

APPLICATION OF SOLAR ENERGY  
TO THE SOLVENT RECLAMATION INDUSTRY

BY

ARTHUR H. LITKA  
B.S., Florida Technological University, 1970

RESEARCH REPORT

Submitted in partial fulfillment of the requirements  
for the degree of Master of Science  
in the Graduate Studies Program of the College of Engineering  
Florida Technological University

Orlando, Florida  
1976

## ACKNOWLEDGMENT

The author would like to express his sincere appreciation to several individuals whose guidance and advice lead to the completion of this research report. First, I want to thank my research advisor and committee chairman, Dr. Bruce Nimmo. Professor Nimmo's patience and guidance throughout the many months spent on this research has made an invaluable contribution to my professional development and future career.

Secondly, my gratitude is extended to the two other members of my research committee, Dr. Marty Wanielista and Dr. Robert Doering. Their helpful suggestions concerning the respective areas of environmental engineering and economic analysis greatly enhanced the scope of this report. A very heartfelt thanks goes to Ms. Gloria McCollum for her efforts in the typing and final preparation of this manuscript.

Finally, I want to thank my wife, Beverly, for her patient understanding and unfaltering moral support which she gave to me during my tenure in graduate school. It is to her that this effort is dedicated.

## ABSTRACT

An analysis of an operational industrial acetone reclamation system is performed to ascertain the possibility of its adaptation to solar thermal energy augmentation using fixed orientation, flat plate solar collectors. Currently, the system utilizes an oil fired heater for the thermal input. The water is heated to 185°F (85°C) and circulated through a heat exchanger which is immersed within the contaminated acetone solution. The solvent is thereby vaporized, condensed, and drawn off for reuse.

Analytical models of two possible configurations utilizing a series of commercially available, flat plate solar collectors, a hot water storage tank, and an oil fired auxiliary are developed. The resulting differential equation is written in finite difference form and integrated with an iterative numerical algorithm. Program listings are included for the solution of this problem on a Texas Instruments, SR-56 programmable calculator.

Results of the analysis indicate that annual fuel savings of between 11 and 31 percent can be realized (compared to present non-solar operation) by the use of 6 to 16 collectors respectively. Based on an "ideal" day's performance, an economic analysis is given which recommends the use of 16 collectors for the present system. At current fuel, equipment,

and fuel cost increase rates, the rate of return attained from the system retro-fit investment is commensurate with that available under a low risk savings investment. Therefore, an economic justification for conversion of the system to solar energy is marginal under the present conditions. A sensitivity analysis is included that indicates the conditions necessary for economic justification. Specifically, if the current collector cost was reduced by 65 percent, the solar system configuration would yield an acceptable rate of return on the investment.

TABLE OF CONTENTS

ACKNOWLEDGMENT . . . . .iii

ABSTRACT . . . . . iv

NOMENCLATURE LIST . . . . .vii

Chapter

I. INTRODUCTION . . . . . 1

II. DESCRIPTION OF SYSTEM CONFIGURATIONS. . . . . 5

    Non-Solar Operation . . . . . 1

    Adaptation of System to Solar Operation . . . . . 7

III. SOLAR SYSTEM THERMAL ANALYSIS . . . . . 11

    System Analytical Model . . . . . 11

    Numerical Solution Procedure . . . . . 15

IV. SYSTEM ECONOMICS . . . . . 32

V. CONCLUSIONS AND RECOMMENDATIONS . . . . . 40

.....

APPENDIX . . . . . 43

FOOTNOTES . . . . . 55

BIBLIOGRAPHY . . . . . 56

## NOMENCLATURE LIST

$A_c$	collector area
$A_s$	storage tank surface area
$C$	first cost
$C_c$	collector cost per unit area
$C_{fi}$	initial cost per gallon of auxiliary fuel
$C_p$	specific heat of storage media
$\dot{E}_{aux}$	auxiliary energy rate
$E_{aux\ total}$	total auxiliary energy required
$F_1$	annual fuel consumption for process 1
$F_2$	annual fuel consumption for process 2
$\dot{G}$	flow rate per unit area of collector
$H$	solar insolation
$i$	rate of return
$i_f$	average annual fuel cost increase
$j$	process subscript (1 or 2)
$l$	liters
$\dot{M}$	mass flow rate of water through evaporator
$M_s$	storage media (water) mass
$N_c$	number of collectors
$n$	summation index
$Q'_u$	collector input energy per unit area

$Q_1$	energy extracted by load from storage
$S_{jn}$	fuel cost savings for $n^{\text{th}}$ year
$t$	time
$T_s$	storage media temperature
$T_{\text{on}}$	auxiliary turn on temperature
$T_{\text{off}}$	auxiliary turn off temperature
$T_a$	ambient temperature
$T_i$	collector inlet temperature
$\bar{T}_G$	estimated value for average storage media temperature (use in numerical solution)
$T_{s,n}$	storage media temperature at beginning of interval
$T_{s,n+1}$	storage media temperature at end of interval
$T_{\text{av}}$	computed average storage media temperature
$UA_s$	storage tank area-loss coefficient product
$\dot{V}$	volume flow rate of water through evaporator
$V_s$	volume of storage tank
Other Symbols and Quantities	
$d$	time derivative
$\Delta$	change in a quantity
$\Delta T_{\text{evap}}$	temperature drop across evaporator
$\Sigma$	summation
$\Delta \tau$	finite time interval
-	average value of a quantity over finite interval (superscript)

## CHAPTER I

### INTRODUCTION

The era of extensive technology in which we live has enabled mankind to attain a standard of living far surpassing the most optimistic dreams of those of a few generations past. However, the preservation of our present lifestyle now strongly depends upon how we address two adverse side effects of this technology: dwindling supplies of fossil fuel energy resources, and increasing environmental pollution. Neglecting the first will possibly force man to return to a primitive existence; neglecting the second will most likely deny him a future existence at all. This study considers one industrial application of solar energy which works toward alleviating both problems: the reclamation of contaminated waste solvent material by the use of solar energy as an aid to the required thermal energy input.

The economic importance of solvents is evidenced by the diverse applications in which they are utilized. These uses include dirt and grease removal from mechanical components, thinning of paints and varnishes, the printing and reproduction trades, manufacture of shoe polish and floor wax, the plastic and synthetics industries, and even in the food industry where the solvent acetone is used in the extraction of caffeine



from raw coffee beans.<sup>1</sup> In fact, among the top fifty chemicals produced in the United States in 1975, the solvents toluene and acetone ranked numbers seventeen and forty respectively.

Together, the total United States production of these two chemicals alone amounted to 7.46 billion pounds in 1975.<sup>2</sup>

Because of the diminishing supply of petroleum-based raw materials used in the manufacture of solvents, the cost of these chemicals is increasing. Until recently, contaminated waste solvents were usually disposed of by landfill dumping, venting to the atmosphere, or incineration. Not only is this practice becoming increasingly unwise economically, but it is also proving hazardous from an environmental viewpoint. A recent survey conducted of 103 companies in the United Kingdom showed that over 37,000 tons of solvents were wasted annually. By far, the greatest percentage of these wastes were from the chemical manufacturing industries. Ranking second in this category was pharmaceutical production.<sup>3</sup> It could be expected that such a survey conducted in the United States would yield similar results.

The United States Environmental Protection Agency defines hazardous wastes as "wastes that pose a substantial danger, immediately or over time, to human, plant, or animal life and which, therefore, must be handled or disposed of with special precautions."<sup>4</sup> Many solvents fall into this category because

they are toxic, flammable, explosive and possibly carcinogenic over long periods of exposure. A study conducted by the National Cancer Institute has recently indicated that prolonged ingestion of trichloroethylene by mice leads to a high incidence of liver cancer. However, inconclusive results were obtained when rats were tested.<sup>5</sup> There is no doubt, however, that at least ten million tons of a variety of wastes are generated annually by industry which are considered hazardous in one way or another.

Two suggestions forwarded by the EPA apply directly to the handling of solvent wastes:

1. the stimulation of a "waste exchange" where one factory's solvent wastes become the feedstock of another industry,
2. the concentration of solvent wastes through one of several techniques so as to reduce handling and transport problems.<sup>4</sup>

Both of these recommendations are applied in the reclamation of usable solvent material from contaminated waste solvents.

Currently there are increasing numbers of industrial operations which are benefiting economically from solvent recovery procedures.<sup>6,7</sup> Also, since the waste volume from this operation is significantly lower than the originally contaminated material, the residues can be disposed of in a more environmentally acceptable manner. In addition, of course, the harmful solvent portion of the waste is practically nonexistent.

Two methods are generally employed in industrial solvent

recovery:

1. adsorption of vapors by high boiling point liquids or by solids such as activated carbon, silica gel, and aluminum hydroxide,
2. distillation of liquid solvent material by evaporation and condensation.

Both of these methods require a thermal energy input. If the energy requirements could be supplied or at least augmented by a solar process, an even greater conservation of fossil fuel resources would ensue from the solvent reclamation operation.

