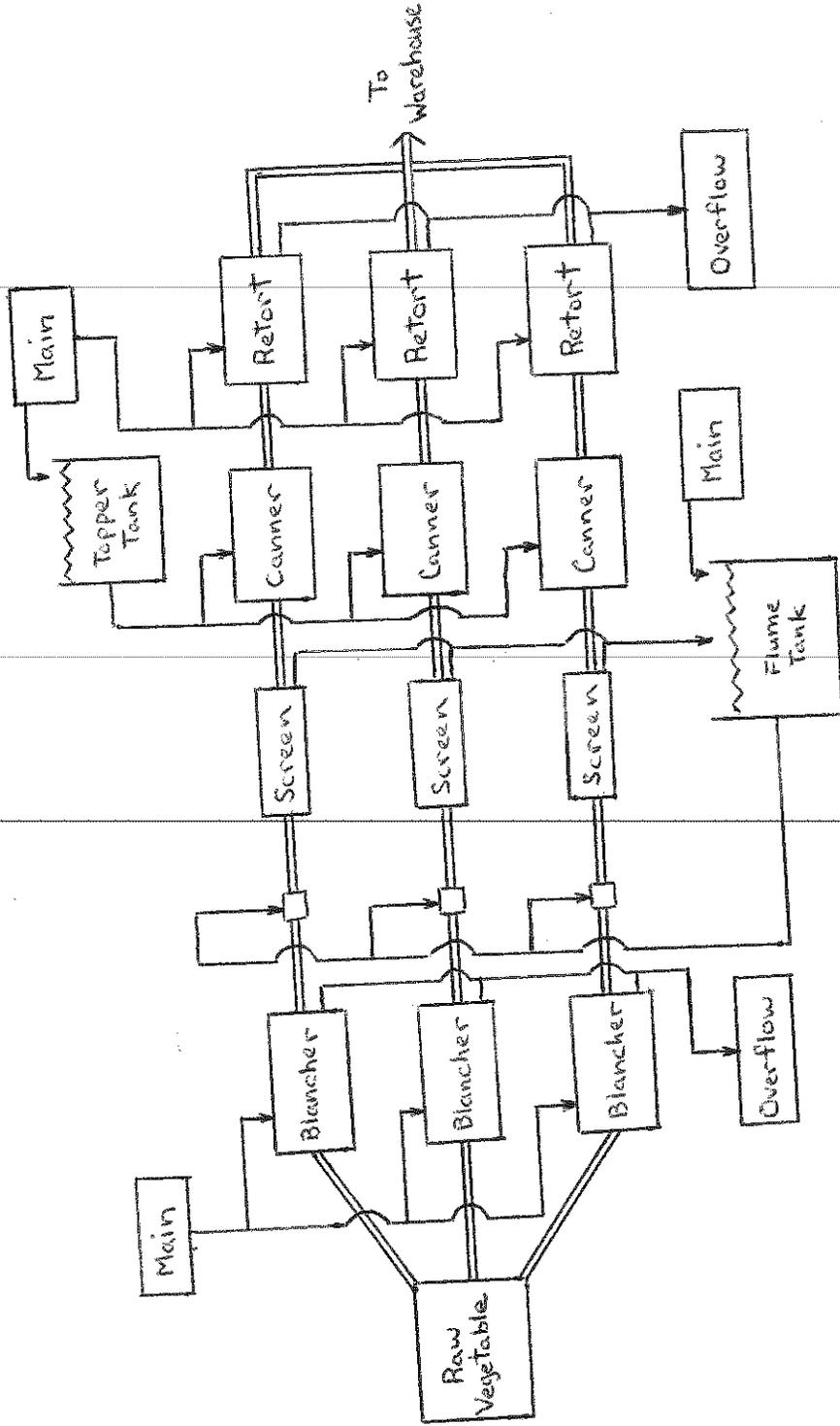


Figure 1. Canning Plant Unit Operations

sterilized at high temperature (180° C) via direct steam and in the same apparatus cooled under pressure to avoid swelling. The cans are then stored in the warehouse.

The plant contains three such separate blancher, canner and cooker lines each serviced by the flume transport system. The three line set-up allows the plant to operate efficiently considering the availability of crops and possible breakdown of one system component.

Considering the present nonfeasibility of producing steam with solar energy it was decided that only those unit operations which required water at temperatures less than 100° C would be considered in the energy demand model. The unit operations, and their respective temperatures clearly identified as being potentially compatible with solar energy are:

- 1) blancher fill and makeup water (87° C)
- 2) can topper fill and makeup water (71° C)
- 3) flume fill and makeup water (71° C)
- 4) clean-up water (60° C)
- 5) boiler makeup water (100° C)
(plant has no condensate return)

Due to the growing season, the canning season can be divided into two periods: the canning of peas and the canning of corn. Production days in a canning plant vary due to weather, availability of crops, etc. From

production records it was readily apparent that for peas there were three distinct model days which differed basically in the start-up and stop times and in the number of lines used. Three days of the production week started at 0800 and ended at 2400 with three lines running, two days started at 1200 and ended at 2230 with two lines running, and one day started at 0830 and shutdown at 1800 with three lines running. On one day no processing occurred. Thus these four model days were used to generate a model week.

For corn processing the harvesting and the production was very constant and hence one model day, starting at 0700 and ending at 0200 with two lines running, was repeated throughout the six day production week. Again the model week contained one nonprocessing day. The only process difference in canning peas and corn is that canned corn is not blanched.

Derivation of hourly water models for each of the unit operations came from actual meter readings or from material balances around the unit operations. Table 1 contains the fill and flow water requirements and the time dependence of each unit operation. These data are presented graphically in Figures 2 thru 10. The sum of the water requirements of these unit operations for each

Table 1. Time Schedule for the Canning Plant

<u>PEAS</u> Operation	<u>Fill</u> <u>Times</u>	<u>Flow</u> <u>Start</u>	<u>Flow</u> <u>Stop</u>	<u>Flow</u> <u>KG/HR</u>	<u>Fill</u> <u>KG</u>
Model 1 (3 days of model week)					
Boiler Feed		0430	2400	5400	
Blanchers	0800	0800	2400	2300	5400
	1200				
	1800				
Flume	0800	0800	2400	4542	14160
	1200				
	1800				
Topper	0800	0800	2400	6000	3785
Clean-up	0430	0500	0800	11360	666
		1800	1830		
Model 3 (1 day of model week)					
Boiler Feed		0530	1830	5200	
Blanchers	0830	0830	1800	2300	5400
	1200				
	1800				
Flume	0830	0830	1800	4542	14160
	1200				
	1800				
Topper	0830	0830	1800	6000	3785
Clean-up	0530	0600	0900	11360	666
Model 4 (2 days of model week)					
Boiler Feed		0830	2300	4120	
Blanchers	1200	1200	2230	1500	4050
	1800				
	1200				
Flume	1200	1200	2230	3028	14157
	1800				
	1200				
Topper	1200	1200	2230	4000	3785
Clean-up	0830	0900	1200	11360	666
<u>CORN</u>					
Model 2 (6 days of model week)					
Boiler Feed		0330	0200	5350	
Flume	0700	0700	0200	3028	14157
	1200				
	1800				
Topper	0700	0700	0200	4000	3785
Clean-up	0330	0400	0700	11360	666

Figure 2

PEA CANNING UNIT OPERATION: BOILER FEED WATER

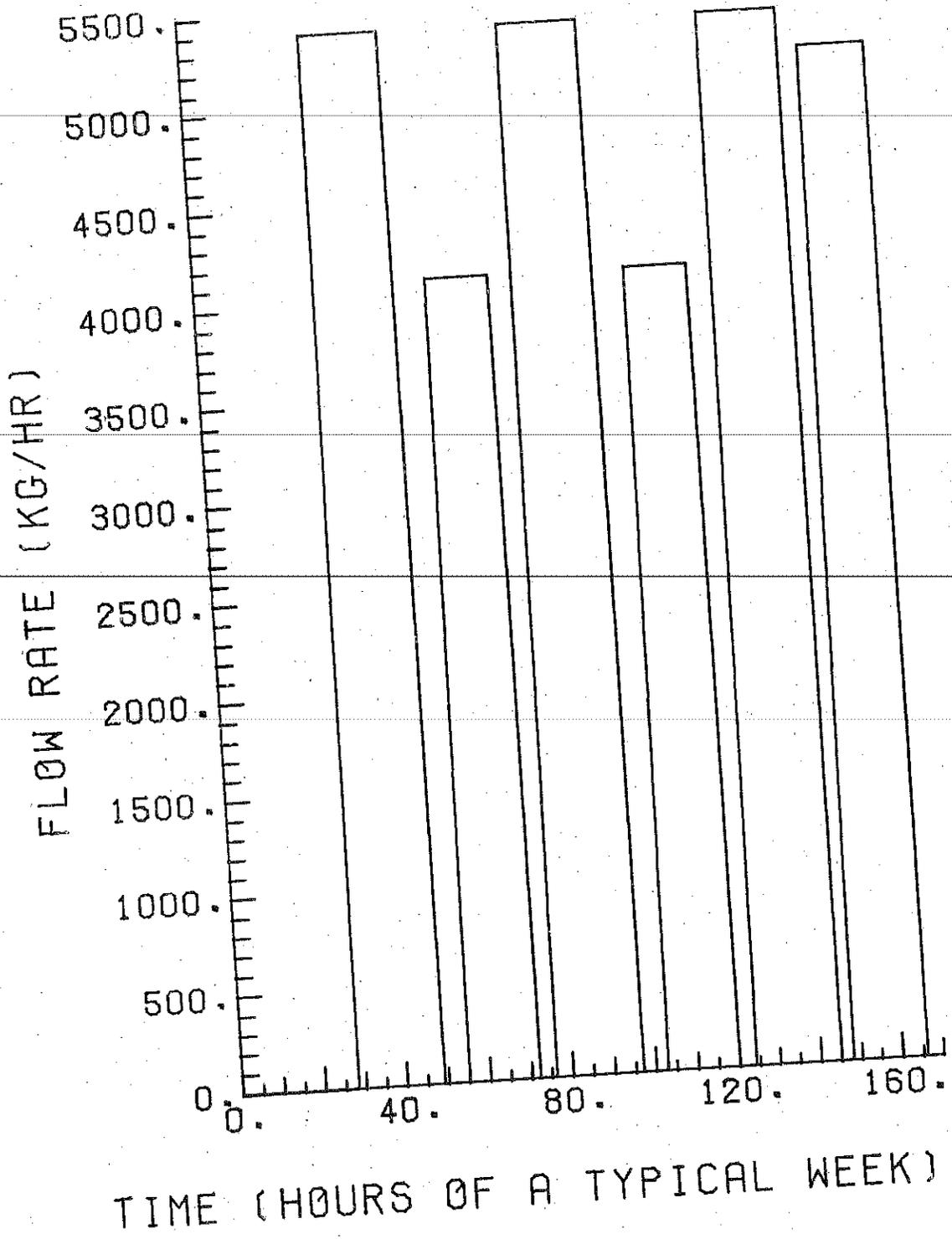
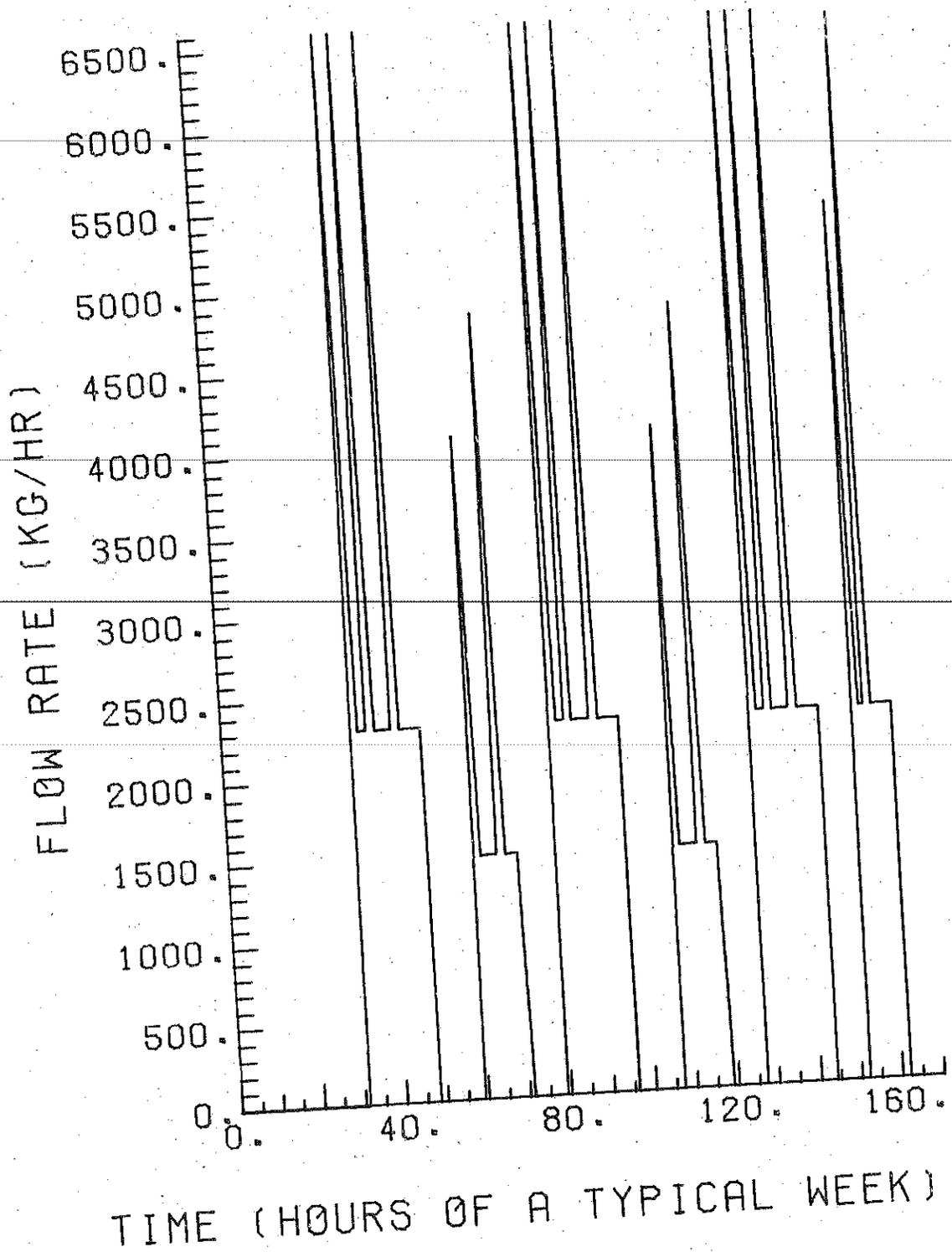


Figure 3

PEA CANNING UNIT OPERATION: BLANCHER (88°C)



PEA CANNING

UNIT OPERATION: FLUME WATER (71°C)