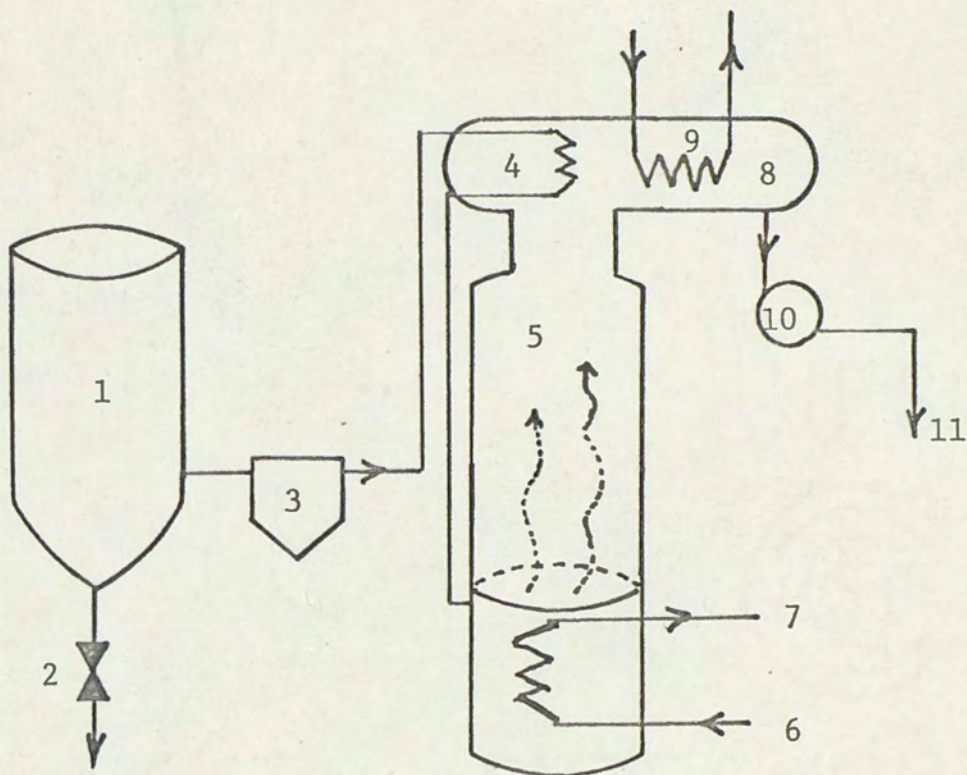
In this study, a small acetone reclamation facility was investigated to determine its adaptability to solar thermal operation with fixed orientation, flat plate solar collectors. The plant uses a simple distillation technique to reclaim acetone contaminated with low-volatility substances.

## CHAPTER II

### DESCRIPTION OF SYSTEM CONFIGURATIONS

#### Non-Solar Operation

At the time of this writing, the oil fired solvent reclamation system is operating on a small scale commercial basis in the Orlando, Florida area. During a six to eight hour operating period the system produces up to 220 gallons of reclaimed, industrial grade acetone. A fuel consumption of approximately ten gallons of #2 diesel oil occurs during this time. A schematic diagram of the present system is shown in figure II-1. The dirty solvent is first placed in a holding tank which allows some suspended contaminants to settle and subsequently be drained off. Further mechanical filtration is provided before the solution is pumped into the evaporator. Prior to vaporization, this solution passes through pre-heat coils which are warmed by the vaporized solvent in the evaporator. This "bootstrap" procedure aids in lowering the heat input required from the evaporator heat exchanger. The heat exchanger is totally immersed in the solvent solution and uses hot water (85-90°C) as the working fluid. The vaporized solvent in the evaporator rises into a condenser chamber which is cooled by cold water coils. The vapor condenses and is then pumped into



## KEY:

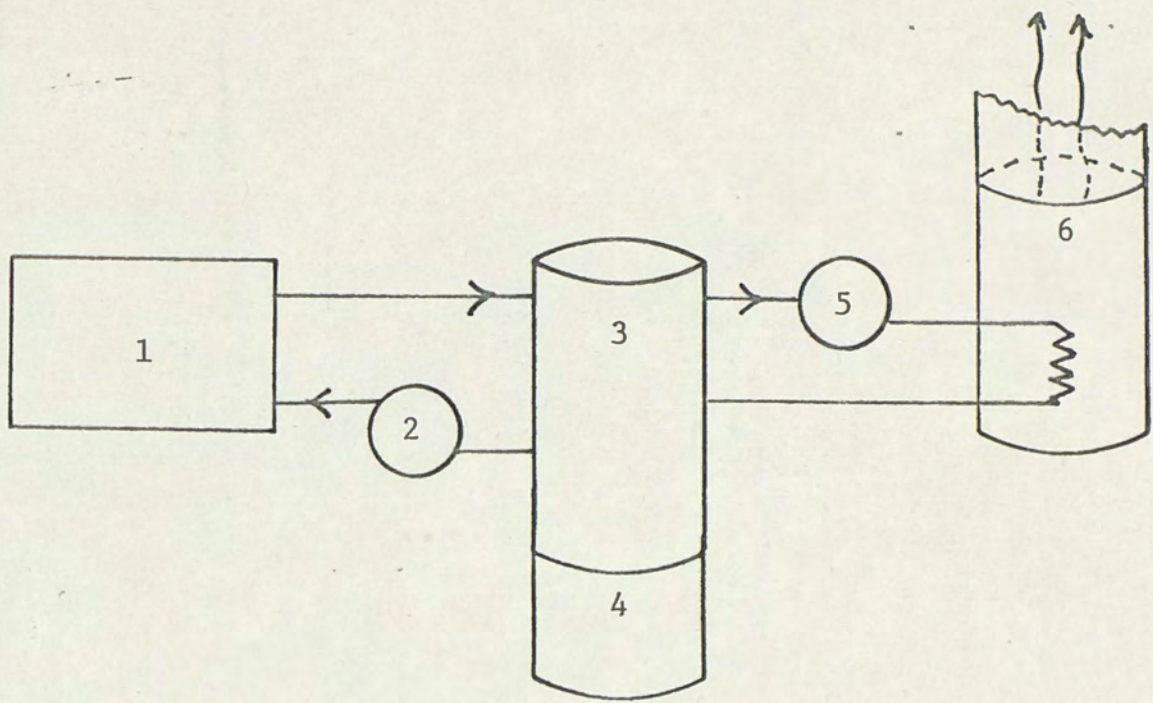
- |                                       |                            |
|---------------------------------------|----------------------------|
| 1. Dirty solvent tank                 | 7. H <sub>2</sub> O return |
| 2. Sludge drain valve                 | 8. Condenser               |
| 3. Filter                             | 9. Cooling Coil            |
| 4. Pre-heat coils                     | 10. Pump                   |
| 5. Evaporator                         | 11. Clean Solvent Out      |
| 6. Hot H <sub>2</sub> O inlet (185°F) |                            |

Fig. II-1. Non-Solar Operation Process Diagram

shipping barrels. This pump also creates a partial vacuum in the evaporator ( $\sim .7$  atm) which causes solvent vaporization to occur at a lower temperature than it would at one atm.

#### Adaptation of System to Solar Operation

In this section, two alternative approaches are proposed for conversion of the present solvent reclamation system to solar operation. These alternatives will be referred to as process 1 and process 2. Each has distinct advantages and disadvantages which require both a thermal and economic analysis to resolve. Figure II-2 shows the configuration for process 1. The solar collectors are connected to the storage tank in a manner such that the flow rate per unit area of the collector may be maintained at  $1 \text{ gal/hr-ft}^2$  ( $41 \text{ l/hr-m}^2$ ). This flow rate appears to be an optimum based on the existing performance curves of the collector chosen for the analytical model.<sup>8</sup> An advantage of this configuration is that it easily allows the collector flow to be optimized independently of the flow through the evaporator. A disadvantage is that the collectors are constantly operating at an inlet temperature which is approximately equal to the average storage media temperature. Since the acetone reclamation process requires the storage media temperature to be approximately  $185^\circ\text{F}$  ( $85^\circ\text{C}$ ), the flat plate collectors would be functioning at reduced efficiency due to the increased thermal losses encountered at these elevated



KEY:

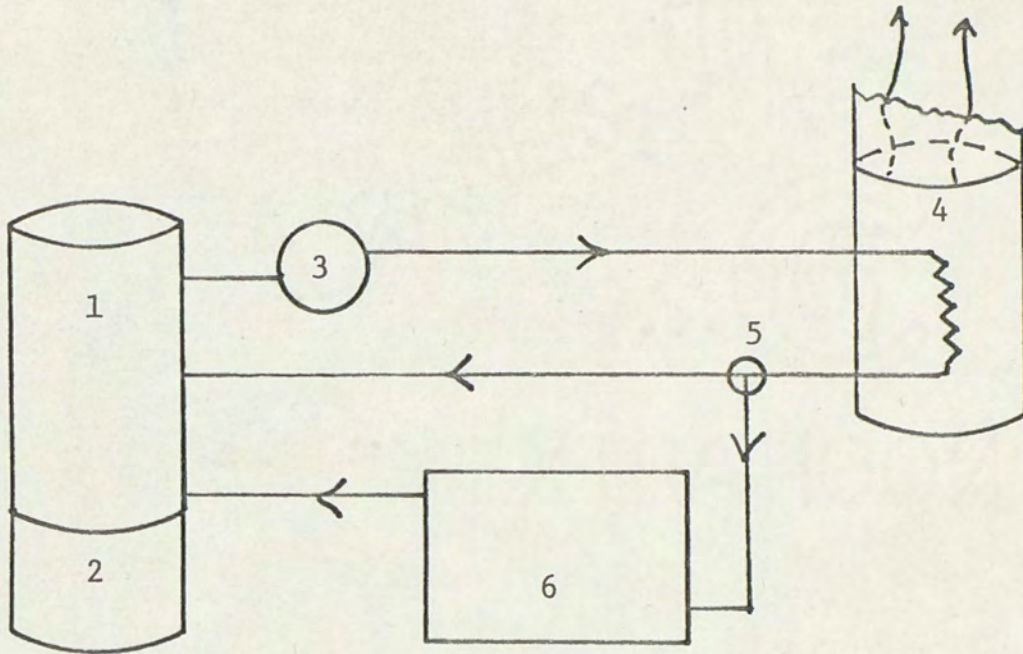
- |                     |                            |
|---------------------|----------------------------|
| 1. Solar collectors | 4. Auxiliary heater        |
| 2. Collector pump   | 5. Heat exchanger pump     |
| 3. Storage tank     | 6. Evaporator (see fig. 1) |

Fig. II-2. Process 1 Configuration

temperatures.