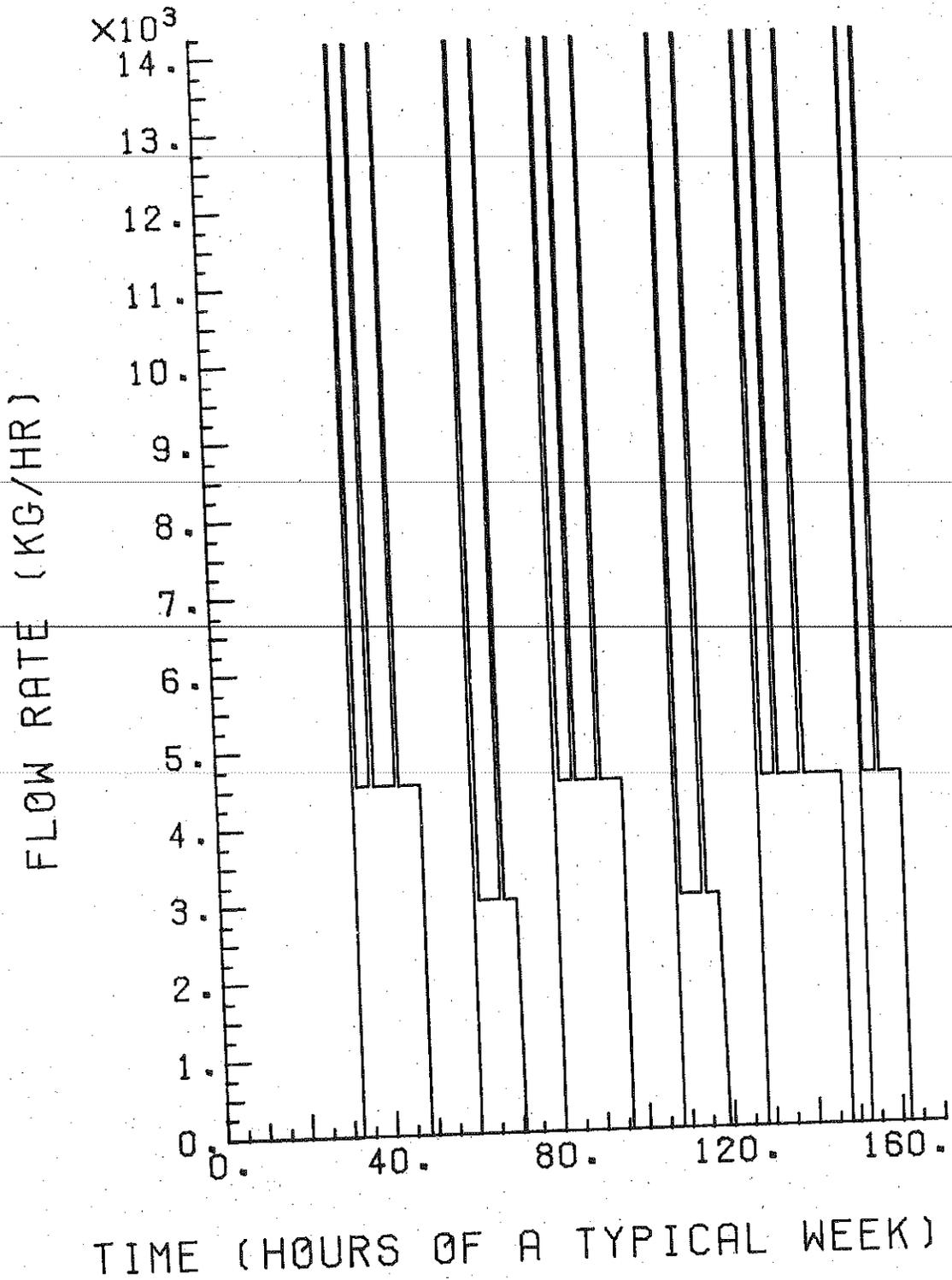
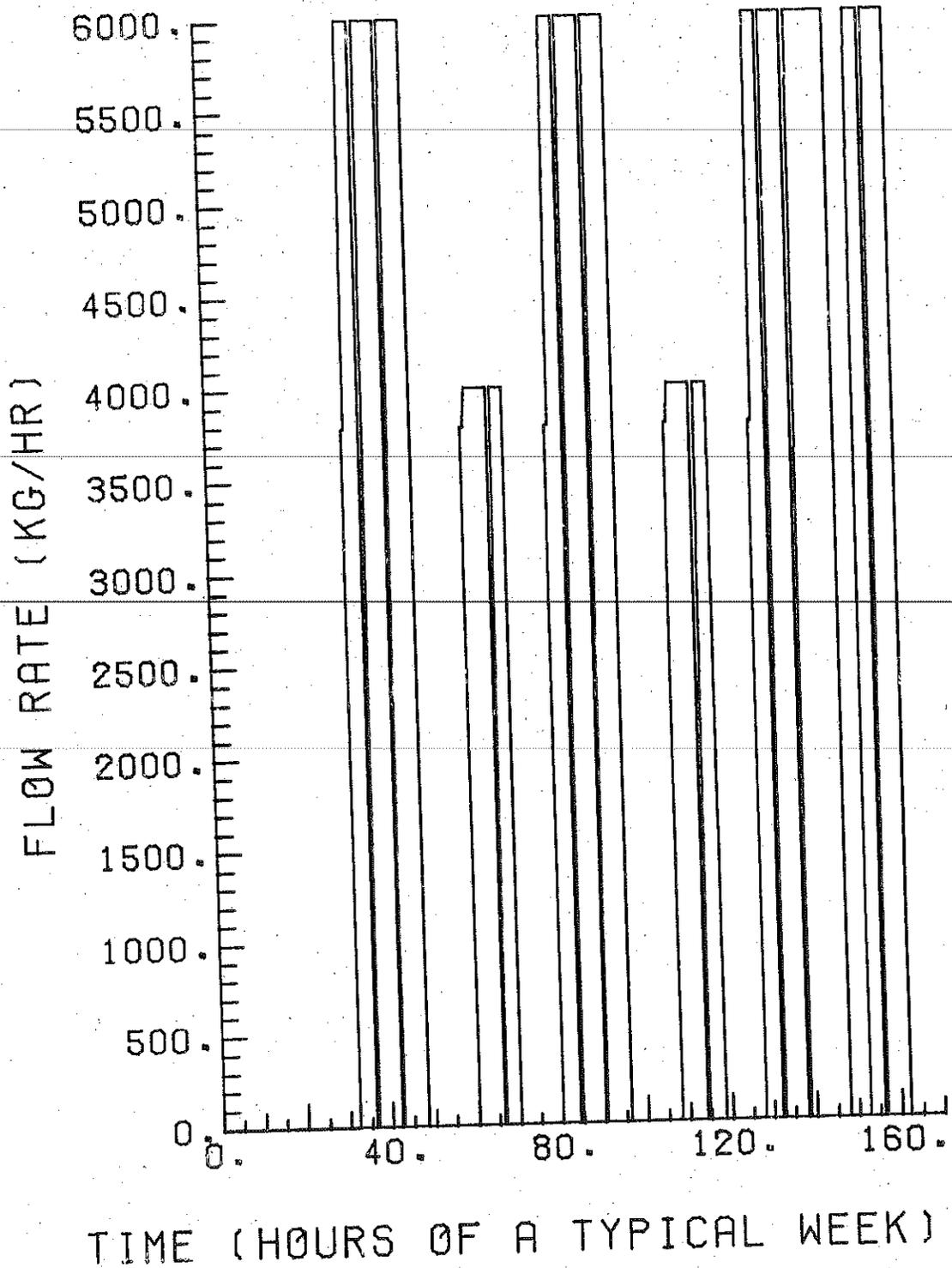


Figure 5

PEA CANNING
UNIT OPERATION: TOPPER WATER (71°C)



PEA CANNING
UNIT OPERATION: CLEAN-UP WATER (60°C)

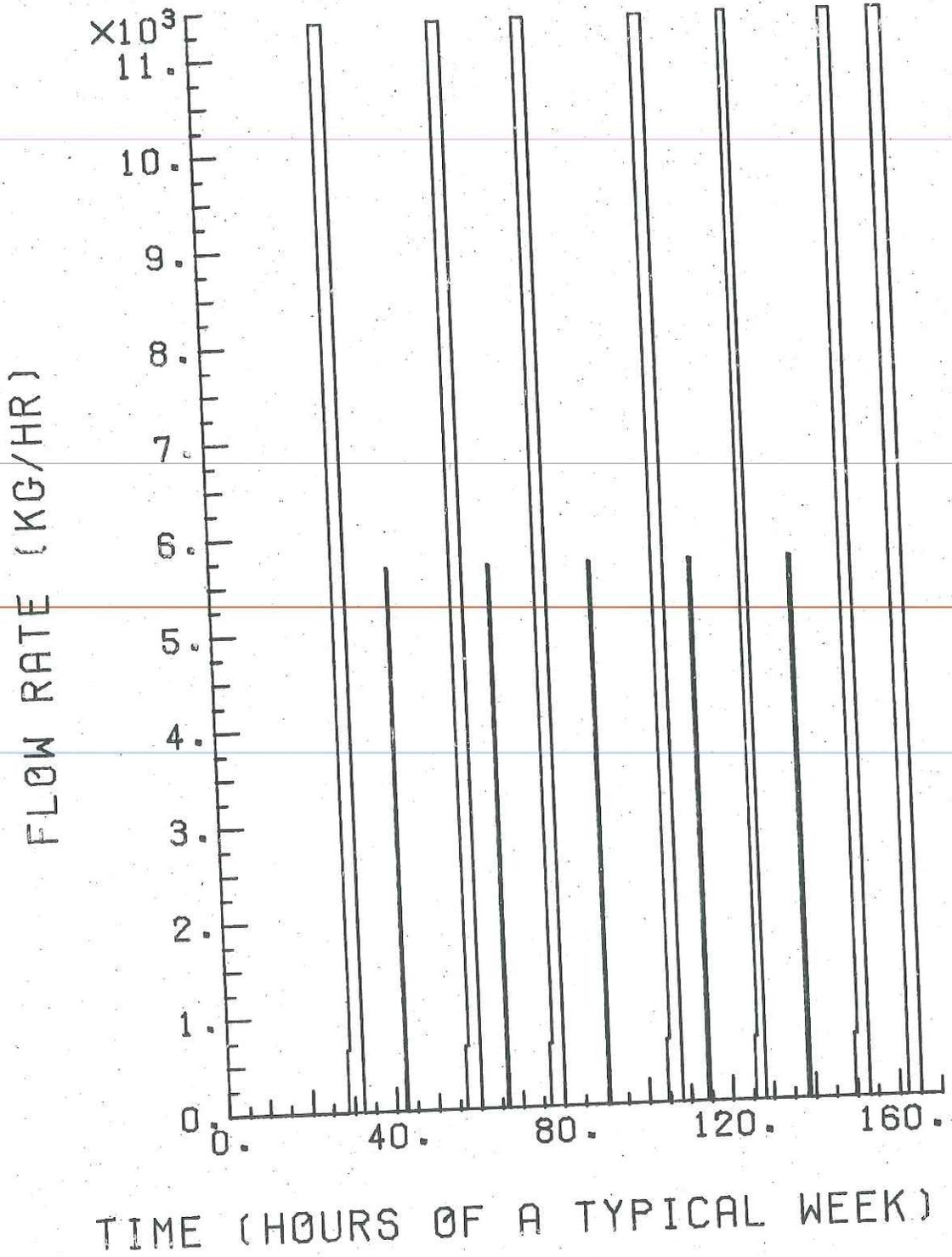


Figure 7

CORN CANNING

UNIT OPERATION: BOILER FEED WATER

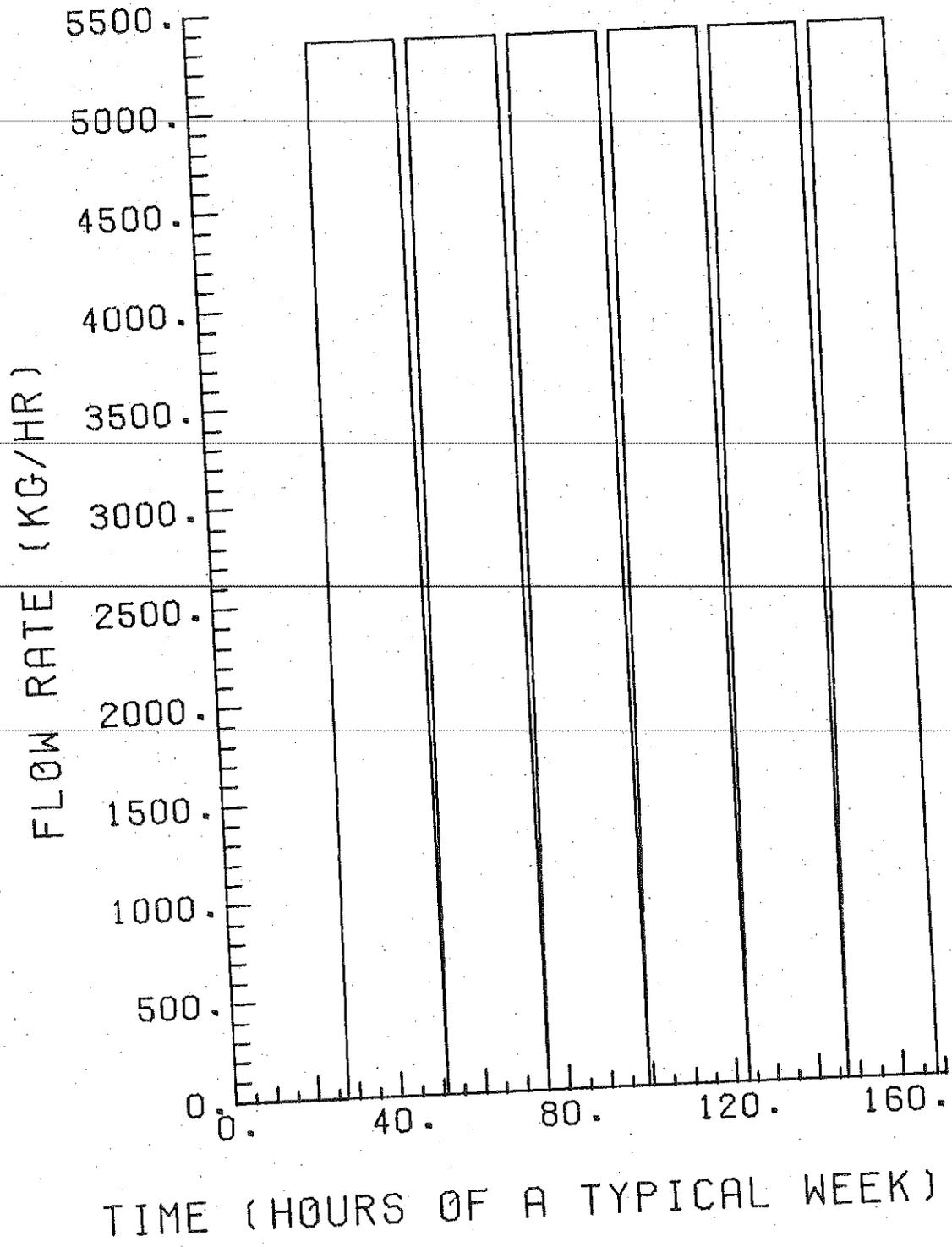
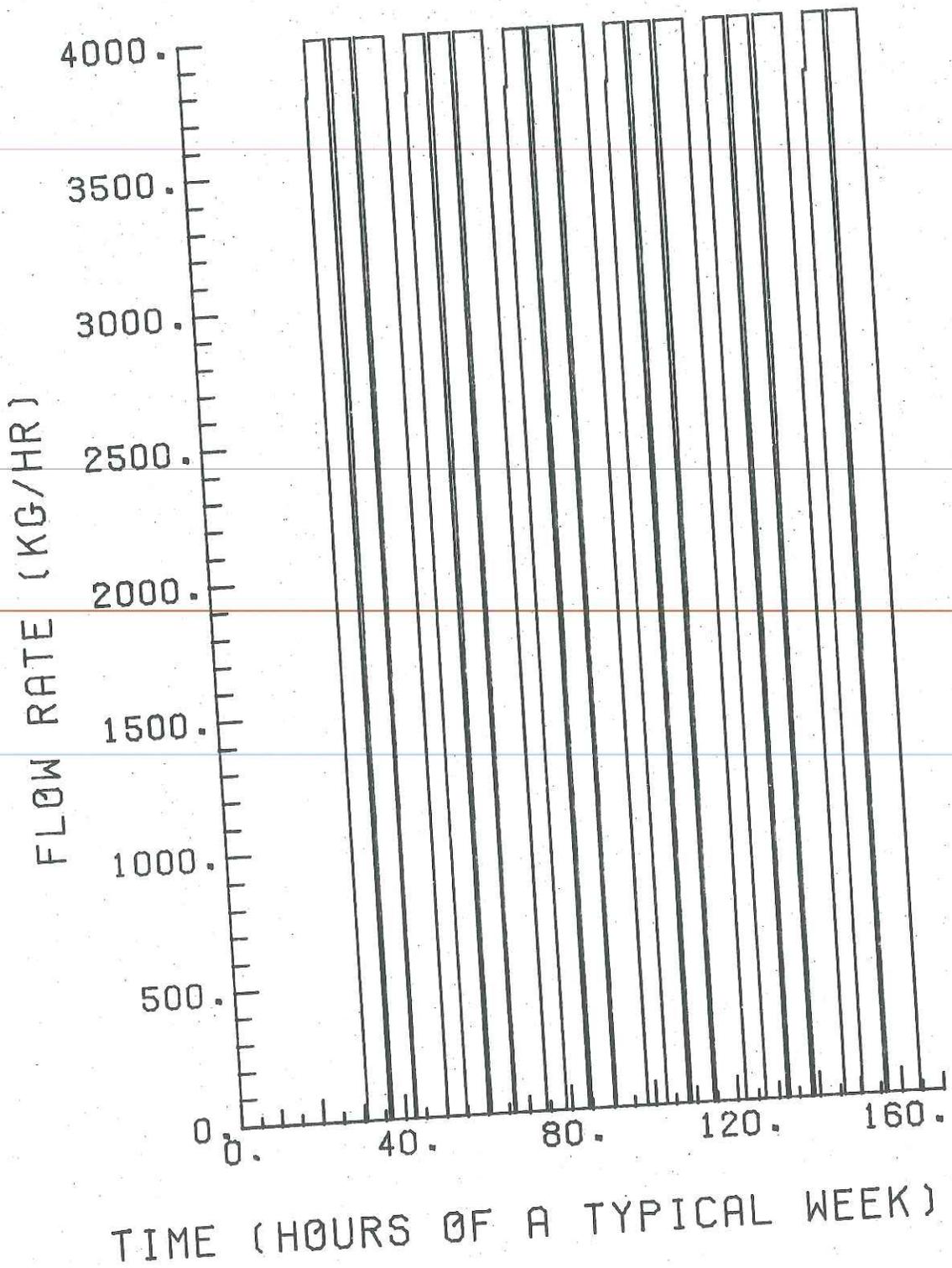


Figure 8

CORN CANNING

UNIT OPERATION: TOPPER WATER (71 °C)



CORN CANNING

UNIT OPERATION: FLUME WATER (71 °C)