To obtain a greater average operating efficiency from the collectors, it is advantageous to operate them such that the collector inlet water is at the lowest temperature in the system. This is achieved in the process 2 configuration shown in figure II-3. As the hot water from the storage tank passes through the heat exchanger, it loses energy to the vaporizing solvent and is therefore cooled. If the water then enters the collectors at this lower temperature, they will operate more efficiently than with process 1. Additional controls are necessary, however, to insure that the optimum flow rate passes through the collectors. Since the evaporator heat exchanger flow and the collector flow must be controlled independently, a by-pass valve is needed to divert some of the water directly back to the storage tank. This additional complexity could be considered a disadvantage of process 2. In addition, the present evaporator heat exchanger flow rate of 350 gal/hr (1325 l/hr) limits the number of collectors (Area = 21 ft<sup>2</sup>) to sixteen if the optimum 1 gal/hr-ft<sup>2</sup> flow rate is to be maintained.





## KEY:

- |                                  |                            |
|----------------------------------|----------------------------|
| 1. Storage tank                  | 4. Evaporator (see fig. 1) |
| 2. Auxiliary heater              | 5. Flow control valve      |
| 3. Heat exchanger-collector pump | 6. Solar collectors        |

Fig. II-3. Process 2 Configuration

## CHAPTER III

### SOLAR SYSTEM THERMAL ANALYSIS

#### System Analytical Model

A thermal analysis of processes 1 and 2 is required to ascertain the auxiliary energy requirements of these configurations. An energy rate balance for both processes is performed by consideration of a control volume drawn about the storage tank. The system can be accurately modeled in this manner if the tank's water capacity is large compared to that of the collectors, evaporator, and plumbing combined. This assumption will be applied here and justified in a later section of this chapter.

The control volume energy rate balance for the solar augmented system must be performed for two different time periods: one for the time when the auxiliary energy supply is on, and the other for when no auxiliary is supplied. For the "auxiliary on" case we have:

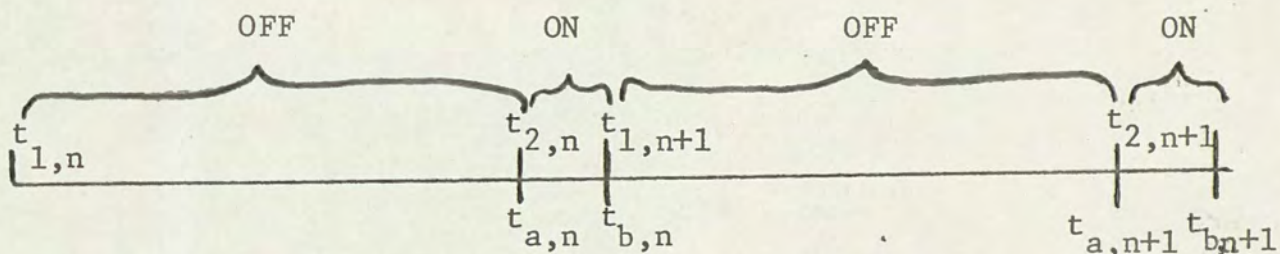
$$(1a) \quad M_s C_p (dT_s/dt)_1 = N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt + \dot{E}_{aux}$$

Rate of change of storage media energy content	=	Input energy rate from solar col- lectors	-	Energy loss rate from system to environment	-	Energy rate ex- tracted by load	+	Energy input rate from auxiliary
---	---	--	---	--	---	--	---	---

When the auxiliary is off, the energy rate balance yields:

$$(1b) \quad M_s C_p (dT_s/dt)_2 = N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt.$$

This system is modeled such that when  $T_s$  falls below some given value,  $T_{on}$ , the auxiliary heater will be activated. The heater returns the storage tank to its initialized temperature,  $T_{off}$ , where  $T_{off} > T_{on}$ . Since no stratification is assumed to exist in the storage tank, the entire volume is at the same temperature at any given time. The auxiliary "on" time interval for the  $n^{th}$  off - on cycle is given as  $T_{b,n} - t_{a,n}$ , where  $t_{a,n}$  is the time when the heater is turned on and  $t_{b,n}$  is the time when it turns off. To account for the period when the auxiliary is off, the interval  $t_{2,n} - t_{1,n}$  is given. A graphical representation of a series of off - on cycles is shown as follows:



If it is assumed that the auxiliary input rate is large compared to the other rate terms in (1) and (1'), then  $t_{b,n} - t_{a,n} \ll t_{2,n} - t_{1,n}$ . Therefore,  $(dT_s/dt)_1 \gg (dT_s/dt)_2$ . Also, since the storage tank is always returned to the same temperature,  $T_{off}$ , then

$$T_s(t_{1,n}) = T_s(t_{1,n+1}) = T_{off}.$$

If the system undergoes N off - on cycles, then (1a) and (1b) can be rearranged and integrated as follows:

$$\begin{aligned}
 (2a) \quad E_{aux\_total} &= \sum_{n=1}^N \int_{t_{a,n}}^{t_{b,n}} M_s C_p (dT_s/dt)_1 dt \\
 &\quad - \sum_{n=1}^N \int_{t_{a,n}}^{t_{b,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) \\
 &\quad - dQ_1/dt\} dt
 \end{aligned}$$

$$\begin{aligned}
 (2b) \quad 0 &= \sum_{n=1}^N \int_{t_{1,n}}^{t_{2,n}} M_s C_p (dT_s/dt)_2 dt \\
 &\quad - \sum_{n=1}^N \int_{t_{1,n}}^{t_{2,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt\} dt
 \end{aligned}$$

where  $E_{aux\_total}$  = the total auxiliary energy required for the N cycles.

From the conservation of energy principle, the net energy removed from the storage media when the auxiliary is off is replaced when it is on if the tank temperature is returned to  $T_{off}$ . Therefore,

$$(3) \quad \int_{t_{1,n}}^{t_{2,n}} M_s C_p (dT_s/dt)_2 dt = \int_{t_{a,n}}^{t_{b,n}} M_s C_p (dT_s/dt)_1 dt.$$

From (1b)

$$\int_{t_{1,n}}^{t_{2,n}} M_s C_p (dT_s/dt)_2 dt = \int_{t_{1,n}}^{t_{2,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt\} dt.$$

Therefore, (2a) becomes

$$E_{aux\_total} = \sum_{n=1}^N \int_{t_{1,n}}^{t_{2,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt\} dt \\ - \sum_{n=1}^N \int_{t_{a,n}}^{t_{b,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt\} dt.$$

But, if  $t_{2,n} - t_{1,n} \gg t_{b,n} - t_{a,n}$ , then

$$(4) E_{aux\_total} \approx \sum_{n=1}^N \int_{t_{1,n}}^{t_{2,n}} \{N_c A_c (dQ'_u/dt) - UA_s (T_s - T_a) - dQ_1/dt\} dt.$$

An analytical solution of (4) is possible if each of the energy rate terms is an integrable function of time. In fact, however, the solar input and ambient temperature are coupled and non-periodic functions of time under general conditions. This makes an analytical evaluation of the first two integrals on the right hand side of (4) a rather complicated operation. On the other hand, the thermal load rate,  $dQ_1/dt$ , for an industrial process should be a constant function of time. The integration of this term would then be easy to carry out. However, only experimental measurements on the actual system can help yield an analytical expression for this term. Further

analytical complications arise in the evaluation of (4) due to the fact that the collector output is not only dependent upon the incident solar radiation, but upon the inlet water temperature and ambient air temperature as well. But, the collector inlet water temperature depends upon the storage media temperature which, in turn, depends upon the collector output and the ambient temperature. This functional cross-coupling is not apparent from the energy rate balance shown in equation (1) and indicates that the exact solution of (4) will be a complex operation even under the most simplified solar input conditions. An alternative procedure would be to make as many simplifying assumptions as possible which are justified by the physical operating parameters of the particular system, and solve (4) with an iterative numerical solution method. This approach has been chosen and is described in the following section.

#### Numerical Solution Procedure

Comparison of equations (2b) and (4) yields the following approximation:

$$(5) E_{aux\_total} \approx \sum_{n=1}^N \int_{t_{1n}}^{t_{2n}} M_s C_p (dT_s/dt)_2 dt.$$

In a finite time interval,  $\Delta T$ , (1b) can be rearranged and written in finite difference form:

$$(6) M_s C_p \Delta T_s = \Delta T \{ N_c A_c (\Delta Q'_u / \Delta t) - UA_s (\bar{T}_s - \bar{T}_a) - \Delta Q_1 / \Delta t \}.$$

The left hand side of (6) now represents the change in energy content of the storage media that occurs over the time interval  $\Delta\tau$ . From (5) this also approximately represents the auxiliary input energy necessary to return the storage media to the temperature it had at the beginning of the interval  $\Delta\tau$ . Therefore, evaluation and summation of (6) for each interval,  $\Delta\tau$ , between times  $t_I$  and  $t_{II}$ , will result in an approximate solution to equation (4). The total auxiliary energy requirements for processes 1 and 2 can then be determined and compared with those of the current non-solar operation. Note that the time interval,  $t_{II} - t_I$ , is the operating period for a given day and includes  $N$  off - on cycles of the auxiliary heater. In this context, the  $\Delta\tau$ 's are fixed intervals and have no direct relationship to the auxiliary off and on times previously defined. In the actual operation of the system a controller would turn on the auxiliary as soon as the tank temperature dropped below a preset value,  $T_{on}$ . For the numerical analysis defined here, it is necessary to first know the storage media temperature at the end of the interval before a decision is made to turn on the heater. The auxiliary energy is then added instantaneously in one lump amount at the end of the interval. Sufficient energy is added to raise the temperature of the storage media from the interval end point value,  $T_{s,n+1}$ , to  $T_{off}$ . The value of  $T_{off}$  is then used as the starting temperature for the succeeding interval.