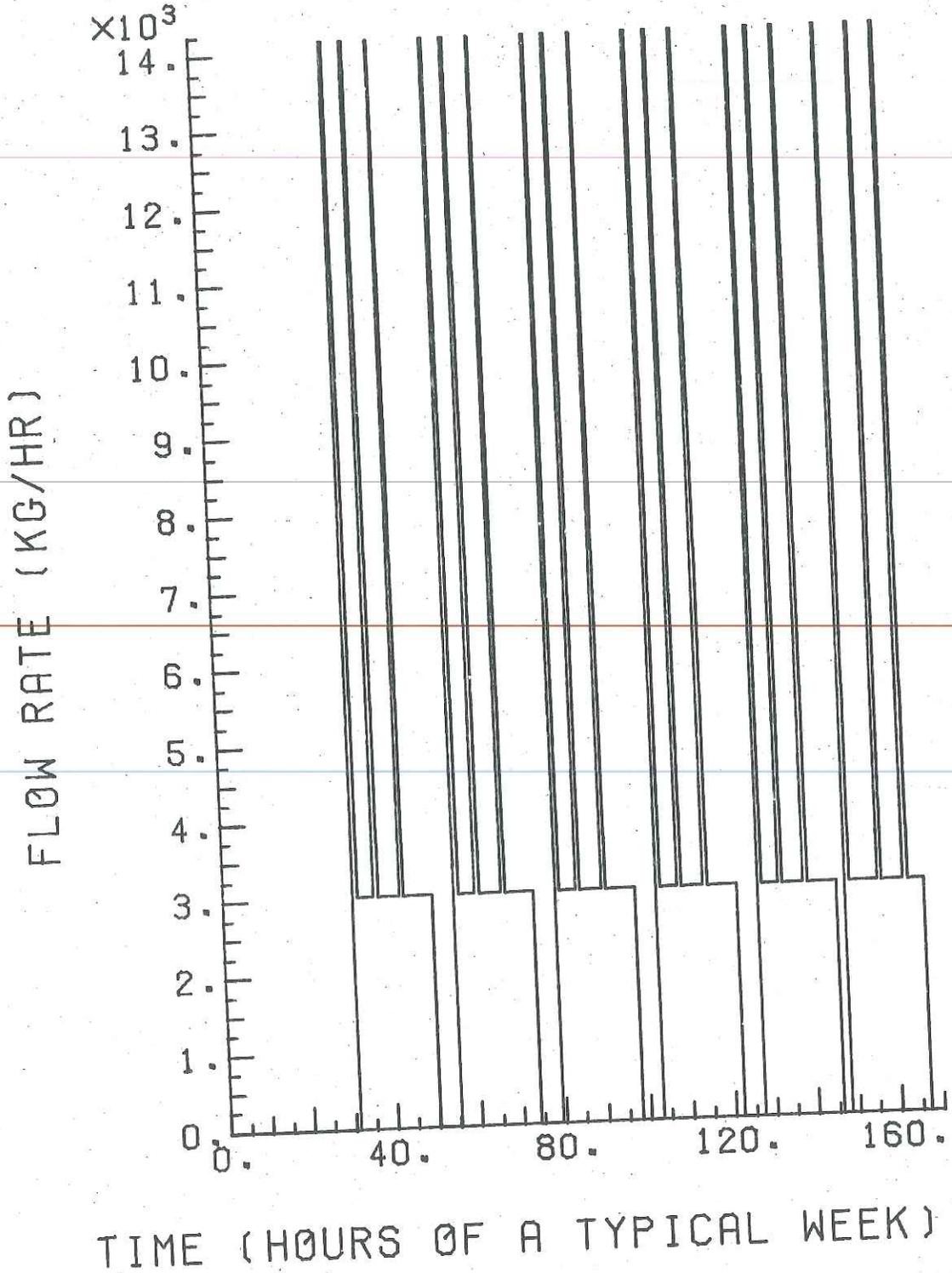


Figure 10

CORN CANNING
UNIT OPERATION: CLEAN-UP WATER (60°C)

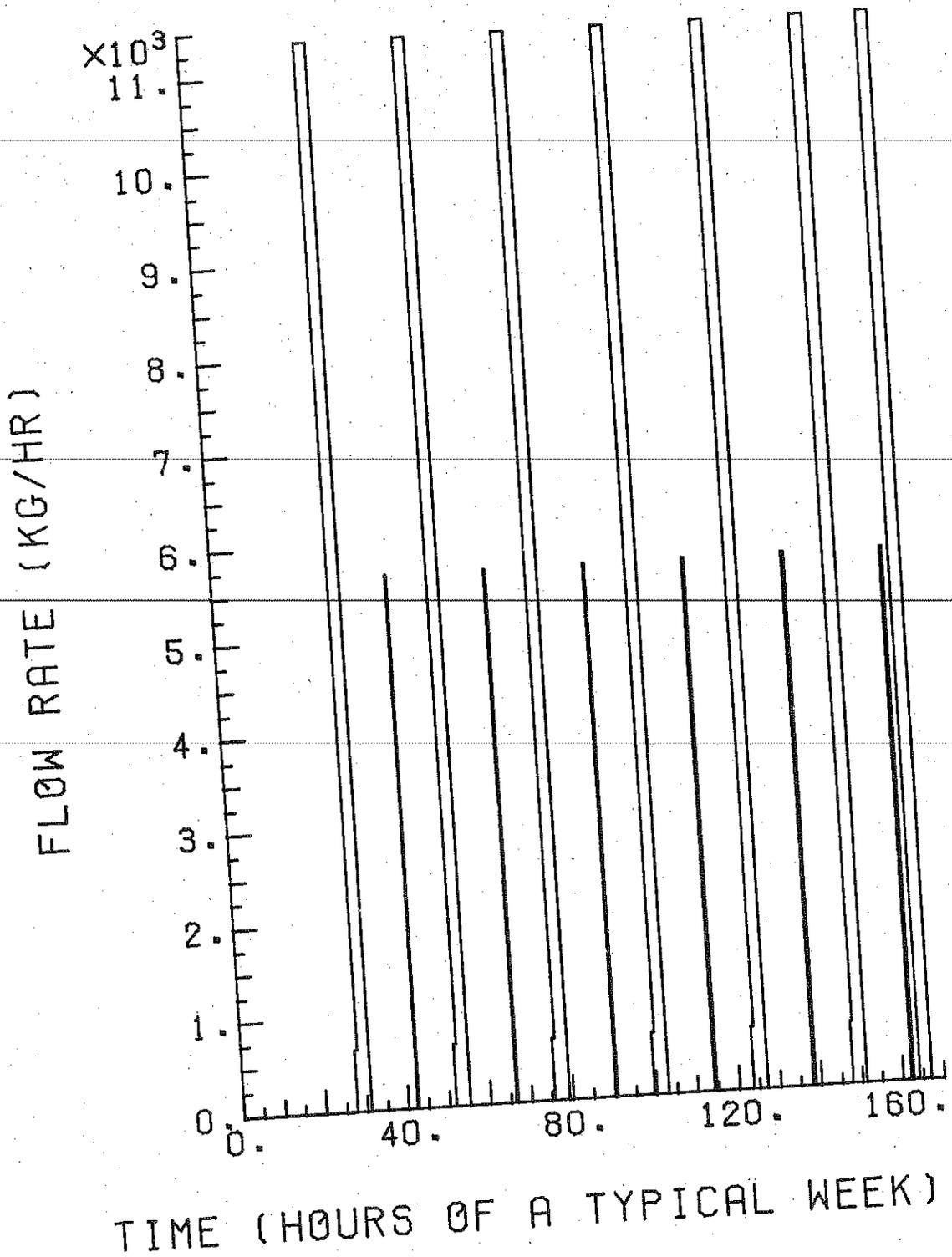


Figure 11

PEA CANNING UNIT OPERATION: TOTAL HOT WATER DEMAND

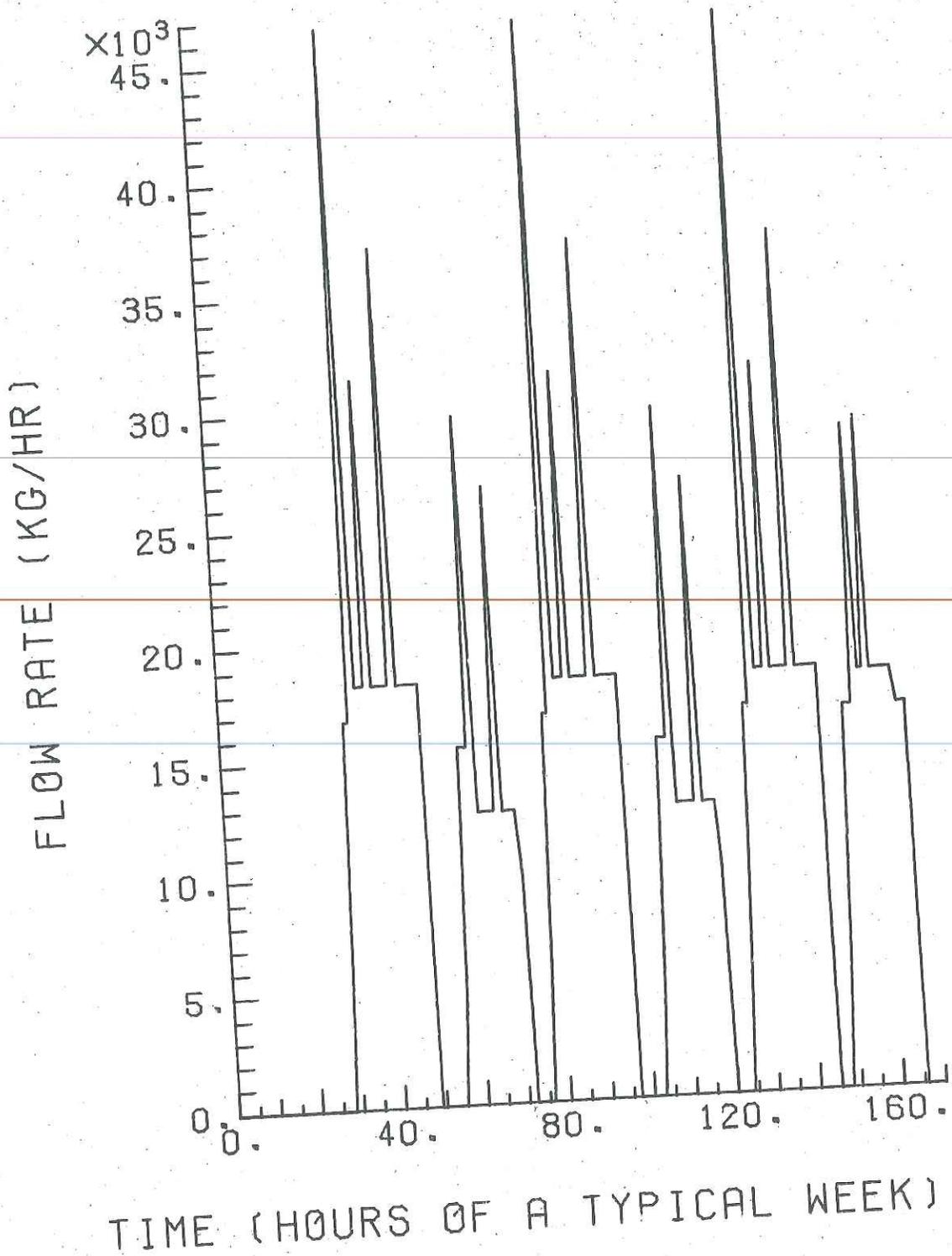
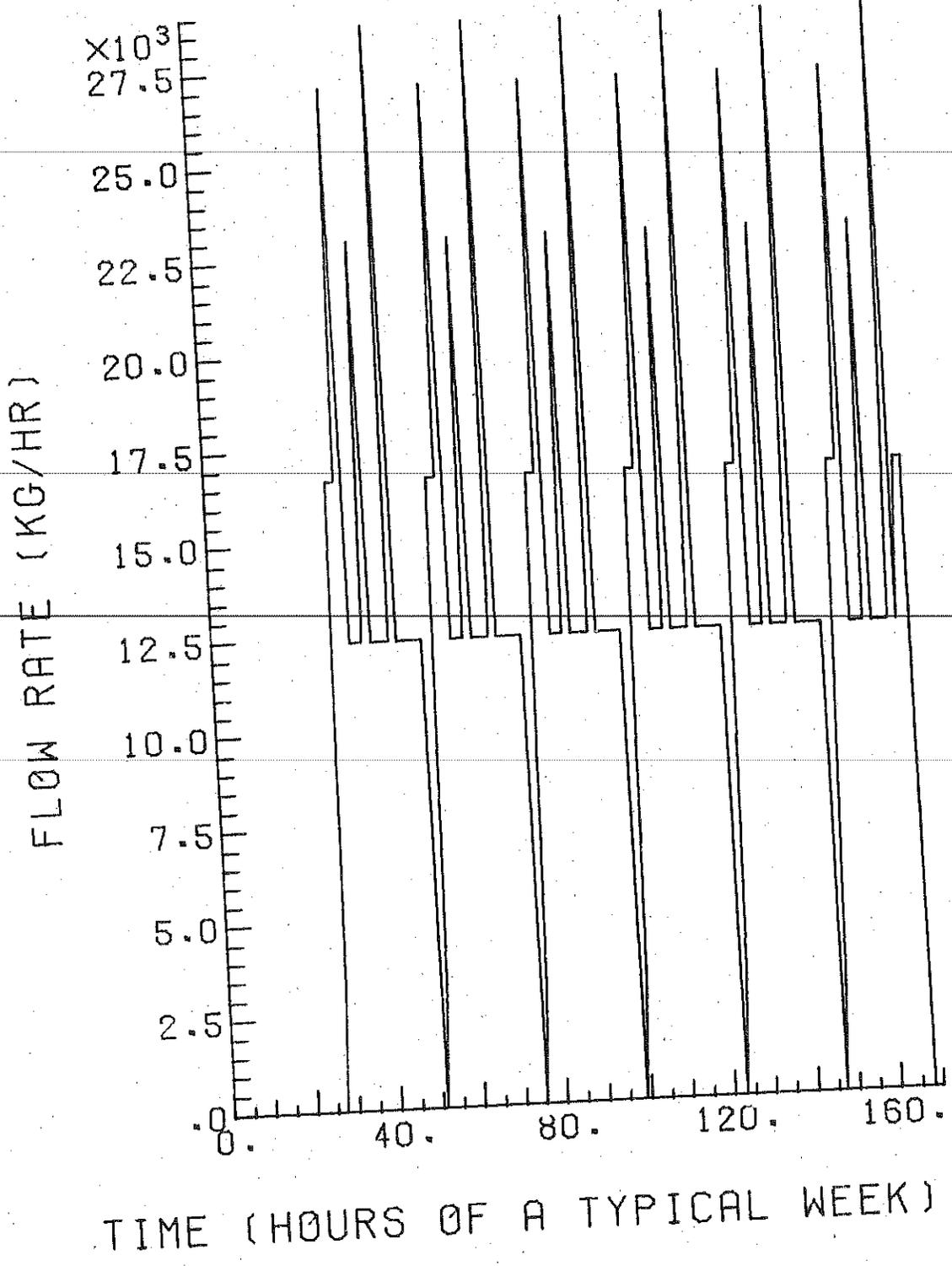


Figure 12

CORN CANNING UNIT OPERATION: TOTAL HOT WATER DEMAND



canning season is displayed in Figures 11 and 12.

The pea pack begins approximately in the middle of June and continues till the first week in August. The corn pack begins soon after the end of the pea pack and continues until about the third week in September. For each of the products the production rates (daily average) were: for peas, 47,000 kilograms per hr. (ca. 3.5 tons peas processed per hr.) and for corn, 80,000 kilograms per hr. (ca. 22 tons unhusked corn per hr.). These production rates come from actual canning records plus the amount that would have been canned had there been no freezing operation.

The energy calculations for each of the unit operations and the determination of the fraction of the total plant processing energy compatible with solar is outlined in Tables 2 thru 4. The total energy used by the plant was obtained from meter readings which were adjusted for boiler efficiency (80%) and line losses (15%) (See Table 2). The energy which went to blanching frozen products (the only large use of energy in the form of hot water for the freezing operation) was determined and subtracted from the plant demand. Also the energy available to the plant was increased by a factor representing the increase in plant energy use if the frozen vegetables were canned.

Table 2
 Total Energy Demand in the Canning Plant
 From Natural Gas Meter Readings
 Basis-A Typical Week

<u>Peas</u>	
Total KJ Available	1.47×10^3 GJ
Boiler Efficiency (80%)	1.18×10^3
Line Loss (15%)	1.00×10^3
Less Frozen Peas	9.39×10^2
Plus Canned Not Frozen	1.29×10^3
e.g. 1.29×10^3 GJ used for processing	

<u>Corn</u>	
Total KJ Available	2.09×10^3 GJ
Boiler Efficiency (80%)	1.67×10^3
Line Loss (15%)	1.42×10^3
Less Frozen Corn	1.33×10^3
Plus Canned Not Frozen	1.85×10^3
e.g. 1.85×10^3 GJ used for processing	

Table 3

Breakdown of Energy Demand
Compatible With Solar
By Season and Unit Operation

$$Q(\text{energy demand compatible with solar}) = \sum t_i M_i C_p (T_i - T_{\text{main}})$$

where

- t_i = time of flow (hr)
 M_i = mass flowrate of water (Kg/hr)
 C_p = heat capacity of water = 4.19 (KJ/Kg-°C)
 T_i = required temperature for unit operation (°C)
 T_{main} = temperature of mains water = 11.1 (°C)

unit operation	T_i (°C)	<u>PEAS</u>		<u>CORN</u>	
		$\sum t_i M_i$ water Kg/7wks	Q GJ/7wks	$\sum t_i M_i$ water Kg/7wks	Q GJ/7wks
Boiler Feed	100	3.8×10^6	1.42×10^3	4.9×10^6	1.84×10^3
Blancher	88	1.6×10^6	5.12×10^2	-	-
Topper	71	2.9×10^6	7.29×10^2	3.0×10^6	7.44×10^2
Flume	71	3.1×10^6	7.70×10^2	3.3×10^6	8.28×10^2
Clean-up	60	1.7×10^6	3.40×10^2	1.8×10^6	3.59×10^2
		1.3×10^7	3.77×10^3	1.3×10^7	3.77×10^3

Total Plant Processing
 Demand Compatible
 With Solar Energy = 7.54×10^3 GJ/14wks

Table 4
 Percent of Canning Plant Energy Demand
 Potentially Compatible with Solar Energy
 Basis - A Typical Week

Pea Canning

Weekly Demand	1.29×10^3 GJ
Demand Compatible w/Solar	5.4×10^2 GJ
% Demand Compatible w/Solar	42.1 %

Corn Canning

Weekly Demand	1.85×10^3 GJ
Demand Compatible w/Solar	5.4×10^2 GJ
% Demand Compatible w/Solar	29.2 %

This last adjustment assumes the linearity of energy demand with production rate which is reasonable considering the nature of the unit operations involved in the canning process.