If  $T_{s,n+1} > T_{on}$ ,  $T_{s,n+1}$  is used as the succeeding interval starting temperature.

The change in the storage media temperature during an interval  $\Delta\tau$  is  $T_{s,n+1} - T_{s,n}$  and is determined by

$$(7) \Delta T_s = \Delta\tau / (M_s C_p) \{ N_c A_c (\Delta Q'_u / \Delta t) - UA_s (\bar{T}_s - \bar{T}_a) - \Delta Q_l / \Delta t \}.$$

For this analysis, the following parameter values were used:

$$\begin{aligned} \Delta\tau &= .5 \text{ hours} \\ UA_s &= 1.6 \text{ BTU/hr-}^\circ\text{F (3 KJ/hr-}^\circ\text{C)} \\ V_s &= 350 \text{ gallons (1328 liters)} \\ T_s^s &= 190.4^\circ\text{F (88}^\circ\text{C)} \\ T_{off}^{on} &= 194^\circ\text{F (90}^\circ\text{C)}.^9 \end{aligned}$$

Selection of these parameters was based on the physical requirements of the particular system modeled, and the practical requirements for solution on a hand held programmable calculator. A time interval of .5 hours was chosen because on a clear day the solar insolation does not vary significantly over this interval. Of course, during the early morning and late afternoon this would not be true, but these portions of the day are not used in the following analysis. The storage tank capacity of 350 gallons is used to satisfy the condition upon which equation (1) was based: the storage capacity is large compared to that of the collectors, evaporator, and plumbing combined. With a collector water capacity of about 1.5 gal/unit and a remaining system capacity of about five gallons, a twenty collector system would contain thirty-five gallons of water



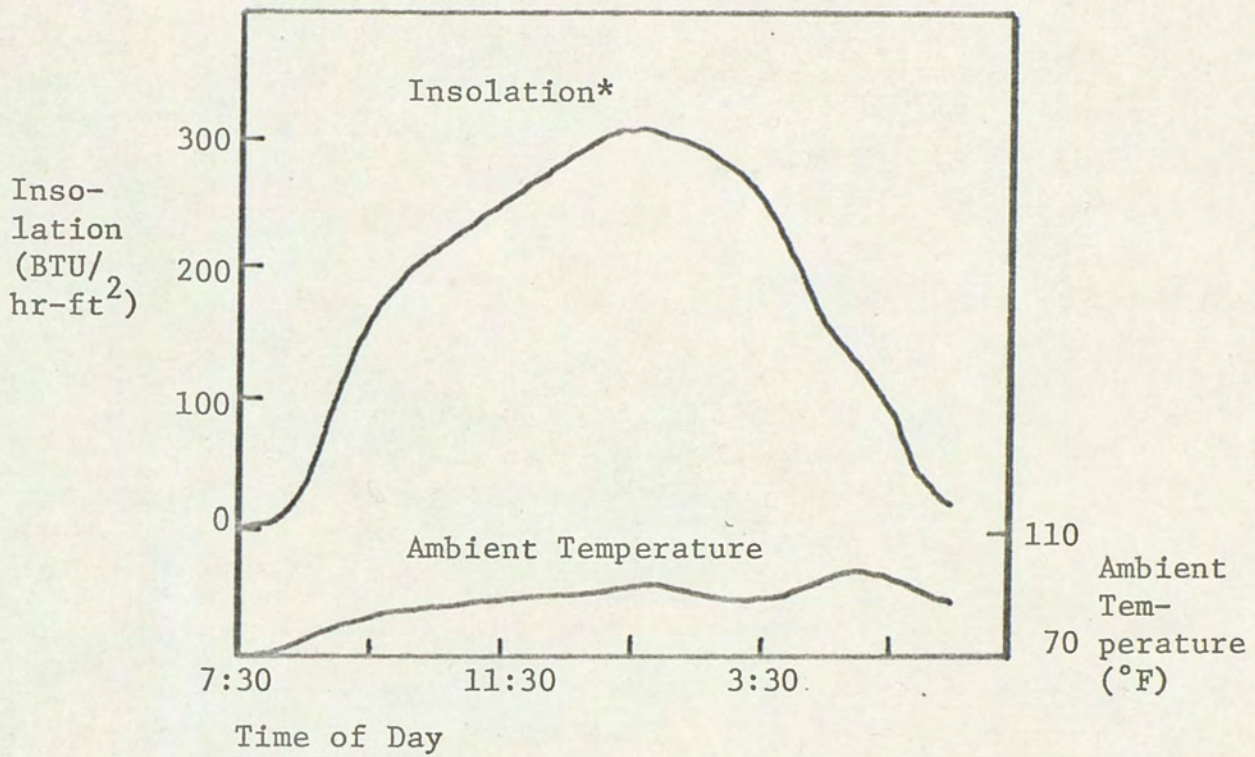
other than the storage volume. For a 350 gallon storage tank capacity, the total water mass is only 10 percent greater than the storage media mass. Hence, limiting storage considerations to the tank is a reasonable assumption if less than twenty collectors are considered. The storage tank area - loss coefficient of 1.6 BTU/hr - °F was selected from an example in reference 9. It is assumed that this value could be obtained in practice if sufficient insulation is provided for the storage tank. The remaining two parameters,  $T_{on}$  and  $T_{off}$ , were chosen so that the storage media temperature never falls below 80°C, the minimum allowable temperature of the evaporator inlet water for the particular system considered. However, it is not desirable to allow the storage tank water to reach a temperature of more than 90°C due to the lower collector efficiencies encountered at this level. Therefore, a value of 90°C was chosen for  $T_{off}$ . For the .5 hour time interval it was determined that under extreme conditions (maximum load and zero insolation) the storage media temperature would drop 8°C. Therefore a controller flag value of 88°C would be necessary to prevent the tank temperature from dropping below 80°C during any interval. Thus,  $T_{on}$  is set at 88°C.

Definition of the rate terms in (7) requires specific information about the insolation profiles, ambient temperature profiles, collector performance, and the system thermal load.

Figure III-1 is a reproduction of an insolation and temperature profile for a practically cloudless day which probably represents a maximum solar input driving function for the mid-Florida area.<sup>10</sup> The conditions under which this data were taken are for a collector oriented due south with a tilt angle of forty-five degrees. The proposed solar collectors for the Orlando, Florida operation will have a collector tilt angle of thirty-eight degrees along with a due south orientation. Hence, the insolation data shown in figure III-1 is corrected for this new angle and tabulated in the appendix.

This model day was broken into .5 hour intervals from 10 A. M. to 6 P. M. with the corresponding interval average insolation and ambient temperatures tabulated. The objective here is to analyze the system performance during the most favorable conditions that can be expected for this geographic area. A daily performance can then be based on a percentage of the maximum obtained. The percentage factor will be estimated from annual insolation data for the mid-Florida area. This analysis will be carried out in the following chapter on the system economics.

A high performance, commercially available, flat plate solar collector was modeled for this study.<sup>8</sup> Figure III-2 gives this unit's thermal output in terms of the incident solar radiation and inlet temperature for an ambient temperature



\*Normal to surface inclined at 45° F, facing due south.

Fig. III-1. Model day (insolation and temperature) profiles (ref. 10).

of 90°F (32.2°C). Reference to appendix A indicates that the mean temperature for the portion of the model day considered was 32.4°C. This validates the use of figure III-2. Using figure III-2, an approximate analytical expression may be obtained for the rate of useful energy produced by the collector:

$$(8a) \quad \Delta Q'_u / \Delta t = .664\bar{H} - 30 - .67(\bar{T}_i - 140) \text{ BTU/hr-ft}^2$$