Next the water and energy requirement for each unit operation for each season is determined. This calculation is presented in Table 3, and represents the amount of plant energy use which is compatible with solar. This corresponds to an (solar-compatible) energy demand for each processing season of 5.4×10^2 GJ per typical week. Table 4 combines the results of Tables 2 and 3 to determine the percent of canning plant energy demand compatible with solar energy. This value for pea and corn processing is 42.1% and 29.2% respectively.

2.2 SPACE HEATING ENERGY DEMAND

2.2.1 GENERAL CONSIDERATIONS

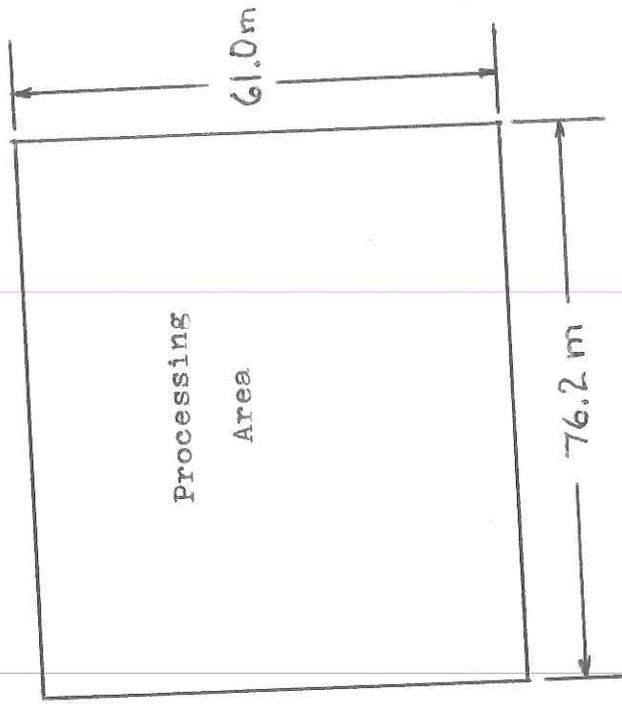
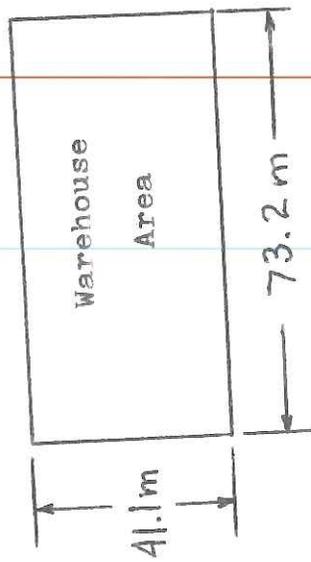
The space heating demand of any structure is influenced by many factors such as its geographic location, architectural design, orientation and construction quality. Many different methods of calculating space heating demands have been developed, ranging in complexity from the simple degree-day method to detailed computer simulations using hourly meteorological data. All of these methods involve some de-

gree of uncertainty.

The design heating load which is used in determining the long term performance of a solar system can be found in several ways. For new structures it may be determined using the building construction and the methods described in the ASHRAE Handbook of Fundamentals (7). Alternatively, if records of fuel requirements are kept, the space heating demand may be estimated using degree-day calculations (8).

2.2.2 CANNING PLANT SPACE HEATING ENERGY DEMAND

The buildings of the canning plant require a minimum set temperature of approximately 12.8°C (55°F) to prevent condensation of water and hence potential surface damage to the cans in storage. The dimensions of the plant and its layout are given in Figure 13. The processing building is of poured concrete construction with no insulation. The warehouse area consists of several connected buildings. Two of these are old wood frames with a sizable amount of window area. The other warehouse areas are sheet metal constructions. The warehouse buildings are in general very poorly insulated. The required space heating is provided by ceiling mounted natural gas fired heaters.



Volume: $V_t = (61.0 \text{ m}) (9.1 \text{ m}) (76.2 \text{ m}) + (41.1 \text{ m}) (9.1 \text{ m}) (73.2 \text{ m}) = 6.95 \times 10^4 \text{ m}^3$

Surface Area: $s_{\text{walls}} = (9.1 \text{ m}) (41.1 + 73.2 + 76.2 + 61.0) (2) = 4.6 \times 10^3 \text{ m}^2$

$s_{\text{ceiling}} = (73.2) (41.1) + (76.2) (61.0) = 7.66 \times 10^3 \text{ m}^2$

Figure 13 Dimensions of Processing and Warehouse Areas For Canning Plant

The space heating energy demand for the buildings was estimated using the degree-day method (8). This method assumes that the space heating load for a month, L_s , is approximately proportional to the number of degree-days in that month, DD , with the overall building energy loss coefficient, UA , being the proportionality constant:

$$L_s = UA \times DD$$

The number of degree-days is the difference between the required building temperature and the mean ambient temperature multiplied by the time period of the analysis.

The effective UA of the plants buildings was calculated using plant records of natural gas usage for the 1976-77 winter season and daily maximum and minimum data of ambient temperature for the same period provided by the National Weather Service Office at Truax Field in Madison, Wisconsin (9). The natural gas usage is presented in Table 5. The data is converted from cubic feet to BTU's corrected for heating efficiency (0.80) and then converted to GJ's. Monthly average demands are estimated using linear corrections. The degree-days during these months were found by subtracting the average ambient temperature from each day

Table 5
Heat Plant Buildings
Used To
Less Heating
Efficiency

Date	Plant	Ware-house	Total	Energy Rating BTU/ft ³	BTU	Less Heating Efficiency .80	GJ
9/24-10/25 '76	---	57	57	1015	5.79x10 ⁶	4.63x10 ⁶	5
10/25-11/23 '76	12360	5355	17715	1015	1.798x10 ⁹	1.438x10 ⁹	1518
11/23-12/23 '76	12760	8702	21462	1015	2.178x10 ⁹	1.743x10 ⁹	1839
12/23- 1/24 '77	12570	12412	24982	1014	2.53x10 ⁹	2.02x10 ⁹	2138
1/24- 2/22 '77	8150	7955	16105	1017	1.64x10 ⁹	1.31x10 ⁹	1382
2/22- 3/23 '77	5850	4058	9908	1022	1.013x10 ⁸	8.101x10 ⁸	810
3/23- 4/25 '77	2910	2182	5092	1018	5.18x10 ⁷	4.15x10 ⁸	438
4/25- 5/23 '77	370	453	823	1024	8.43x10 ⁷	6.74x10 ⁷	71

	Plant	Ware-house	Total	Conversion To Months	Heating Load GJ
January '77	(24)	2138	31	1382	2001
February '77	(22)	1382	28	810	1243
March '77	(23)	810	31	438	718
April '77	(25)	438	30	71	376
-----		5	31	1518	308
October '76	(25)	31	30	1839	1579
November '76	(23)	1518	31	2138	1916
December '76	(23)	1839	31		

from the required set temperature, 12.8°C , and summing the positive differences over the month. These values and the calculations of UA for each month are presented in Table 6.

Degree-day calculations work best for periods of time where the ambient temperature is always much lower than the desired building temperature. For this reason the UA found for January, February and December were averaged to obtain an effective building UA of $2.856 \times 10^4 \text{ W/}^{\circ}\text{C}$. Using this value for UA and values of design degree-days per month, an average space heating demand for each month can be found.

These design degree-days per month are found by subtracting the long term average ambient temperature for a month from the desired building temperature and multiplying by the days in the month. Monthly long term average ambient temperatures for a number of locations may be found in reference (8). Table 7 shows the calculation of the design degree-days per month and the design heating load per month. This space heating demand is a suitable estimate for design purposes.

Table 6

Determination of Average UA

$$UA \left(\frac{W}{^{\circ}C} \right) = \frac{\text{Heating Load (GJ)}}{\text{Month}} \times \frac{\text{Month}}{\text{Degree-Days} (^{\circ}C)}$$

$$\times \frac{\text{day W}}{86400 \text{ J}} \times \frac{10^9 \text{ J}}{\text{GJ}}$$

	Heating Load from Plant Rec. (GJ)	Degree $^{\circ}C$ Days	UA $\left(\frac{W}{^{\circ}C} \right)$
January '77	2001	882	2.626×10^4
February '77	1243	504	2.854×10^4
March '77	718	257	3.234×10^4
April '77	376	61	7.134×10^4
- -			
October '76	308	192	1.857×10^4
November '76	1579	446	4.098×10^4
December '76	<u>1916</u>	<u>718</u>	3.089×10^4
	8141	3060	

$$UA_{\text{Avg}} = \frac{UA_{\text{Jan}} + UA_{\text{Feb}} + UA_{\text{Dec}}}{3} = 2.856 \times 10^4$$

Table 7
 Determination of Design Space Heating Load

$$(D.D.)_{design} = (12.8 - T_{amb}) \times \text{days/month}$$

$$\text{Design Heating Load} = UA_o \frac{W}{C} \times (D.D.)_{design} \times (86400 \frac{GJ}{\text{day W}})$$

$$UA = UA^{avg} = 2.856 \times 10^4 \frac{W}{C}$$

	<u>(D.D.)_{design}</u>	<u>Design Heating Load (GJ)</u>
January	$(12.8 - (-8))(31) = 644$	1589
February	$(12.8 - (-6))(28) = 526$	1298
March	$(12.8 - (0))(31) = 396$	977
April	$(12.8 - 7)(30) = 174$	429
October	$(12.8 - 10)(31) = 87$	215
November	$(12.8 - 1)(30) = 354$	874
December	$(12.8 - (-5))(31) = \frac{552}{2733}$	$\frac{1362}{6744}$

3.0 THE SOLAR ENERGY COLLECTION SYSTEM

3.1 GENERAL SYSTEM DESCRIPTION

Solar energy intensity incident on the earth's surface is low. Integrated energy quantities however are sizable. For instance, in Madison, Wisconsin the average annual solar energy incident per day on an acre of ground is equivalent to about 10 barrels of oil (10).

In this study the solar collection systems considered contain flat-plate collectors. The flat-plate collector is a unique heat exchanger which uses a black absorber plate to absorb solar energy. Ducts or tubes carry air or liquid that remove energy from the plate. Layers of air between the plate and its cover (usually made of glass) provide transparent insulation and thus reduce heat loss. Conventional insulation is provided on the backs and edges of the plates. The collectors are mounted in a fixed position which maximizes the amount of useful collected energy.

Flat-plate collectors are designed for applications requiring energy delivery at moderate temperatures, up to about 100° C. They have the advantage of not requiring orientation toward the sun and needing little maintenance. They are mechanically simpler than con-

centrating reflector, absorbing surfaces and orientation devices of focusing collectors. A more detailed discussion of the flat-plate collector is presented in Solar Energy Thermal Processes (11).

Considering the large amount of hot water required in food processing plants and their already existing backup system (steam boiler) a liquid solar system is a more appropriate choice than an air system for retrofit. An air solar system circulates air through the flat-plate collectors and then either directly to the room for space heating purposes, through air-water heat exchanger to provide hot water or to a large packed bed of rocks for sensible heat storage for energy use later. The air-water heat exchanger required for the air system to provide processing hot water would have to be very large. A liquid solar system circulates liquids and stores sensible energy in a large tank of water. In this system a large liquid air heat exchanger is required to provide space heating. Since the space heating load in a food processing plant is usually smaller than the processing energy load, the liquid system seems to be the more appropriate choice.

A schematic diagram of a liquid solar heating system integrated into a food processing plant is shown in Figure 14. The system considered uses antifreeze and water as the energy transfer and storage mediums, respectively. The antifreeze solution is circulated through the collector to avoid the problems of freezing and corrosion. A double-walled heat exchanger is generally required between the antifreeze and water used in processing foods by government regulations. The plant's boiler and steam lines provide energy for both the space and water heating loads when the energy in the storage tank is not sufficient to do the job. Controllers, relief valves, pumps and piping make-up the remaining equipment.

3.2 DESIGN PARAMETERS

When designing a solar energy system, a number of important parameters must be considered. Three such parameters which have attracted much attention are the collector fluid flowrate per unit collector area, the storage volume per unit collector area and the size of the space heating load heat exchanger.

Obviously for maximum solar energy collection, the liquid fluid flowrate would have to be infinitely

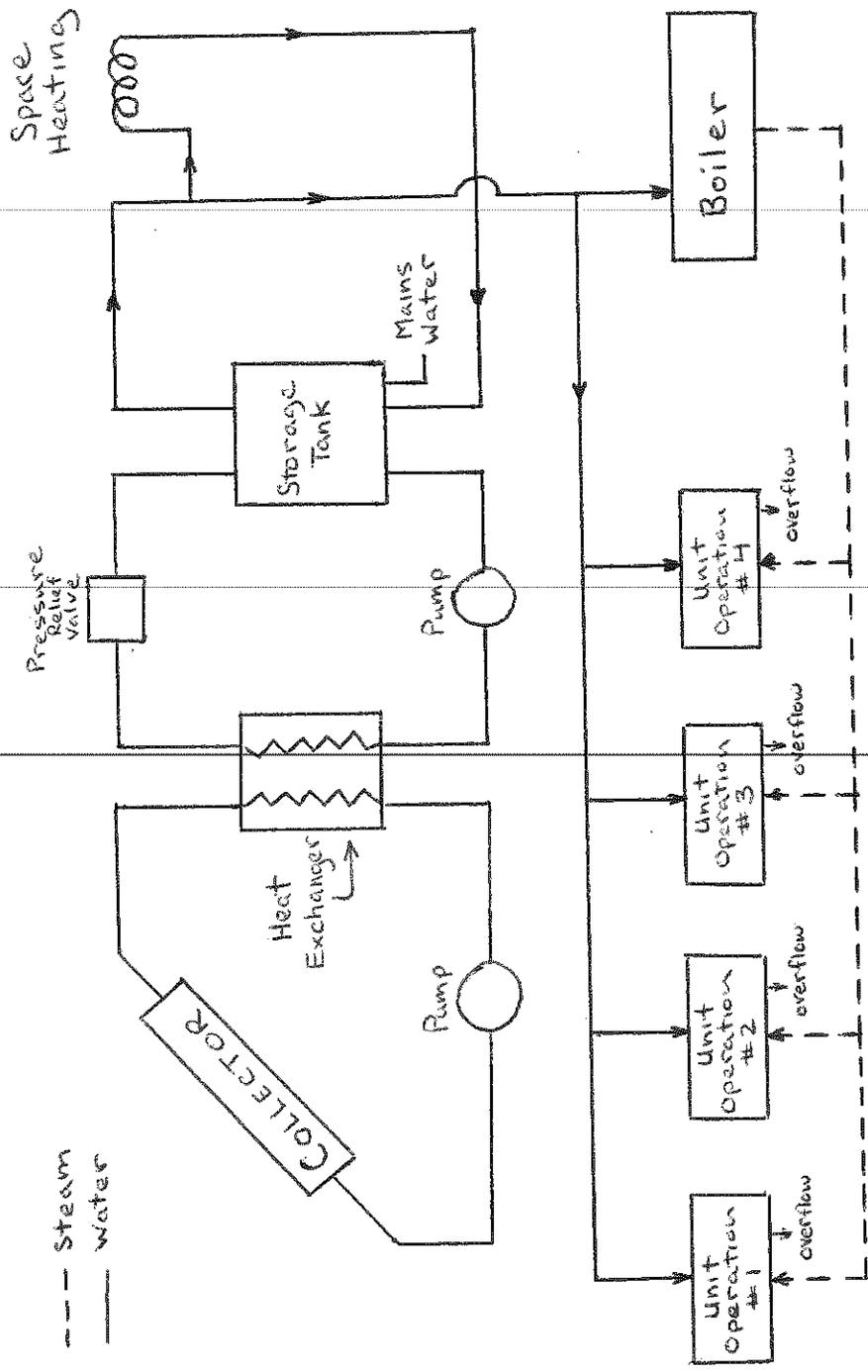


Figure 14 Schematic of Solar System Retrofit Into A Food Processing Plant

large. It has been found however, that only a small gain in energy collection is realized if the collector fluid flowrate is increased above about 54 liters per hour-square meter. This value is widely used in solar system design (8).

From many simulation studies, it has been found that if the storage capacity is greater than about 50 liters of water per square meter of collector, only small improvements in system performance is attained from added storage volume. Considering the costs of the storage area, broad optima in the range of 50 to 100 liters of water per square meter of collector have been found for domestic space heating applications (8). The value of 75 liters of stored water per square meter of collector is commonly used for design purposes.

The third important design parameter is the size of the space heating load heat exchanger. The smaller this heat exchanger is, the higher the storage tank temperature must be to supply the same amount of heat. A larger storage tank temperature results in higher fluid temperature entering the collector with necessary reduction in collector efficiency. The size of the heat exchanger can be represented by the dimensionless

parameter:

$$e_L C_{\min} / UA$$

where:

e_L is the effectiveness of the water-air load heat exchanger

C_{\min} is the minimum fluid capacitance rate (specific heat of the fluid times the mass flowrate) in the heat exchanger. This is generally that of the air for this heat exchanger.

UA is the overall energy loss coefficient-area product for the building.

The optimum value for this parameter is infinitely large. However, only a small improvement in solar system performance is achieved for values greater than about 10. When costs are considered, practical values of the parameters are found in the range of 1 to 3 (8).

Other important design parameters of solar systems are the collector area, the transmittance of the transparent collector cover system, the absorptance of the collector plate, collector orientation, collector heat loss coefficient, storage tank heat loss coefficient, collector efficiency factor, ground reflectance and heat exchanger effectiveness. Typical values of these parameters can be arrived at by the methods outlined by Duffie and Beckman (11).

3.3 DETERMINATION OF SOLAR SYSTEM PERFORMANCE

The performance of a solar energy collection system in a food processing plant can be determined using two computer programs developed by the Solar Energy Laboratory of the University of Wisconsin-Madison. These programs are TRNSYS and FCHART.

TRNSYS (12) is a modular solar energy simulation program written in Fortran that solves for the transient performance of system components (collectors, storage, pumps, etc.) joined together by information flow which represents pipes, ducts and wires in response to time varying forcing functions like hourly meteorological data and the hourly hot water demand.

TRNSYS component models are self-contained sub-routines having constant parameters, user supplied, describing the modelled hardware, time varying "inputs" representing time dependent information flowing into the model, and time varying "outputs" representing time dependent information flow out of the model. TRNSYS includes all of the mechanics necessary to govern input / output operations and solve the components' simultaneous algebraic and differential equations repeatedly.

TRNSYS models the thermal performance of flat-

plate solar collectors with forced fluid circulation using the model of Hottel (13) and Whillier (14). (See also Bliss (15).) This model, HW, leads to computational simplicity and excellent agreement with more elaborate models. For a detailed description of the HW model see Duffie and Beckman (11).

FCHART is a computer program which estimates the long-term thermal performance of a standard solar energy system developed by Klein, et. al. (8). The f-chart approach is to identify the important dimensionless variables of solar energy systems and to use detailed computer simulations to develop correlations between these variables and the long-term performance of these systems. The result is a simple method requiring only monthly average meteorological data which can be used to estimate the long-term thermal performance of solar heating systems as a function of the major system design parameters.

FCHART has the advantage of being computationally simpler and hence more economical than TRNSYS but necessarily does not give sufficiently accurate results for design purposes. This is especially true in the case of industrial hot water demand. The f-chart method is based on an average time distribution of water usage

typical of a residential home, basically the same hourly distribution, seven days a week. Hot water supplies for industries are needed on five or six days of the week, and not on the weekend. If water is not used for one or two days of the week, the temperature of the water in the storage tank will rise, and energy will then be collected less efficiently. In this case, the fraction of the heating load supplied by solar energy as determined by the f-chart method will be too high.

The f-chart method can be used to estimate the fraction of the space heating load which would be supplied by the solar system. This can be done with reasonable accuracy when the space heating and processing seasons do not overlap and when the desired room temperature is not far from 72° F. If the space heating and processing seasons do overlap, the storage tank will be supplying energy to both demands. Here, combining FCHART space heating and TRNSYS processing simulations would underestimate the performance of the system by not taking into account the lowered storage tank temperature and hence higher collection efficiency. In this case TRNSYS should be used to determine the performance of the solar system in meeting the processing and space heating demands simultaneously. If the processing and space heating sea-

sons do not overlap, FCHART would be able to give a sufficiently accurate determination of the fraction of the space heating demand met by the solar system.

Due to the change in incidence angle of solar radiation with season of the year, and the uneven division of plant energy demand between space heating and processing, an optimum collector orientation must be determined which will be unique to the plant in question. This orientation can be determined with sufficient accuracy using FCHART with the appropriate approximate monthly space heating and processing energy demand. The orientation parameters are varied until the fraction of energy supplied by the solar system is maximized. These optimum parameters are used in the individual FCHART and/or TRNSYS experiments.

The recommended procedure to evaluate the thermal performance of a solar energy system is to combine the accuracy of TRNSYS with the less expensive nature of FCHART. This can be done by first carrying out TRNSYS (and FCHART if the space heating season does not overlap a processing season) determination for each seasonal demand and then combining results to obtain a yearly fraction of the energy demand supplied by solar energy.

These determinations should be done at equally spaced solar systems sizes (collector areas) up to a reasonable limit. This limit could be imposed by availability of roof area for collectors, economic constraints, or energy requirements.

FCHART can be made to duplicate the above calculated results of the solar system performance. Using f-chart version 3.0 (which allows variable water set temperatures per month and thus different monthly energy demand for hot water) a model is constructed consisting of parameters to match the total energy demand for the plant in question. The parameters are then adjusted such that the f-chart predicted system performance compares as favorably as possible to the above calculated results (keeping the energy demand constant). In effect, even though the f-chart method is not designed to investigate the performance of an industrial solar system, it can be forced to match calculated results at equally spaced collector areas and then be used to interpolate performance at other collector areas. These results are sufficiently accurate and less expensive to obtain.

3.4 PERFORMANCE OF CANNING PLANT SOLAR SYSTEM

In order to determine the performance of a solar

energy system in the canning plant, it is necessary to characterize the system by realistic parameters. Table 8 lists the values of the parameters used in this study. These values are typical of a collector system with two glass covers. Multiple transparent covers reduce convection heat losses. The collector slope of 36° is the optimum collector orientation for the plant. It was determined by inserting into FCHART the monthly space heating demand and approximate monthly processing demand (along with the parameters in Table 8). The slope was then varied until the yearly performance of the solar system was maximized. This collector slope is used in all simulations.

3.4.1 CANNING PLANT SOLAR PROCESS ENERGY

The performance of the solar system in meeting the processing demand is determined using TRNSYS. The meteorological data used in the simulations is the "design" year for Madison developed by the Solar Energy Laboratory of the University of Wisconsin (16), using eight years of meteorological data. The design year was constructed by selecting, for each month of the year, that month of data from the eight year period which most closely corresponded to the average monthly insolation and ambient

Table 8
 Specifications of a Two Glass Cover
 Flat-Plate Collector Solar System
 Madison, Wisconsin

Latitude	43°
Collector Slope	36°
Azimuth Angle	0°
Ground Reflectance	0.2
Collector Efficiency Factor	0.95
Heat Capacity, Glycol	3.5 KJ/Kg°C
Heat Capacity, Water	4.19 KJ/Kg°C
Collector Loss Coefficient	14.4 KJ/m ² hr
Transmittance	0.82
Plate Absorbance	0.94
Collector-Storage Heat Exchanger Effectiveness	0.85
Space Heating Heat Exchanger Effectiveness	0.80
Temperature of Mains Supply Water	11.1° C
Storage Tank Energy Loss Coefficient	1.5 KJ/m ² hr
Ratio of Storage Tank Height to Volume	3.35
Ratio of Storage Tank Volume to Collector Size	0.075 m ³ /m ²
Collector (and Storage) Fluid Flowrate	54.0 Kg/hr m ²
$\frac{e_L C_{min}}{UA}$	2.00

temperature. Hourly values of solar energy incident on the tilted collector surface are determined from hourly values of total radiation on a horizontal surface by the Liu and Jordan method (17). This method involves taking the total radiation on a horizontal surface and separating it into beam and diffuse components. The beam component is corrected for incidence angle on the tilted collector surface and the diffuse component is assumed to be evenly distributed throughout the collector-to-sky view factor.

To simplify the calculations and minimize the computational effort both the collector heat loss coefficient and the transmittance of the transparent collector cover system are considered constant. Also, for the same reason, the liquid storage tank is modeled as a fully mixed tank.

The performance of the solar system as determined by TRNSYS can be observed through the following output. Most important is the amount of useful energy provided by the system to meet the energy demand. The fraction of the energy demand met by solar is then found by dividing the useful energy supplied by the total amount of energy required. The efficiency of solar energy collection, which is the amount of solar energy collected

divided by the amount of solar radiation incident on the collector surface, is a good measure of system performance. The efficiency is directly related to the storage tank temperature. TRNSYS has the ability to output both hourly and an average storage tank temperature.

The above defined TRNSYS simulation program, used in this study, is schematically portrayed in Appendix A. It was used to investigate the performance of the retrofit solar system in the canning plant in two experiments. It was first used to evaluate the performance of individual solar energy systems dedicated to each of the unit operations in pea canning. The results of these experiments are displayed in Table 9. The second experiment used one solar energy system to service all of the unit operations in pea canning. The results of this experiment are displayed in Table 10 along with the results of a similar investigations for the corn canning season. For both experiments, the water demand models used were those determined in this section and displayed graphically in Figures 2 thru 12.

The results of these experiments are best observed through analysis of the relation between solar collection efficiency and collector area shown in Figure 15. At all practical collector areas, the efficiency of

Table 9

49

Results of TRNSYS Simulations of
Solar Systems Used Exclusively For Each
Unit Operation of Pea Canning

<u>Collector Area (m²)</u>	<u>Useful Solar Energy GJ</u>	<u>Solar Collection Efficiency</u>	<u>Average Storage Temperature (°C)</u>	<u>Percent Solar</u>
<u>Boiler Feed</u>				
100	6.34x10 ¹	.75	18.2	4.5
500	2.60x10 ²	.62	29.0	18.3
1000	4.34x10 ²	.53	40.0	31.2
2000	6.99x10 ²	.41	55.5	49.3
3000	8.76x10 ²	.35	66.3	61.7
4000	1.00x10 ³	.30	74.1	70.7
<u>Flume</u>				
100	6.17x10 ¹	.73	19.9	8.0
200	1.16x10 ²	.69	23.1	15.0
500	2.47x10 ²	.59	32.2	32.0
1000	4.12x10 ²	.49	44.3	53.5
2000	6.34x10 ²	.38	60.8	82.3
<u>Topper</u>				
100	6.13x10 ¹	.73	20.2	8.4
200	1.14x10 ²	.69	23.5	15.7
500	2.44x10 ²	.58	32.8	33.4
1000	4.04x10 ²	.48	45.2	55.4
2000	6.18x10 ²	.37	62.1	84.7
<u>Blancher</u>				
100	5.83x10 ¹	.69	22.7	11.4
200	1.05x10 ²	.62	28.6	20.4
500	2.09x10 ²	.50	43.2	40.9
1000	3.23x10 ²	.38	59.5	63.0
2000	4.49x10 ²	.27	77.9	87.6
<u>Clean-up</u>				
100	5.31x10 ¹	.63	31.7	15.6
200	1.01x10 ²	.60	35.8	29.6
500	2.10x10 ²	.50	48.1	61.6
1000	3.28x10 ²	.39	63.0	96.4
2000	4.59x10 ²	.27	80.0	100.0

Table 10

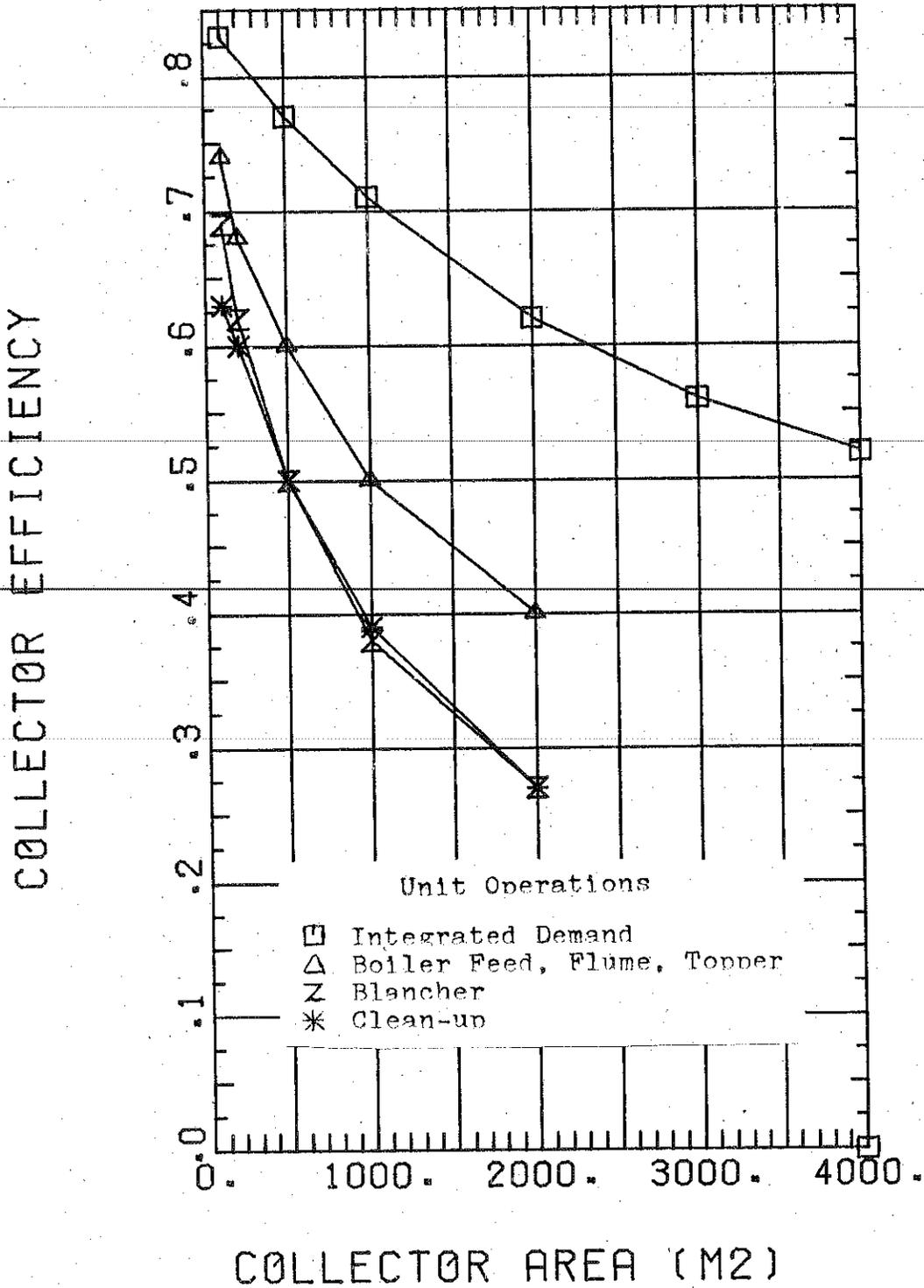
Results of TRNSYS Simulations of a
Solar System Used to Service all
of the Unit Operations of the Canning Plant

<u>Peas</u>				
<u>Collector Area (m²)</u>	<u>Useful Solar Energy GJ</u>	<u>Solar Collection Efficiency</u>	<u>Average Storage Temperature (°C)</u>	<u>Percent solar</u>
100	8.38x10 ¹	.83	16.7	2.2
500	3.91x10 ²	.77	20.6	10.4
1000	7.17x10 ²	.71	24.8	19.0
2000	1.26x10 ³	.62	33.0	33.3
3000	1.71x10 ³	.56	40.4	45.4
4000	2.10x10 ³	.52	46.8	55.8

<u>Corn</u>				
500	3.47x10 ²	.72	20.3	9.2
1000	6.45x10 ²	.67	24.4	17.1
2000	1.16x10 ³	.60	32.3	30.9
3000	1.61x10 ³	.56	39.2	42.7
4000	2.00x10 ³	.52	45.1	53.0

<u>Total</u>		
<u>Collector Area (m²)</u>	<u>Useful Solar Energy (GJ)</u>	<u>Yearly Percent Solar</u>
500	7.38x10 ²	9.8
1000	1.36x10 ³	18.1
2000	2.42x10 ³	32.1
3000	3.32x10 ³	44.1
4000	4.10x10 ³	54.3

COLLECTOR EFFICIENCY OF INTEGRATED AND SEPARATE SOLAR SYSTEMS AS A FUNCTION OF COLLECTOR AREA



energy collection is higher for one solar system servicing all of the unit operations. This is reasonable considering that for a given system the larger the demand (flowrate of water) the lower the average storage tank temperature and thus the higher the collection efficiency. Therefore in all further experiments, one solar system used to service all compatible unit operations of the plant will be analyzed.