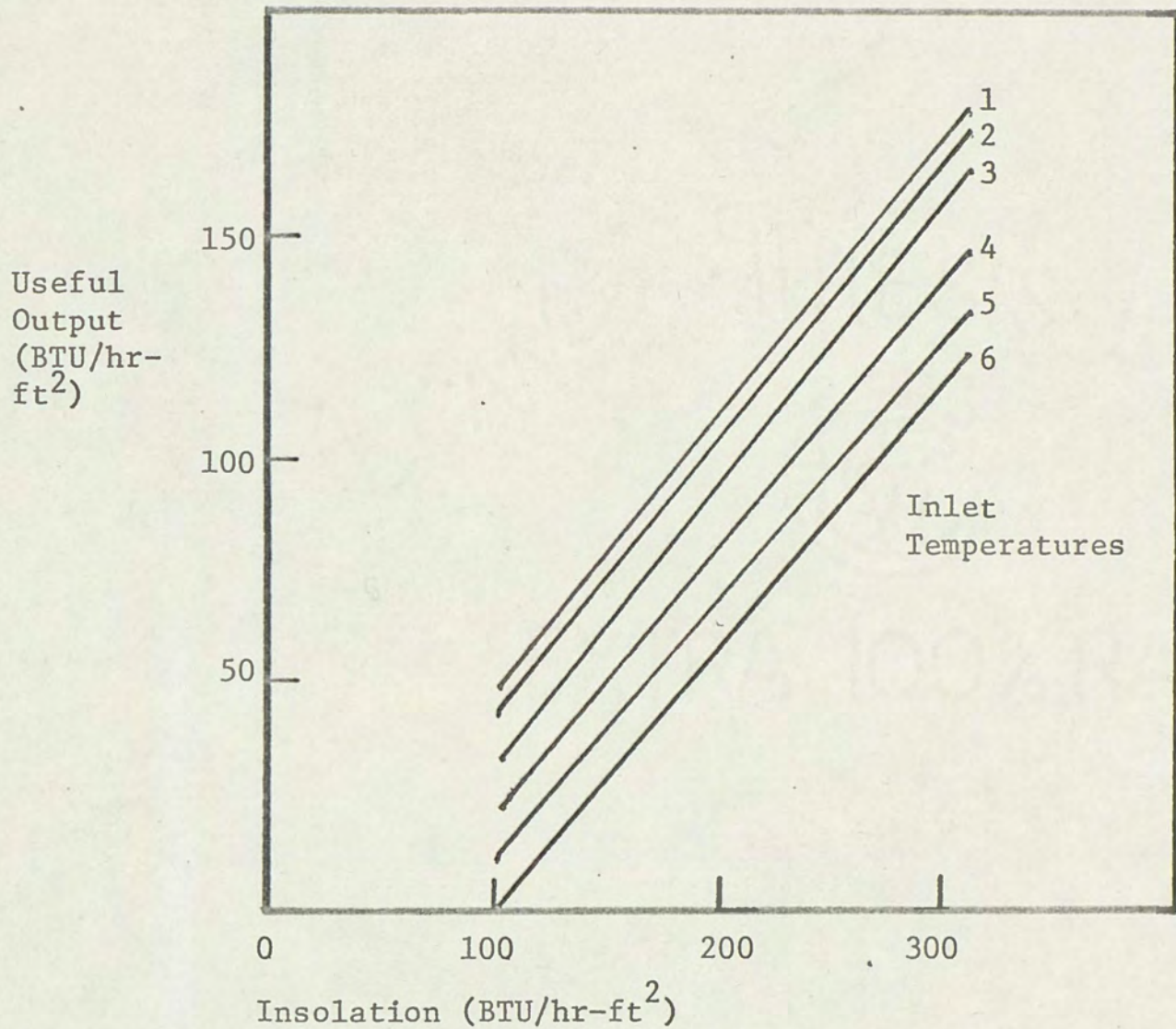
or

$$(8b) \quad \Delta Q'_u / \Delta t = .664\bar{H} - 340 - 13.7(\bar{T}_i - 60) \text{ KJ/hr-m}^2.$$

Heat losses from the system occur from the collectors, piping, and storage tank. The collector losses, however, are incorporated in equations (8a) and (8b) which apply for the model day considered. It is assumed that the piping losses can be made extremely small by proper insulation and they are therefore neglected. The storage tank losses, on the other hand, are difficult to totally eliminate in practice. As mentioned previously, the tank loss coefficient-area product,  $UA_s$ , is assumed to be 1.6 BTU/hr-°F (3 KJ/hr-°C). Hence, the loss rate term in (7) is given by:

$$(9) \quad UA_s (\bar{T}_s - \bar{T}_a) = 3(\bar{T}_s - \bar{T}_a) \text{ KJ/hr.}$$

Measurements on the system studied indicate that the thermal load decreases with time due to sludge build-up on the heat exchanger. After six to eight hours from system start-up, the heat exchanger's thermal resistance is so great that it is incapable of transferring sufficient energy to the solvent to



Inlet Temperature Key:

- |          |          |
|----------|----------|
| 1. 100°F | 4. 160°F |
| 2. 120°F | 5. 180°F |
| 3. 140°F | 6. 190°F |

Fig. III-2. Model collector performance characteristics (ref. 8).

cause vaporization. At this time, the operation is terminated and the heat exchanger is cleaned. Although there are solvent reclamation systems available which have an automatic cleaning feature, this particular one does not and therefore its load is not a constant function of time. Figure III-3 was generated from the measurement of the start-up and endpoint heat exchanger inlet-outlet temperatures. For this study, an assumed monotonically decreasing linear function of time connects the measured endpoints. The load profile may thus be approximated analytically by:

$$(10) \quad \Delta Q_1 / \Delta t = -12,350 t_i + 113,500 \text{ BTU/hr}$$

where  $t_i$  is the time elapsed (hours) at the midpoint of the " $i^{\text{th}}$ " interval. Hence, for a given  $\Delta \tau$ ,

$$(11) \quad t_i = \Delta \tau / 2 (2i - 1).$$

With  $\Delta \tau = .5$  hours,

$$(12a) \quad \Delta Q_1 / \Delta t = -12,350 (.25(2i - 1)) + 113,500 \text{ BTU/hr}$$

or

$$(12b) \quad \Delta Q_1 / \Delta t = -13,030 (.25(2i - 1)) + 119,749 \text{ KJ/hr.}$$

It is now possible to substitute all of the rate expressions into (7). The resulting finite interval equation is

(in MKS units):

$$(13) \quad \Delta T_s = \Delta \tau / (4.19 V_s) \{ N_c A_c (.664 \bar{H} - 340 - 13.7(\bar{T}_i - 60) - 3(\bar{T}_s - \bar{T}_a) - (-13,030(.25(2i - 1)) + 119,749) \},$$

where  $V_s$  is in liters.

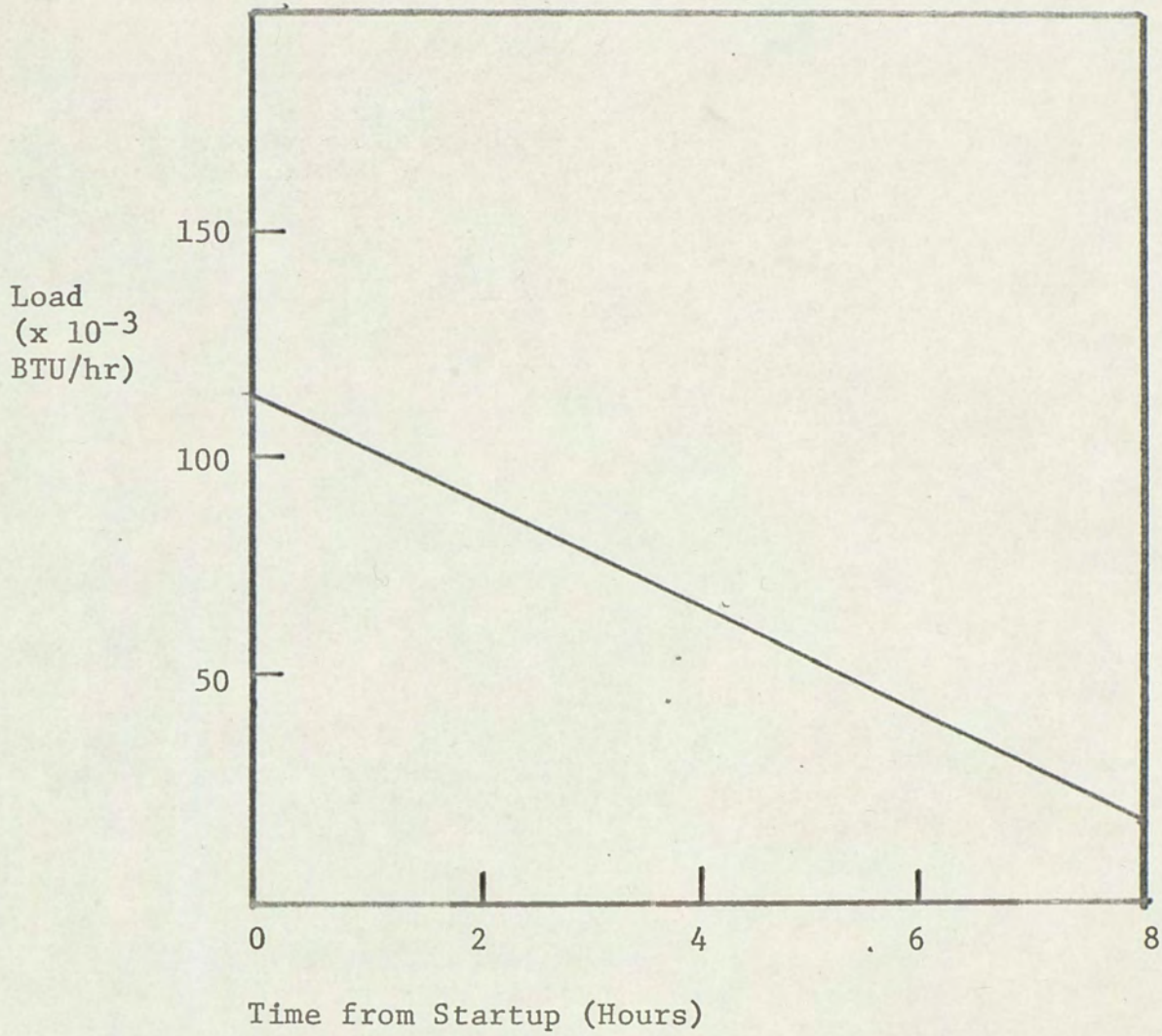


Fig. III-3. Load energy extraction rate as a function of time.