Another possibility that was considered was a solar system containing no storage system. This system would apply solar radiation directly to heat mains water. Upon simulation a considerably smaller fraction of solar energy was obtained using this direct solar system compared to the system employing storage. The non-storage system has higher solar collection efficiency but is severely penalized by being unable to get useful energy out of the one non-processing day per week. A further penalty is the fact that a considerable amount of processing occurs during evening hours when there is no solar radiation. A solar system with storage would be better able to supply energy at all times it is needed. Also, and probably most important, is the necessity that the solar energy system would have to be compatible with space heating needs for the plant and warehouse during

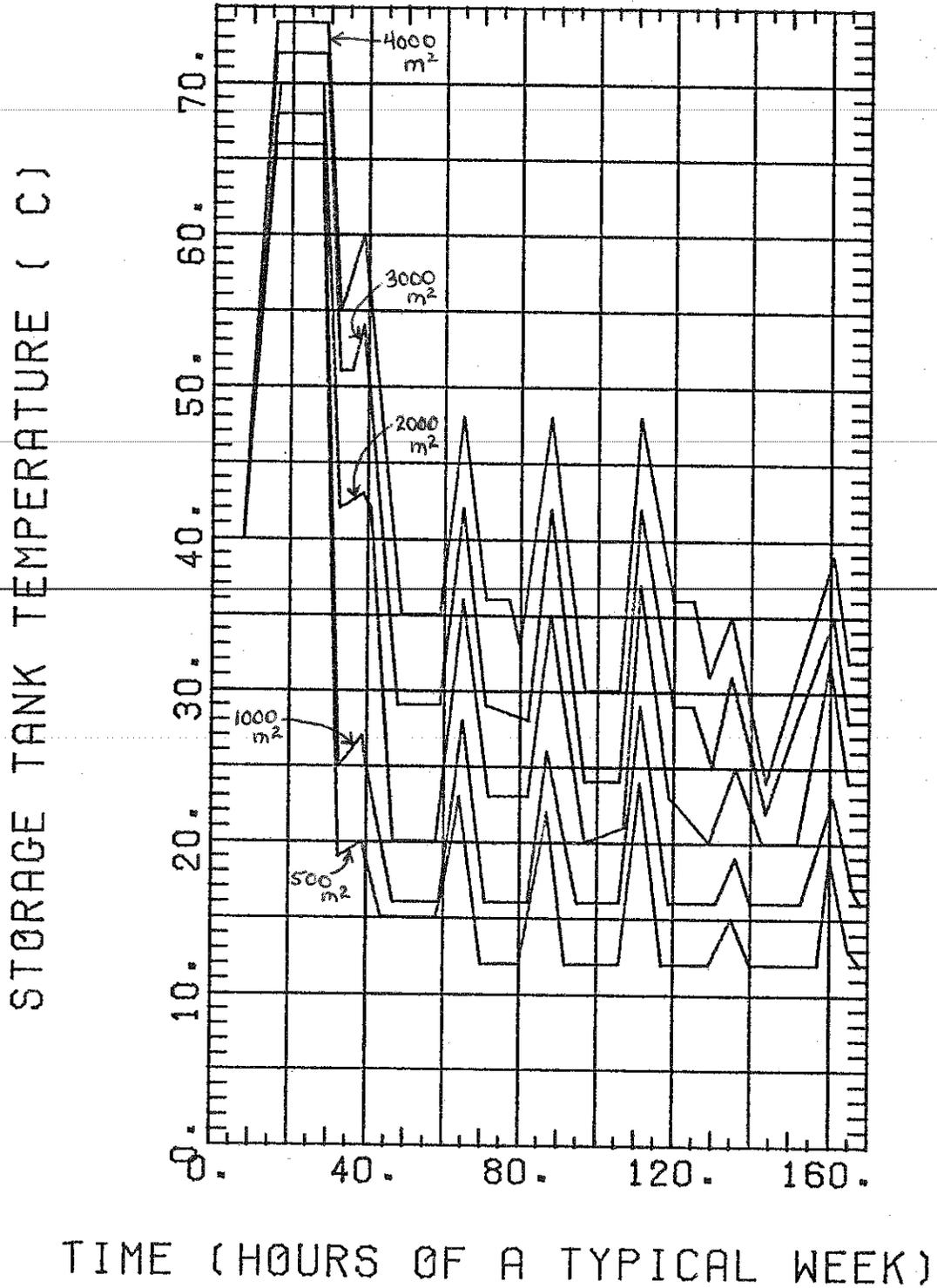
the non-processing season. A non-storage system would not be adaptable to space heating needs.

Thus the recommended solar system for the canning plant is one system with a storage tank which services all of the unit operations. The performance of this type of system in meeting the processing demand of the plant for pea and corn canning is displayed in Table 10. In the calculations, the boiler makeup rate was not adjusted as the other unit operations switched from auxiliary heat (boiler) to solar energy. This would have required considerable modification of the TRNSYS program involving an iterative solution and it was felt that this would not be worth the invested time. However, the consequence of not correcting for changes in the boiler feed water rate is that the percent contribution from solar is actually underestimated. Thus solar would actually perform slightly better than the predicted results.

Another anticipated problem is the possibility that the storage tank temperature may at times be above the set temperature for a unit operation and hence waste energy. Figure 16 shows a plot of storage tank temperature for various collector areas as a function of hours of a typical week for pea processing. The minimum tank tem-

Figure 16

VARIATION OF STORAGE TANK TEMPERATURE WITH COLLECTOR AREA
PEA CANNING - MADISON WISCONSIN



perature is the temperature of mains water, 11.1° C. The week chosen for this plot was the week with the best solar radiation of the seven week pea canning season determined by inspection of the weather data for that period. This insures an upper bound on the storage tank temperatures. As can be seen at no time during the six day processing period is the storage tank temperature above the set temperature for a unit operation. For this reason, pre heat tanks with variable temperature controllers would not be needed.

3.4.2 CANNING PLANT SOLAR SPACE HEATING

The performance of the solar system in meeting the space heating load is determined using FCHART. The determination of the space heating demand was presented in Table 7. These monthly heating demands were input into FCHART along with the solar system design parameters presented in Table 8. The results of the FCHART determination of solar system performance in meeting the heating demand is presented in Table 11. These results may be slightly in error due to the fact that FCHART is set up to handle domestic heating applications with required temperature of 65° F instead of the 55° needed by the plant. This error however should not have much affect

Table 11
 Results of FCHART Analysis of Performance of Solar System
 In Meeting the Space Heating Demand

	Space Heating Demand (GJ)	BAISI-ONE AVERAGE YEAR											
		500m ² (GJ) Solar %	1000m ² (GJ) Solar %	2000m ² (GJ) Solar %	3000m ² (GJ) Solar %	4000m ² (GJ) Solar %							
JAN	1589	62	122	235	342	440	27.7	3.9	7.7	14.8	21.5	27.7	
FEB	1298	88	173	327	466	588	45.3	6.8	13.3	25.2	35.9	45.3	
MAR	977	123	236	431	588	712	72.9	12.6	24.2	44.1	60.2	72.9	
APR	429	121	218	350	419	429	100	28.2	50.8	81.6	97.7	100	
MAY	-	-	-	-	-	-	-	-	-	-	-	-	-
JUN	-	-	-	-	-	-	-	-	-	-	-	-	-
JUL	-	-	-	-	-	-	-	-	-	-	-	-	-
AUG	-	-	-	-	-	-	-	-	-	-	-	-	-
SEP	-	-	-	-	-	-	-	-	-	-	-	-	-
OCT	215	96	158	212	215	215	100	44.7	73.7	98.6	100	100	
NOV	874	52	102	193	274	347	39.7	6.0	11.7	22.1	31.4	39.7	
DEC	<u>1362</u>	<u>38</u>	<u>75</u>	<u>146</u>	<u>212</u>	<u>276</u>	<u>20.3</u>	<u>2.8</u>	<u>5.5</u>	<u>10.7</u>	<u>15.6</u>	<u>20.3</u>	
	6744	580	1084	1894	2516	3007	44.6	8.6	16.1	28.1	37.3	44.6	

on the results (18).

3.4.3 CANNING PLANT YEARLY SOLAR FRACTION

The fraction of the plant's total energy demand supplied by solar on a yearly basis is then calculated by summing the products of fraction solar and energy required (per month for space heating and per season for processing) and dividing by the total energy demand compatible with solar energy. The analysis was done at collector areas at equal intervals up to 4000 square meters. This is the approximate roof area of the canning plant's processing building. The results of these calculations is presented in Table 12.

An f-chart model is next constructed to match the results of Table 12. This model contains the monthly space heating energy demand found in Table 7. The processing demand was distributed over the months as follows:

	Water Flowrate <u>l/day</u>	Required Water (°C) Set <u>Temperature</u>	Energy Demand <u>(GJ)</u>
June	3.55×10^5	20.8	433
July	3.55×10^5	64.7	2471
Aug	3.55×10^5	61.0	2301
Sept	3.55×10^5	63.5	2338
			<u>7543</u>

The storage capacity was set at $560 \text{ KJ}/^\circ\text{C}\text{-m}^2$. The other parameters of Table 8, were not changed. The f-chart model with these parameters matches the plant's actual

Table 12

Calculation of Percent of Total
Plant Energy Demand Supplied
By Solar From Combined
TRNSYS and FCHART Results

Yearly Plant Energy Demand	= Processing Energy Demand Compatible With Solar Energy	+ Space Heating Energy Demand	
	= 7.54×10^3 GJ + 6.74×10^3 GJ		= 1.43×10^4 GJ
Percent of Total Plant Energy Demand Supplied By Solar Energy	= FCHART calculated useful Solar Energy supplied to meet <u>space heating demand</u>	+ TRNSYS calculated useful Solar Energy supplied to meet <u>processing demand</u>	
	Yearly Plant Energy Demand		x 100
<u>Collector Area (m²)</u>			<u>Yearly Percent Solar</u>
500	$\frac{(580 \text{ GJ}) + (738 \text{ GJ})}{(14340 \text{ GJ})} \times 100 =$		9.2
1000	$\frac{(1084 \text{ GJ}) + (1360 \text{ GJ})}{(14340 \text{ GJ})} \times 100 =$		17.1
2000	$\frac{(1894 \text{ GJ}) + (2420 \text{ GJ})}{(14340 \text{ GJ})} \times 100 =$		30.2
3000	$\frac{(2516 \text{ GJ}) + (3320 \text{ GJ})}{(14340 \text{ GJ})} \times 100 =$		40.8
4000	$\frac{(3007 \text{ GJ}) + (4100 \text{ GJ})}{(14340 \text{ GJ})} \times 100 =$		49.7

Table 13

Comparison of Calculated % Solar
From TRNSYS and FCHART Results
With % Solar From f-chart Model

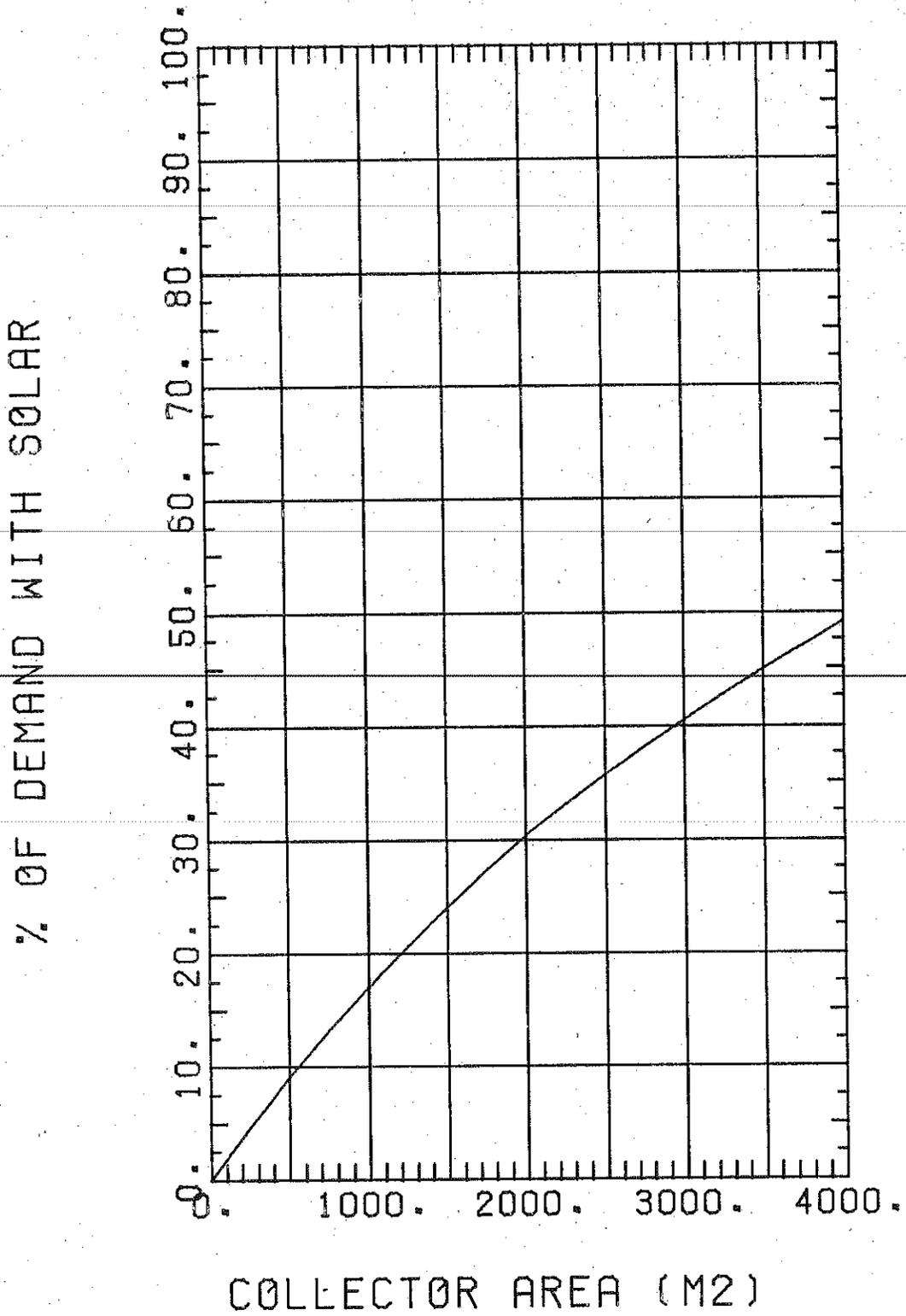
Collector Area (m ²)	% Solar (yearly plant energy demand)	
	<u>Calculated (Table-10)</u>	<u>f-chart model</u>
500	9.2	9.1
1000	17.1	17.1
2000	30.2	30.4
3000	40.8	40.5
4000	49.7	49.2

total energy demand and the calculated results of Table 12. A comparison of the results determined by the f-chart model and those calculated is displayed in Table 13. As can be seen, the results of the f-chart model are certainly within experimental error.

This f-chart model can then be used to determine the performance of the solar system at any system size between 0 and 4000 square meters of collector area. The results of these interpolations is presented in Figure 17.

The above determined f-chart model not only predicts the thermal performance of a solar energy system, but it can also be used to evaluate its economic feasibility using a life cycle cost analysis. The next section considers solar heating economics.

PERCENT OF CANNING PLANT ENERGY DEMAND SUPPLIED BY SOLAR



4.0 SOLAR ENERGY ECONOMICS

The installment of a solar energy system is warranted if the fuel savings due to the system are greater than the mortgage payments required to buy the solar equipment. Although this is a simple criterion, problems arise due to the uncertainty of accounting for the rise of certain economic parameters. Examples of these parameters are fossil fuel costs, property taxes, income taxes, insurance and maintenance.

The life cycle cost method is a convenient manner in which to evaluate the feasibility of installing a solar system. It is accepted by most economists as the soundest approach for making an economic decision (19). A problem with life cycle cost analysis as with any economic study is the necessity to predict future costs.

4.1 LIFE CYCLE COST ANALYSIS

4.1.1 GENERAL CONSIDERATIONS

The life cycle cost economic study provides a means of comparison of future costs with today's costs, by reducing all costs to the common basis of present worth. Present worth is the amount of money that would have to be invested today in order to have funds available to meet all of the anticipated future expenses.

In a life cycle cost analysis, an estimation is made

for the required net payment for heating. The life cycle cost is determined by discounting each yearly net payment to its present value and then finding the sum of these discounted costs. The discounting accounts for the time value and the declining purchasing power of the dollar. Due to the uncertainty in predicting future costs, it is customary to make a set of pessimistic and a set of optimistic assumptions of these costs. A life cycle analysis is conducted to determine the most cost effective system for each set of guesses. The system design is then chosen by intuition.

4.1.2 APPLICATION TO SOLAR ENERGY SYSTEMS

The principles of life cycle economics have been incorporated into the FCHART solar energy program discussed in the previous section. FCHART allows a number of user supplied parameters representing existing economic conditions and others forecasting future costs. The program estimates the amounts of annual cash flows using the equations:

$$\text{Yearly Cost with Solar} = \text{Mortgage payment} + \text{Backup Fossil Fuel cost} + \text{Misc. Costs} + \text{Property Tax Increase}$$

$$+ \text{"Solar" tax credit}$$

$$\text{Yearly Cost Without Solar} = \text{Fossil Fuel cost} - \text{"Nonsolar" income tax credit}$$

These two costs are evaluated for each year of the specified period of analysis and then discounted to present worth values. Comparison of these values indicate whether installation of a solar system is a good investment. The program has the ability of performing the economic analysis either on a solar system of specified size or it can conduct a numerical search for an optimum collector area and perform the analysis on that system.

A complete discussion of FCHART parameters and program capabilities can be found in reference (8). FCHART allows an inexpensive economic analysis to aid in decision making. The f-chart model which was developed to interpolate the thermal performance of a solar system in a food processing plant can be simultaneously used to perform a life cycle cost analysis. As constructed, the f-chart model was forced to duplicate the thermal performance of the plant's solar energy system determined from FCHART and/or TRNSYS results (see section 3.3). Since FCHART's economic analysis is only concerned with the fraction of the plant's energy demand supplied by solar and the energy demand itself, the f-chart model which predicts the correct thermal performance will also predict the life cycle economic analysis.

4.2 FEASIBILITY OF CANNING PLANT SOLAR SYSTEM

From discussions with the Solar Energy Laboratory of the University of Wisconsin-Madison (18) and canning plant officials (20), values and ranges for the economic parameters necessary for an FCHART life cycle cost analysis were determined. The values for these parameters used in this study are presented in Table 14.

The canning plant presently pays approximately \$3.5 per useful GJ for natural gas. This figure was obtained from an analysis of plant records of natural gas bills and consideration of boiler efficiency (80%) and estimated energy loss (15%).

The plant was assumed to have certain economic constraints. The annual nominal market discount rate (real rate of return plus the general inflation rate) was estimated as 10% per year. The effective federal-state income tax which allows for deduction of state income taxes from federal returns was estimated to be 50%. Factors which are included in tax credits allowed with installation of a solar system are paid interest, property taxes, backup fuel costs, depreciation and miscellaneous expenses.

In all the economic investigations considered in this study, the general inflation rate was assumed to be 6% per

Table 14
Parameters For FCHART
Economic Analysis

Solar System Thermal Performance Degradation	0 %/yr
Period of Economic Analysis	20 yrs
Collector Area Dependent Costs	200-300 \$/m ²
Constant Solar Costs	0 \$
Down Payment (% of Original Investment)	10 %
Annual Interest Rate On Mortgage	8 %
Term of Mortgage	20 yrs
Annual Nominal (Market) Discount Rate	10 %
Extra Insurance, Maintenance in Year 1 (% of Orig. Inv.)	1 %
Annual % Increase in Above Expenses	6 %
Present Cost of Solar Backup Fuel (BF)	3-7 \$/GJ
BF Rise	8-12 %/yr
Effective Federal-State Income Tax Rate	50 %
True Prop. Tax Rate Per \$ Of Orig. Inv.	3 %
Annual % increase in Property Tax Rate	6 %
Salvage Value (% of Original Investment)	0 %
Depreciation : Straight Line-1	1
Useful Life For Depreciation Purposes	20 yrs

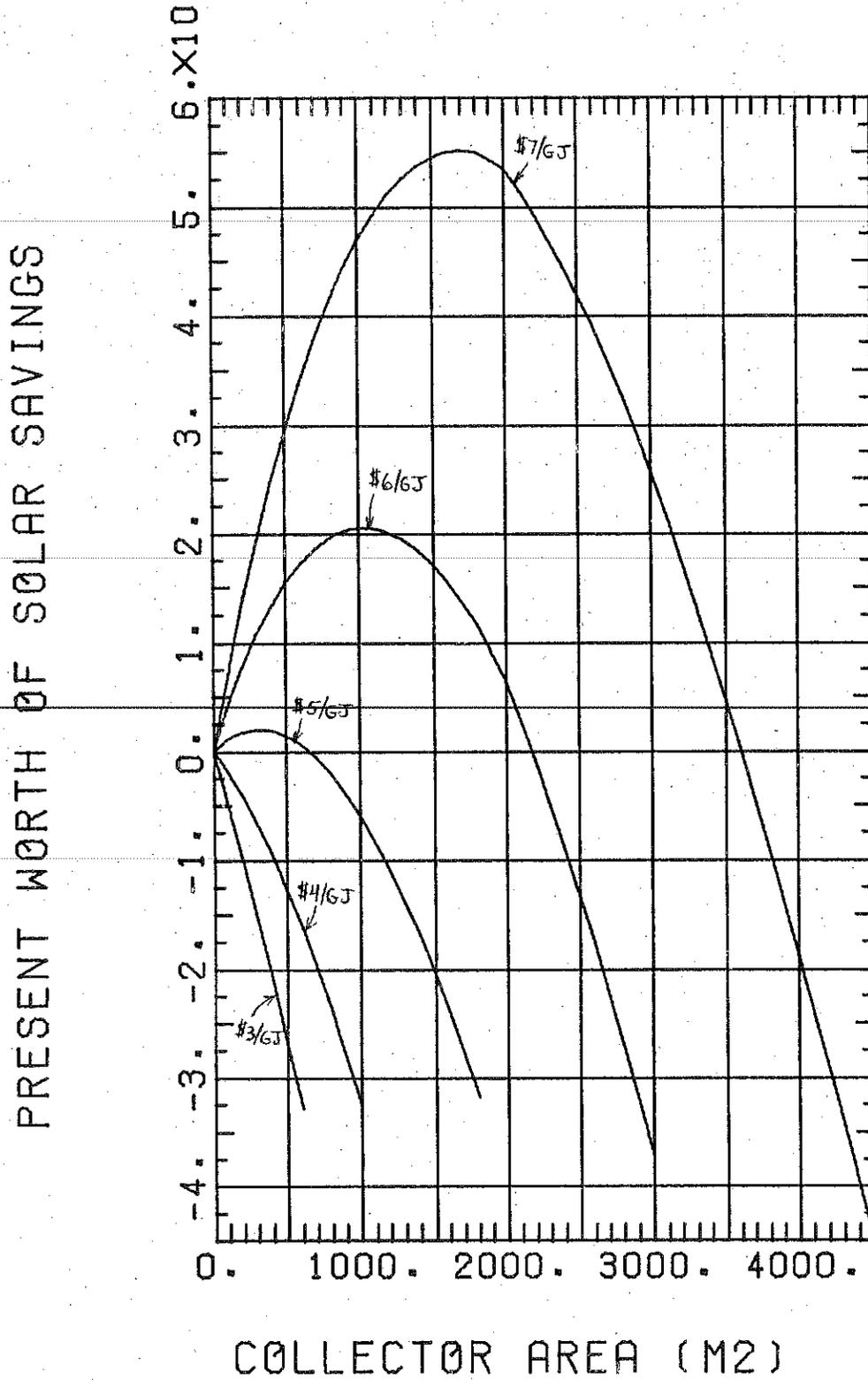
year and the purchase of a solar energy system was financed with a 10% down 20 year mortgage at an annual interest rate of 8%. FCHART investigations indicate that if a shorter term of mortgage is used, it is necessary to use a longer term of analysis to obtain comparable results.

The versatility of the FCHART program allows a number of experiments to determine the effect on the economics of the solar assist system with variation in economic parameters. For the canning plant, three parameters were considered to be the most sensitive of those considered. These are backup fuel cost, backup fuel inflation rate, and the collector cost. To simplify calculations all solar system costs were represented in a single charge per square meter of collector installed.

The first of these experiments investigates the importance of the parameter, backup fuel cost. In this analysis the fuel cost is varied between \$3 and \$7 per GJ while the other two important parameters are held constant. The collector cost (installed) was assumed to be \$200 per square meter and the fuel inflation rate approximated as 10% per year. The results of this experiment are presented in Figure 18. As can be seen, the fuel cost must be between \$4 and \$5 per GJ for the solar system to

Figure 18

CANNING PLANT ECONOMICS AS A FUNCTION OF FUEL COST
FUEL INFLATION RATE 12%/YR AND COLLECTOR COST \$200/M²



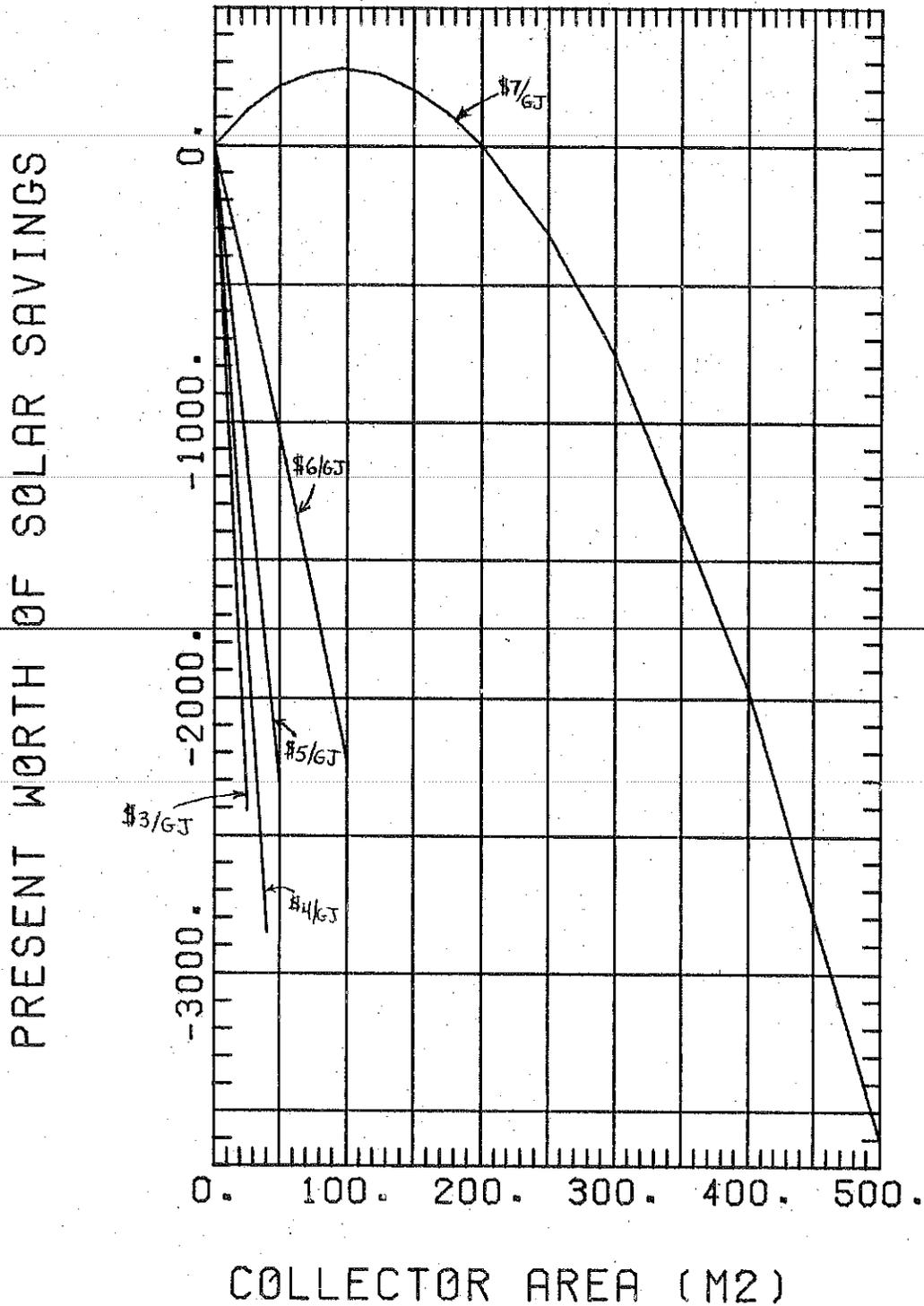
break even at any system size. For all fuel costs above the break even fuel cost, as the collector area is raised from zero, the present worth of solar savings increases until a maximum is reached, which is the optimum collector area. As the collector area is further increased, the fuel savings continue to increase, but the excessive system costs force the net savings to decrease. This experiment involves selection of optimistic values for collector cost and fuel inflation rate as far as solar system economics is concerned. At present, solar collectors can be bought and installed for a total cost of \$250 to \$300 per square meter and best guesses indicate that the fuel inflation rate will be about 10% per year for the near future.

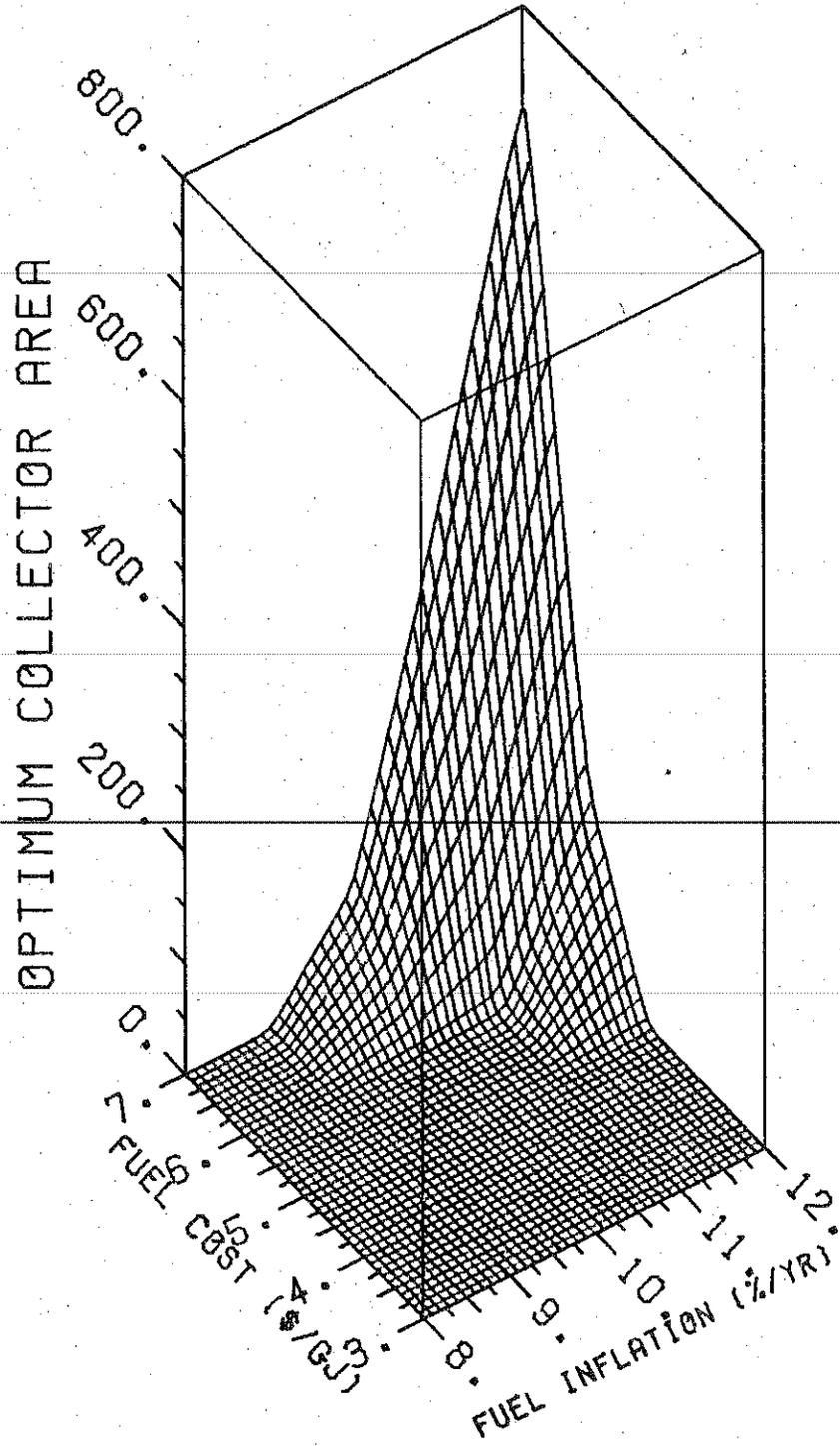
The variable fuel cost analysis was redone at collector cost of \$250 per square meter and fuel inflation rate of 10% per year. The results are displayed in Figure 19. As can be seen the change in the two parameters makes dramatic changes in the results. The break even fuel cost has jumped to between \$6 and \$7 per GJ.

The qualitative effect of fuel cost and forecasted fuel inflation rate can be examined using three dimensional plots like Figures 20 and 21. The data for these