The advent of the programmable pocket calculator has afforded a convenient solution to equation (13). Figures III-4 and III-5 represent the process 1 and process 2 simulation flow diagrams respectively. The solutions have been obtained with a Texas Instruments, SR-56 programmable calculator. Both simulations are begun by inputting an average storage media temperature estimation,  $\bar{T}_{\text{guess}}$ , the number of collectors,  $N_c$ , and the storage volume,  $V_s$ . For each interval,  $\Delta\tau_i$ , average values for the insolation,  $H$ , ambient temperature,  $\bar{T}_a$ , evaporator load rate,  $\Delta Q_1/\Delta t$ , and the storage media temperature at the start of the interval,  $T_{s,n}$ , are entered. For process 1, the collector inlet temperature is equal to the average storage media temperature for the interval. In the process 2 simulation, the inlet temperature is equal to the average tank temperature minus the temperature drop across the evaporator. The evaporator temperature drop for the given interval is given by

$$(14) \quad \Delta T_{\text{evap}} = (\Delta Q_{1,i}/\Delta t)/(4.19 \dot{V}) \quad ^\circ\text{C},$$

where, for the present system  $\dot{V} = 350 \text{ gal/hr} = 1328 \text{ l/hr}$  and is entered for each interval. From here on, both process simulations are identical. The storage media temperature at the end of the interval,  $T_{s,n+1}$ , is computed and an average storage media temperature for the interval,  $\bar{T}_s$ , is then determined. If this temperature differs from the guessed value,  $\bar{T}_{\text{guess}}$ , by



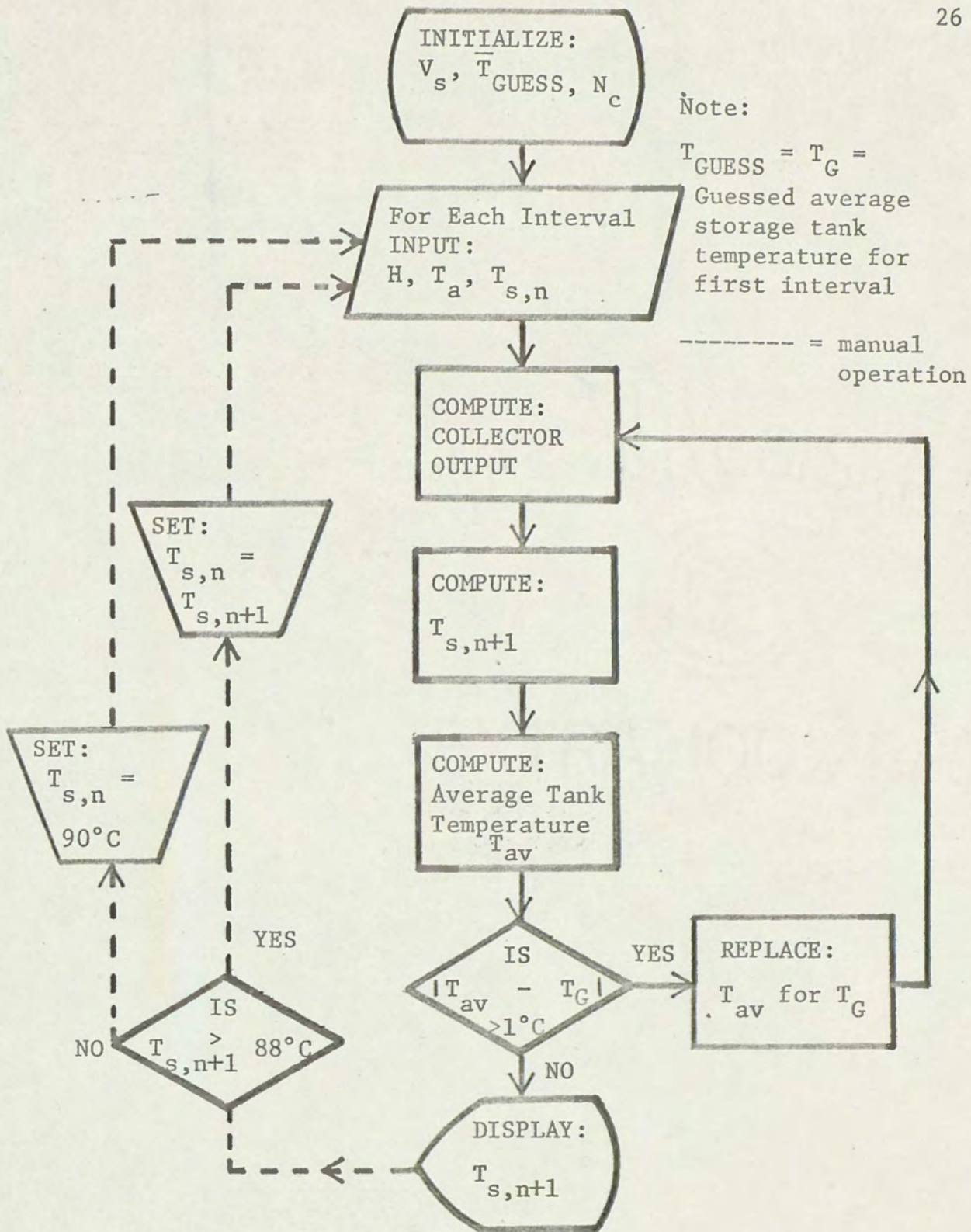


Fig. III-4. Process 1 Flow Diagram For SR-56 Programmable Calculator.

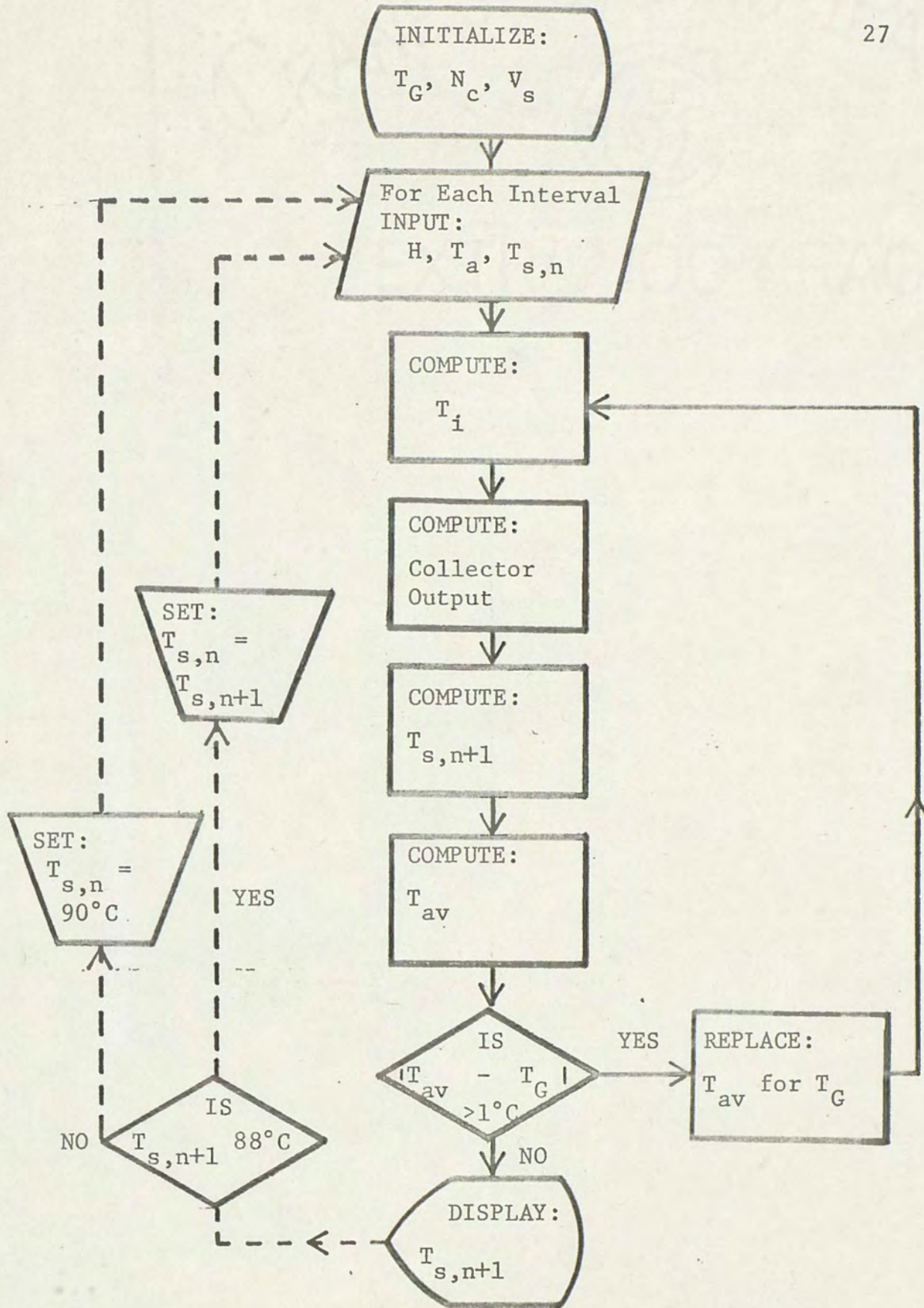


Fig. III-5. Process 2 flow diagram for SR-56 programmable calculator.

more than  $1^{\circ}\text{C}$ ,  $\bar{T}_s$  is substituted for  $\bar{T}_{\text{guess}}$  and the loop is repeated until the necessary convergence occurs. The final tank temperature at the end of the interval,  $T_{s,n+1}$ , is then displayed. If  $T_{s,n+1} \geq 88^{\circ}\text{C}$ , it is entered as  $T_{s,n}$  for the next interval. If less than  $88^{\circ}\text{C}$ , then  $90^{\circ}\text{C}$  is entered as  $T_{s,n}$  for the succeeding interval. In this manner, a complete storage tank temperature profile is generated for the time period  $t_{\text{II}} - t_{\text{I}}$ . Figure III-6 represents a sample of the temperature profiles for process 2. The auxiliary energy required to return the storage tank temperature to  $90^{\circ}\text{C}$  is summed for each interval that ends with a temperature of less than  $88^{\circ}\text{C}$ . The summation results in the total auxiliary energy required for the day's operation and is an approximate solution to (5).