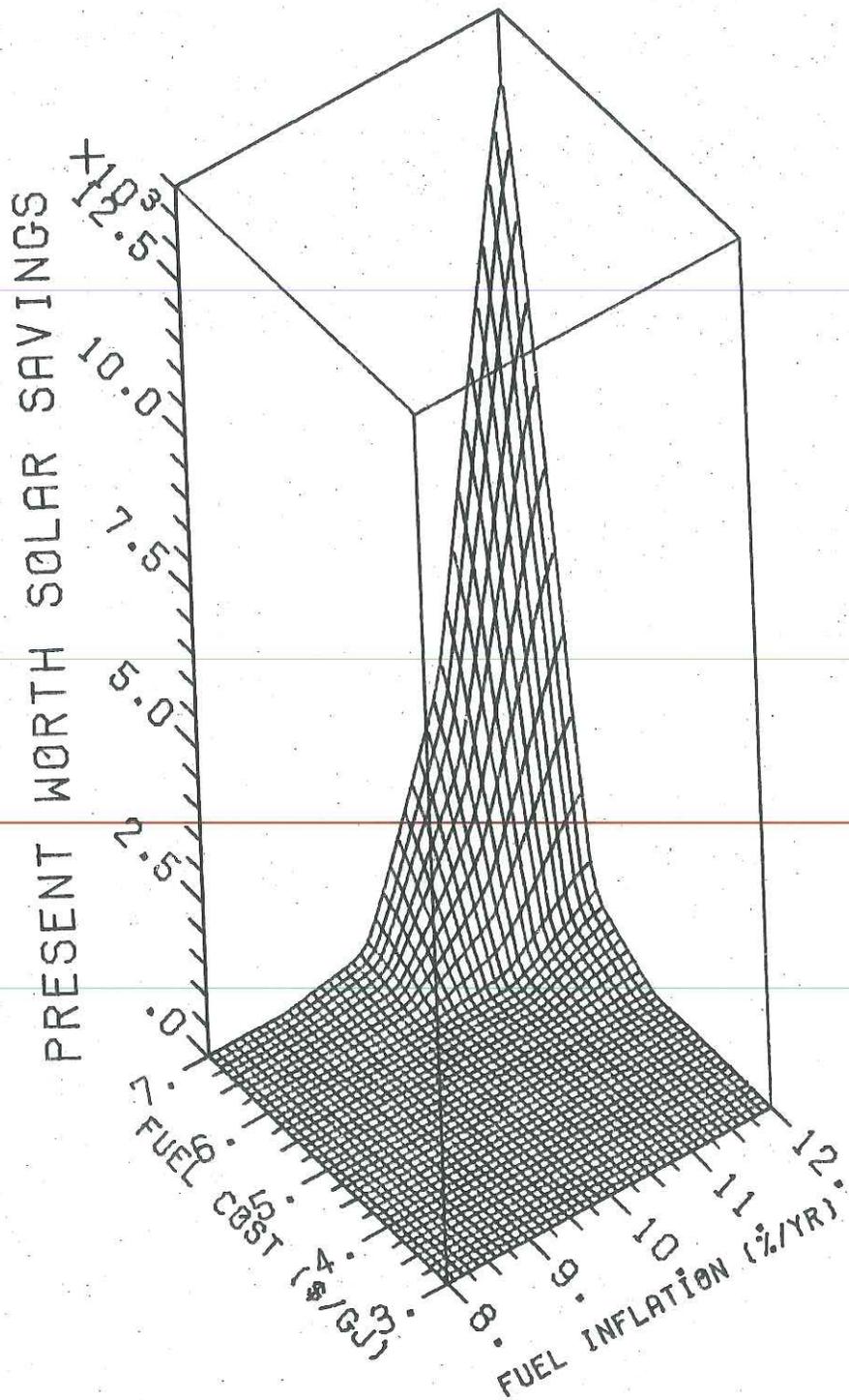
Figure 19

CANNING PLANT ECONOMICS AS A FUNCTION OF FUEL COST
FUEL INFLATION RATE 10%/YR AND COLLECTOR COST \$250/M²





CANNING PLANT ECONOMIC FORECAST
COLLECTOR COST \$250/M2

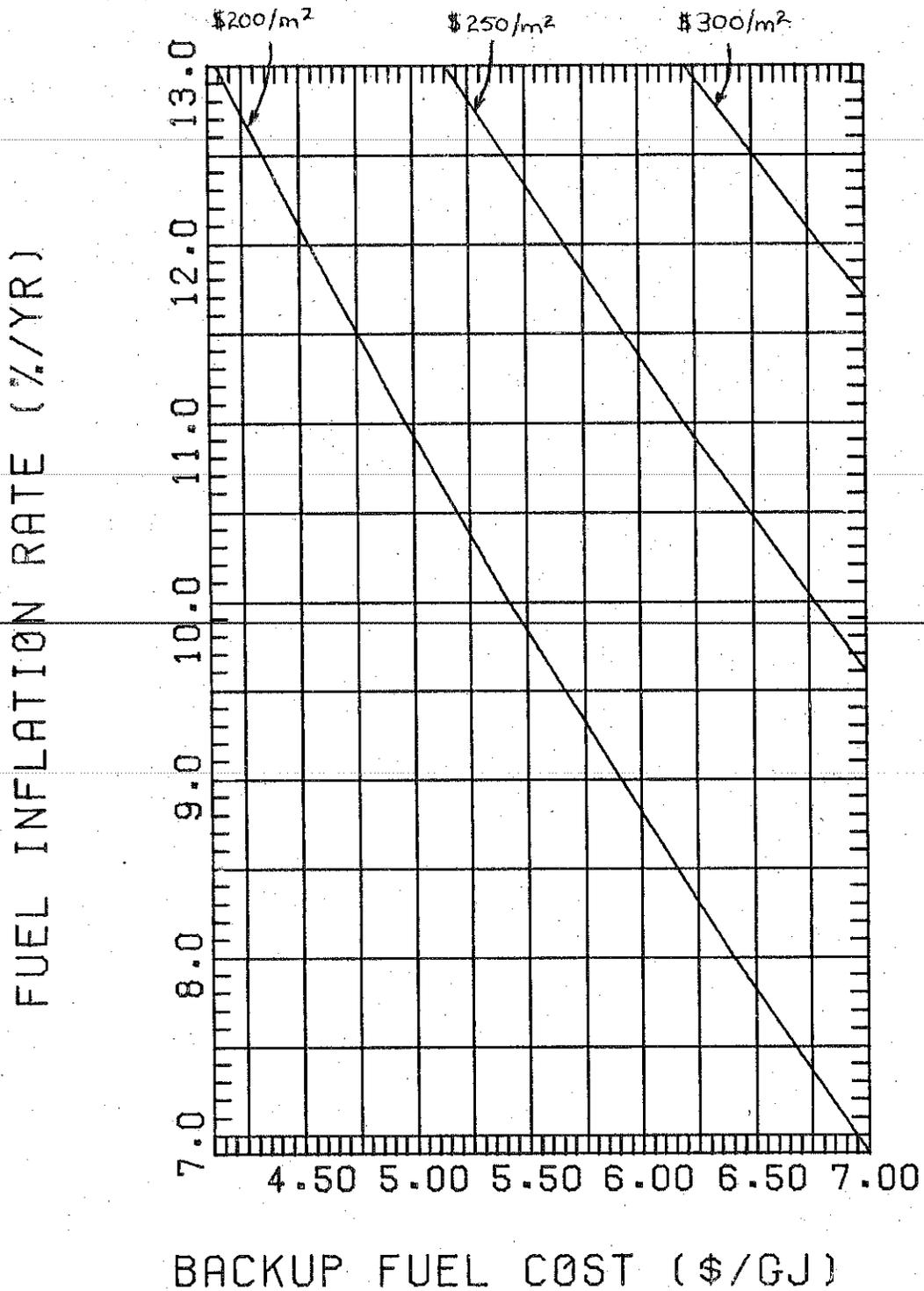


CANNING PLANT ECONOMIC FORECAST
COLLECTOR COST \$250/M²

plots were obtained at an installed collector cost of \$250 per square meter by varying fuel cost between \$3 and \$7 per GJ and fuel inflation rate between 8 and 12% per year. These plots indicate the economically optimum size of the solar system and the corresponding present worth of savings realized by installing the solar system. That portion of the curves extending upward from the bottom plane is the economically feasible region. The plots indicate that even at an estimated high fuel inflation rate of 12% per year the plant must be paying over \$5 per GJ of fuel for the solar system to be competitive. The quantitative results of this experiment are tabulated in Appendix B to aid in estimating particular values from the curves.

An easier way of determining the economically feasible region is by the use of break even curves like that of Figure 22. This plot was generated by holding all economic parameters constant except for fuel cost. The fuel cost was then varied until the present worth of solar savings became greater than zero. Figure 22 shows three such break even curves for installed collector costs of \$300, \$250 and \$200 per square meter. The region to the right of these curves is the economically

CANNING PLANT BREAK-EVEN CURVE AS A FUNCTION OF COLLECTOR COST



feasible region; to the left not feasible at any solar system size.

It is seen that for the canning plant in question, at installed collector cost of \$250 per square meter and predicted fuel inflation rate of 10% per year the plant would have to be paying \$6.80 per GJ for fuel to make a solar energy system competitive. Since the canning plant presently pays about \$3.5 per GJ for fuel, it is not expected that installation of a solar energy system in the plant will be economical until fuel costs rise and collector costs decrease substantially.

Improvement in canning plant solar economics could be realized by finding an income producing use of solar hot water during those periods when the plant presently has no need for energy or when the solar system provides more useful energy than required. This new energy savings could result from establishment of a new plant product or the "selling" of energy to nearby industries.

Appendix C contains the results of other life cycle cost studies of solar energy systems in the canning plant. These investigations determined the optimum collector areas and present worth of solar savings for different nominal discount rates.

5.0 CONCLUSION

The design of any alternative energy system must be performed with consideration of both thermal performance and consideration of long term costs. This study outlines a method using existing computer programs to evaluate the feasibility of using solar energy in meeting a particular processing plants energy demand. The method is rigorous enough to be accurate in determining performance, simple enough to limit the computing cost, and flexible enough to consider the economic constraints of any plant.

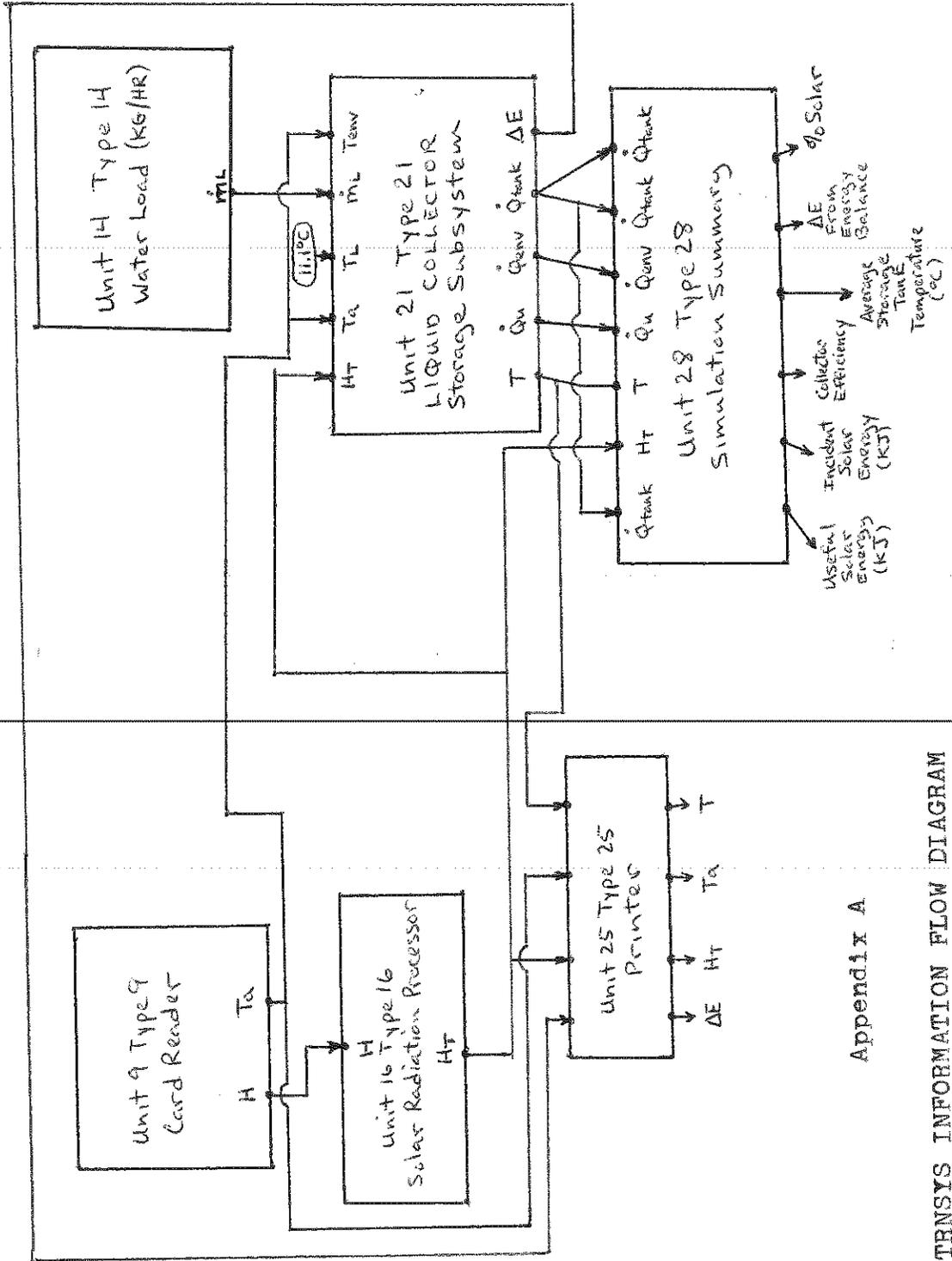
A vegetable canning plant located near Madison, Wisconsin was analyzed using this method. The plant, per hr., produces approximately 3.5 tons of canned peas and 7.4 tons of canned corn during a fourteen week processing period. The plant requires 7.54×10^3 GJ or about 40% of its total energy need during this period to produce hot water between 60° and 100° C. This energy was broken down in terms of unit operation requirement both seasonal and hourly. The plant also requires buildings at or near 12.8° C (55° F). The design space heating was calculated to be 6.74×10^3 GJ per year using the degree-day method.

The fraction of this energy demand which could be met by forced circulation liquid solar energy systems (with flat-plate collectors) of various sizes up to 4000 square meters was estimated. Twenty year life cycle cost studies of these systems were analyzed. Results indicate that fossil fuel costs must rise from the present \$3.5 per useful GJ to about \$6.0 or collector costs must drop significantly from present values of about \$300 per square meter before the installation of a solar system is economical.

The results are not altogether a condemnation of using solar energy in the canning plant. It is generally accepted that solar energy will become more competitive with conventional energy sources with increasing time. As supplies of low cost fossil fuels become more difficult to obtain, deregulation of prices would result leading to higher costs. Mass production, improved technology and large modular-type installations of solar system components could lower the cost of solar systems. Governmental action could also improve solar economics by institution of tax incentives such as write-off of investments in solar energy producing equipment.

An analysis, similar to that outlined in this study, of a dairy processing plant and a meat processing plant

can be found in reference (21).



Appendix A

TRNSYS INFORMATION FLOW DIAGRAM

TRNSYS Program Listing

SIMULATION WITH STORAGE SUBSYSTEM
 SIMULATION 0 1176 .25
 UNIT 14 TYPE 14 LOAD
 TRNSYS SIMULATION IN A VEGETABLE CANNING PLANT

UNIT 9 TYPE 9 DATA READER
 PARAMETERS 7
 2 1.0 1 3.6 0.0 0 1
 (18X,F5.0,6X,F6.1)
 UNIT 16 TYPE 16 SOLAR RADIATION PROCESSOR
 PARAMETERS 8
 1.0 169.0 43.0 4871. 0.2 0.0 58.0 0.0
 INPUTS 1
 9,1
 0.0
 UNIT 21 TYPE 21 LIQ. COLL.-STO. SUB
 PARAMETERS 15
 1000. 54000. 3.5 54000. 4.19 0.95 0.77
 14.4 100. 0.82 75.0 1000. 1.5 3.35 40.
 INPUTS 5
 16,1 9,2 0,0 14,1 9,2
 0.0 0.0 11.1 0.0 21,0
 UNIT 25 TYPE 25 PRINTER
 PARAMETERS 1
 1176
 INPUTS 1
 21,6
 DELTIN
 UNIT 28 TYPE 28 SIMULATION SUMMARY
 PARAMETERS 31
 1176 0 10000 0 0 -3 0 -1 1000 1 -3 2 -4 0 -22-4
 0 0 4 0 4 -4 0 -1 3.402E8 2 -1 100. 1 -3
 INPUTS 7
 21,5 16,1 21,1 21,3 21,4 21,5 21,5
 LABELS 6
 QLOAD HCOL EFFIC TAVRG EBALAN ZSOLAR
 UNIT 26 TYPE 26 PLOTTER
 PARAMETERS 3
 1 0 168
 INPUTS 1
 21,1
 TANK-T
 END

Appendix B

Madison Canning Plant Optimum Collector Area and
Present Worth of Solar Savings Used to make Figures 20 and 21

<u>Fuel Inflation</u> (%/Yr)	<u>Fuel Cost</u> (\$/GJ)	<u>Optimum Collector Area (m²)</u>	<u>Present Worth of Solar Savings (\$)</u>
12	7	750	13760
11	7	404	4146
10	7	96	280
9	7	0	0
8	7	0	0
12	6	170	807
11	6	0	0
10	6	0	0
9	6	0	0
8	6	0	0
12	5	0	0
11	5	0	0
10	5	0	0
9	5	0	0
8	5	0	0
12	4	0	0
11	4	0	0
10	4	0	0
9	4	0	0
8	4	0	0
12	3	0	0
11	3	0	0
10	3	0	0
9	3	0	0
8	3	0	0

Appendix C
Canning Plant Economics

Discount Rate 10%

Fuel Inflation	Fuel Cost	Collector Cost \$200/m ²		Collector Cost \$300/m ²	
		OCA	PWSS	OCA	PWSS
12	3.0	0	0	0	0
12	4.0	0	0	0	0
12	5.0	315	2059	0	0
12	6.0	1034	20569	0	0
12	7.0	1703	55187	78	230
11	3.0	0	0	0	0
11	4.0	0	0	0	0
11	5.0	22	14	0	0
11	6.0	670	8822	0	0
11	7.0	1309	32774	0	0
10	3.0	0	0	0	0
10	4.0	0	0	0	0
10	5.0	0	0	0	0
10	6.0	336	2330	0	0
10	7.0	941	17093	0	0
9	3.0	0	0	0	0
9	4.0	0	0	0	0
9	5.0	0	0	0	0
9	6.0	47	60	0	0
9	7.0	597	7052	0	0
8	3.0	0	0	0	0
8	4.0	0	0	0	0
8	5.0	0	0	0	0
8	6.0	0	0	0	0
8	7.0	283	1679	0	0

OCA - Optimum Collector Area (m²)

PWSS - Present Worth Solar Savings (\$)

Canning Plant Economics
Variance with Discount Rate
Fuel Inflation 10%

CAC	Fuel Cost (\$/GJ)	Discount Rate 8%		Discount Rate 10%		Discount Rate 12%	
		OCA	PWSS	OCA	PWSS	OCA	PWSS
200	2.0	0	0	0	0	0	0
200	3.5	0	0	0	0	0	0
200	5.0	0	0	0	0	0	0
200	6.5	851	16251	642	8100	438	3403
200	8.0	1747	66989	1511	43521	1281	27564
225	2.0	0	0	0	0	0	0
225	3.5	0	0	0	0	0	0
225	5.0	0	0	0	0	0	0
225	6.5	389	4025	201	988	34	31
225	8.0	1226	37475	1006	21934	791	11996
250	2.0	0	0	0	0	0	0
250	3.5	0	0	0	0	0	0
250	5.0	0	0	0	0	0	0
250	6.5	32	42	0	0	0	0
250	8.0	788	17484	581	8348	380	3236
275	2.0	0	0	0	0	0	0
275	3.5	0	0	0	0	0	0
275	5.0	0	0	0	0	0	0
275	6.5	0	0	0	0	0	0
275	8.0	415	5572	225	1498	53	89
300	2.0	0	0	0	0	0	0
300	3.5	0	0	0	0	0	0
300	5.0	0	0	0	0	0	0
300	6.5	0	0	0	0	0	0
300	8.0	108	474	0	0	0	0

CAC - Collector Area Cost (\$/m²)

PWSS - Present Worth Solar Savings (\$)

OCA - Optimum Collector Area (m²)

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