The auxiliary energy requirements for processes 1 and 2, using the model day solar and temperature inputs, have been computed and the results indicated in figure III-7. An accuracy test was performed by halving the .5 hour interval and repeating a set of calculations from figure III-7. No significant differences were noted. The load percentage handled by the solar collectors is given by the ratio of the auxiliary energy required with the solar system to that required by the current non-solar operation. As can be seen, process 2 is the more efficient configuration, but is limited to 16 collectors as

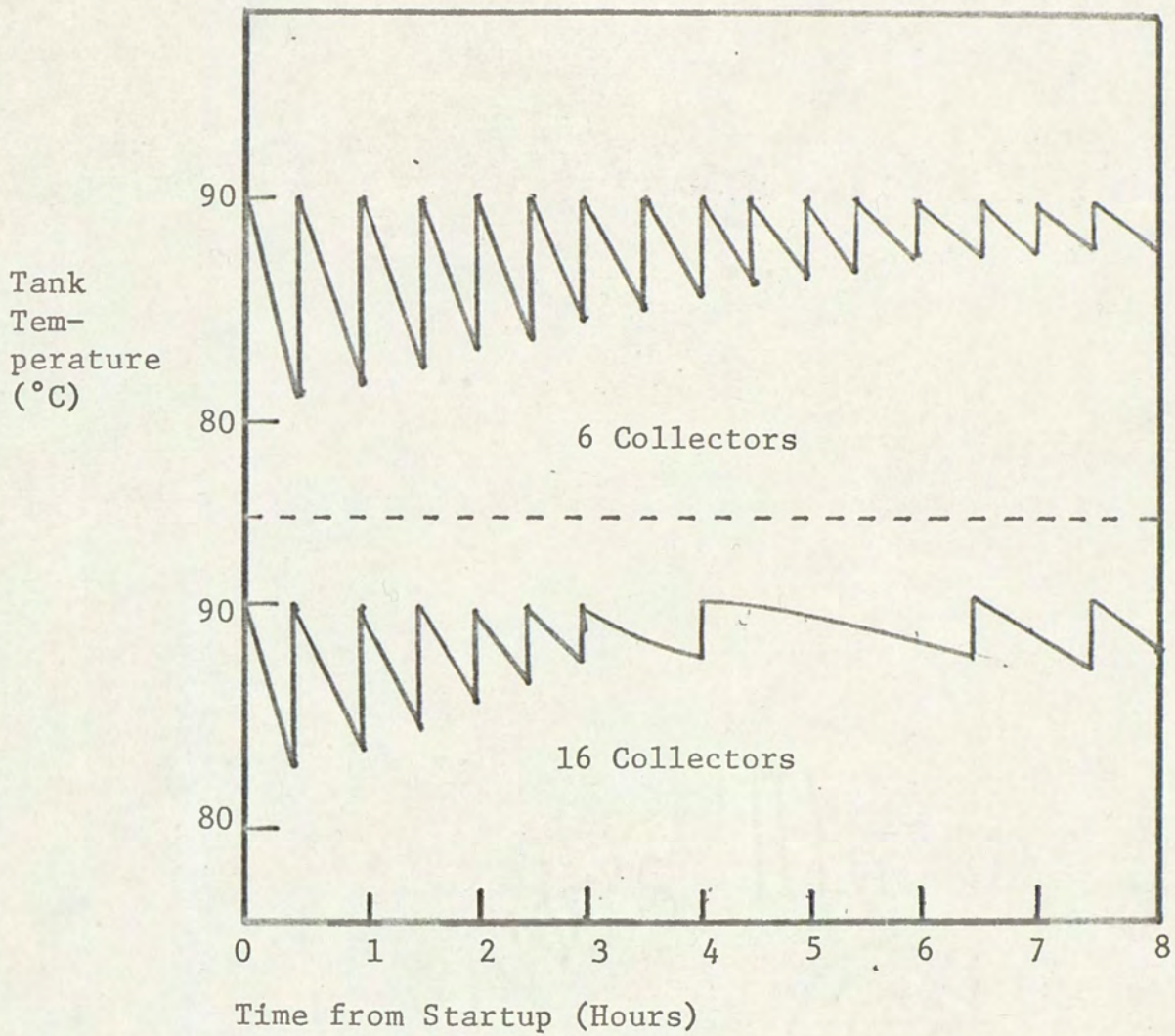


Fig. III-6. Storage media temperature profiles for process 2.

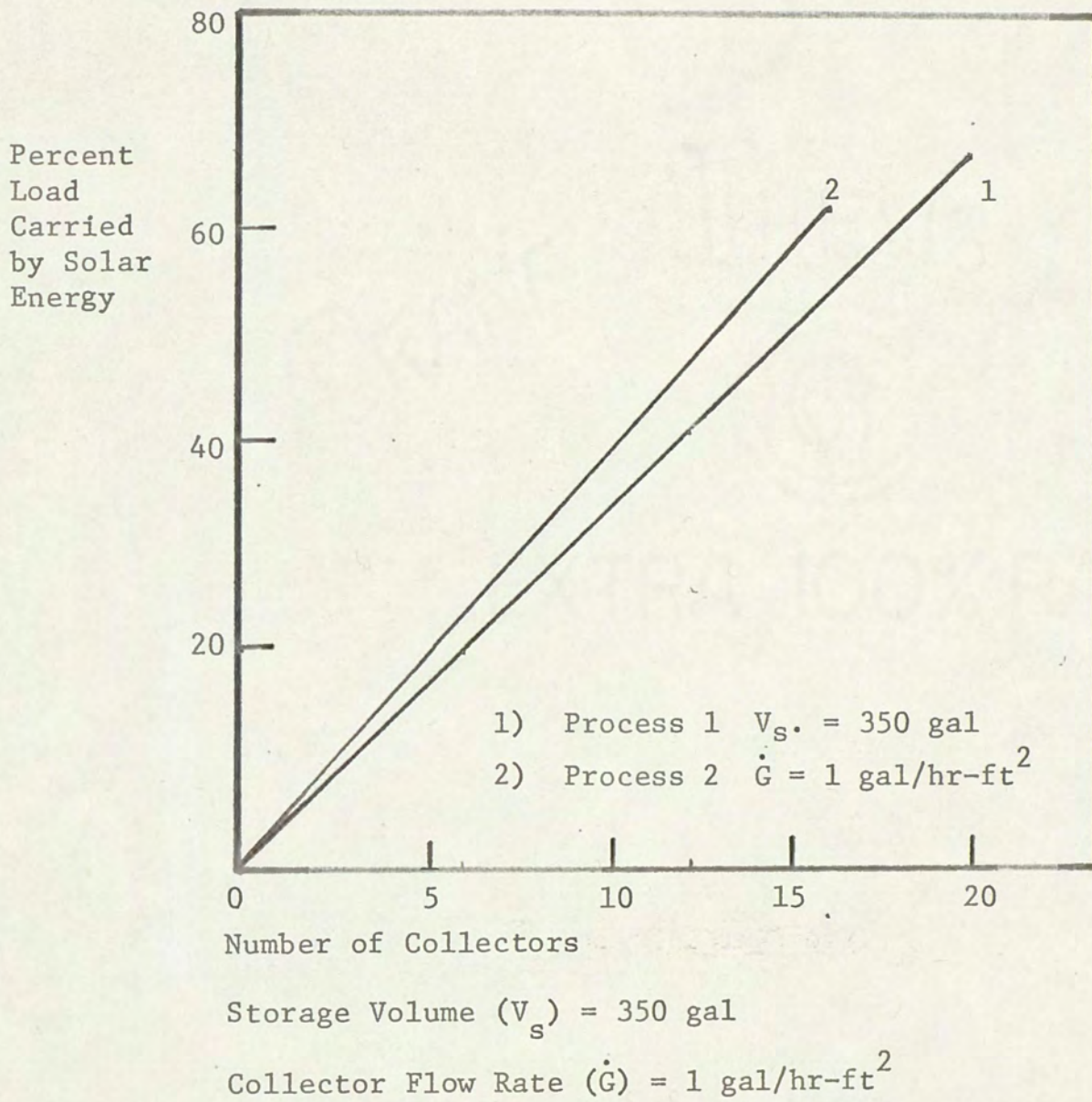


Fig. III-7. Percentage of load carried by solar energy as a function of the number of collectors use.

previously noted. Although process 1 can carry a greater load percentage, its lower efficiency may limit the performance on an economic "cost effectiveness" basis.

## CHAPTER IV

### SYSTEM ECONOMICS

The decision to retro-fit a solvent reclamation system for solar energy augmentation is based upon the same motive underlying the system's existence in the first place: economics. Unless a suitable monetary gain can be realized over the system lifetime, the impetus for "going solar" will be negligible. In this chapter, a first order, parametric economic analysis will be conducted on the solar retro-fitting of the present reclamation apparatus. This study will be based upon the thermal performance simulation performed previously.

For the solar system to be economically viable, the savings in fuel oil expenditures during the system lifetime must exceed that of the extra equipment, maintenance, labor, and financing (if any). In addition, the savings incurred should equal or exceed the return via compounded interest which could be earned by investing the retro-fit cost for the system in a low risk savings account over the system lifetime.

Since the auxiliary heater fuel requirements strongly depend upon the insolation level, it would be desirable to simulate the system operation with a full year of sunshine and meteorological data for the area in which it is located.

However, this can be a time consuming and costly analysis even if such extensive data is available. An alternate procedure would be to base the performance on seasonally averaged, integrated insolation data for the general geographical area. This information is more readily obtainable and is sufficient for a first order analysis. From 9, the average annual mean for daily total solar insolation incident upon a horizontal surface in mid-Florida was found to be  $441 \text{ cal/cm}^2$ . Upon conversion of the insolation data in figure III-1 to that incident upon a horizontal surface, and integrating over the entire daylight period, we obtain a value of  $756 \text{ cal/cm}^2$ . Therefore, it can be seen that the average daily radiation is about 58 percent of that of the maximum performance day used in the thermal analysis. If the assumption is made that the system load handled by the solar collectors is directly proportional to the incident radiation, and if some conservatism is included, then an average daily performance of 50 percent of that indicated in figure III-7 can be expected. In other words, for a given number of collectors, the load carried by solar energy is 50 percent of that indicated by figure III-7 on an average basis. The balance of the load must, of course, be carried by the auxiliary heater.

Prior to undertaking the economic computations, the following additional assumptions are given:



i) The system lifetime is twenty years.

ii) Annual fuel consumption is based on a five day per week operation (260 days per year).

iii) Maintenance and labor costs for the solar and non-solar systems are identical and are, therefore, neglected in this comparison (this is, perhaps, one of the weaker assumptions).

iv) The solar system has zero salvage value at the end of the system lifetime.

v) Other than the collectors, the additional equipment cost for the solar system (storage tank, pumps, piping, controls, and labor) is \$1200 and is independent of the number of collectors used.

vi) Interest rates and fuel cost increases are compounded annually.

vii) Rates of return are computed on a "before taxes" basis.

Using the 50 percent performance factor with figure III-7, the annual fuel consumption of the system is approximately given by:

$$(15) \quad F_1 = 2600 - 43.4N_c \quad \text{gallons} \quad (\text{process 1})$$

$$(16) \quad F_2 = 2600 - 50.4N_c \quad \text{gallons} \quad (\text{process 2}).$$

For the case with no collectors ( $N_c = 0$ ), these expressions reduce to the annual fuel requirement of 2600 gallons (9880 liters) of fuel oil for 260 days of operation at approximately ten gallons per day.

If the fuel oil cost per gallon is initially  $C_{fi}$ , and the annual rate of fuel price increase is  $i_f$ , then the fuel cost for the  $n^{\text{th}}$  year for the non solar operation is:<sup>11, 12</sup>

$$C_{fn} = 2600C_{fi}(1 + i_f)^{n-1}$$

provided that the fuel requirements for the year are purchased at the price that exists at the beginning of the particular year. If the difference in the fuel cost between the non-solar and solar system for the  $n^{\text{th}}$  year is considered as a net receipt for that year, then it is possible to define a rate of return on the investment made for the solar retro-fit. The  $n^{\text{th}}$  year savings in fuel expenses is given by:

$$S_{1n} = C_{fi}(1 + i_f)^{n-1}43.4N_c \quad \text{dollars} \quad (\text{process 1})$$

$$S_{2n} = C_{fi}(1 + i_f)^{n-1}50.4N_c \quad \text{dollars} \quad (\text{process 2}).$$

If the present worth of each year's net cash flow is summed for the life of the system, then

$$(17) \quad \sum_{n=1}^N P = \sum_{n=1}^N \{S_{jn}/(1 + i)^{n-1}\} - (N_c A_c C_c + 1200).$$

where  $N$  = system lifetime in years.

Here,  $j$  is the subscript for either process 1 or 2, and  $i$  is an interest rate. The rate of return,  $i$ , is defined as the interest rate at which the present worth of the net savings is equal to the required investment. Hence, for a given set of parameters, we seek a value for  $i$  such that

$$(18) \quad \sum_{n=1}^N \{S_{jn}/(1 + i)^{n-1}\} - (N_c A_c C_c + 1200) = 0,$$

where the term  $(N_c A_c C_c + 1200)$  is the first cost.

The first cost,  $C$ , is the investment required to retro-fit the current apparatus and, as such, represents a disbursement. This quantity is negative, whereas the net receipts from the annual fuel savings are considered positive. Equation (18) is solved through trial and error by testing for the value of  $i$  which makes the expression true. Table IV-1 compares process 1 and 2 for a system lifetime of twenty years, an initial fuel cost of \$ .35 per gallon, and an annual fuel price increase rate of .04. It can immediately be seen that process 2 exceeds process 1 in the rate of return received. Even with twenty collectors, the process 1 configuration does not perform as well economically as process 2 with sixteen collectors. Therefore, for any given set of parameters process 2 is the best design alternative for the stated assumptions. The increased load percentage that process 1 accommodates is offset economically by the cost of the increased number of collectors required. The optimum number of collectors is sixteen, which is also the maximum that process 2 can utilize under the current and assumed operating parameters.

Table IV-2 compares the process 2 rate of return with sixteen collectors against various annual fuel increase rates, collector unit area costs, and initial fuel prices. Obviously, if the collector cost was reduced and the price of fuel increased

at a high annual rate, then very competitive rates of return could be realized.

TABLE IV-1

$N =$  twenty years

$C_{fi} = \$ .35/ \text{ gal}$

$i_f = .04$

$N_c$	$C_c$	$i$ (process 1)	$i$ (process 2)
6	\$14.29*	----	.005
12	\$14.29	.011	.026
16	\$14.29	.018	.033
20	\$14.29	.022	----
6	\$ 7.00	.026	.041
12	\$ 7.00	.064	.082
16	\$ 7.00	.077	.097
20	\$ 7.00	.086	----
6	\$ 5.00	.039	.056
12	\$ 5.00	.087	.109
16	\$ 5.00	.106	.129
20	\$ 5.00	.119	----

\*Current model collector cost/ft<sup>2</sup>

TABLE IV-2

$N =$  twenty years

$N_c = 16$

Process 2

$C_c$	$i_f$	$i (C_{fi} = \$ .35/\text{gal})$	$i (C_{fi} = \$ .45/\text{gal})$
\$14.29	.02	.013	.041
\$14.29	.04	.033	.061
\$14.29	.08	.073	.102
\$14.29	.10	.093	.123
\$ 5.00	.02	.107	.152
\$ 5.00	.04	.129	.175
\$ 5.00	.08	.172	.220
\$ 5.00	.10	.194	.243

## CHAPTER V

### CONCLUSIONS AND RECOMMENDATIONS

The preceding thermal and economic analyses have indicated that the process 2 configuration, utilizing sixteen collectors, yields the most favorable rate of return under the assumed set of economic parameters. It is now necessary to compare these rates with those that would be attained if the cost of the retro-fit was instead placed in a low risk investment alternative. As previously stated, the rate of return derived from the solar conversion of the solvent reclamation system must be greater than that from the lower risk alternatives if it is to be economically justified. The assessment of a minimum acceptable rate of return (MARR) must take into account expected inflation and the assumptions and uncertainties inherent in the preceding analysis. Because of the difficulty of quantifying uncertainties, the ultimate determination of the MARR will most likely be arrived at through a somewhat subjective decision.

Presently, a rate of return of between .070 and .080 can be realized by the investment of capital in a long term, low risk savings certificate type of account. Certainly, if the rate of return from the system modification was less than this value, it would be wiser to simply deposit an amount

equal to the modification cost in a long term savings certificate and continue with the non-solar operation. If a 25 percent uncertainty factor is added to the above interest rate, then a MARR of approximately 0.10 results. Therefore, attention is confined to the conditions under which this rate (or greater) can be achieved with the solar modification.

Table IV-2 indicates the sensitivity of the rate of return to variations in the given external economic parameters. Currently, the collector unit area cost is \$14.29/ft<sup>2</sup> and the fuel cost is about \$ .35/gal. Under these conditions it can immediately be seen from Table IV-2 that the rate of return is below the MARR even when the fuel cost increase rate is .10 per annum. Therefore, the solar retro-fit would probably not be advisable at the present time from an economic standpoint. However, if collector prices drop and/or fuel prices increase to about \$ .45/gal, the solar system alternative could then be a profitable venture. Reduction of current collector costs by 65 percent to \$5.00/ft<sup>2</sup> would result in a rate of return greater than the MARR if fuel increase rates were .02 or greater. Since the cost of fuel oil is expected to increase annually by at least 2.0 percent, a \$5.00/ft<sup>2</sup> collector cost would at least insure an attractive rate of return. It is necessary, however, to realize that the MARR may have to be modified due to inflation rate changes. Since these trends are difficult to predict, an average



value of inflation should be assumed in determining the MARR.

The above discussion leads the author to the conclusion that if solar thermal systems are to make any contribution to low grade industrial heating applications, the cost of the collectors must decrease significantly to make them a competitive alternative to systems which depend totally on fossil fuel energy. This cost decrease must not be at the expense of collector performance, however, or else little advantage will be achieved economically. In addition, the collectors and supporting equipment must be capable of maintaining their performance for the twenty year life of the system. If repairs or replacement become necessary, the economic benefit could be totally negated.

Finally, mention is made of the possibility of tax credits and incentives which may be afforded the operator of a solar operated system. Such incentives are presently under consideration by the legislative bodies of many states. Such tax "breaks" could definitely cause the rate of return factor to more positively favor the solar system configuration under the conditions herein assumed.

APPENDIX 1

MODEL DAY "A"

June 19, 1974

Melbourne, Florida

Interval (10:00 A. M. Start)	H (kJ/Hr-M <sup>2</sup> ) (At Mid Pt. of i)	T <sub>ambient</sub> (°C)	ΔT <sub>Evap</sub> (°C)	Q <sub>Load</sub> (kJ/Hr)
1	2483	30	20.8	116,492
2	2835	32	19.6	109,977
3	2937	32	18.5	103,462
4	3243	32	17.3	96,974
5	3413	32	16.2	90,432
6	3606	32	15.0	83,917
7	3720	33	13.8	77,402
8	3720	33	12.7	70,887
9	3674	32	11.5	64,372
10	3481	32	10.3	57,857
11	3243	31	9.2	51,342
12	2948	32	8.0	44,827
13	2279	33	6.8	38,322
14	1860	35	5.7	31,797
15	1383	35	4.5	25,282
16	851	32	3.4	18,767
17	340	31	2.2	12,252

APPENDIX 2



## SR-56 Coding Form

TEXAS INSTRUMENTS  
DAVIS, TEXAS

**Q<sub>Load</sub> &**

TITLE ΔT Evaporator (At mid interval, n) PAGE 1 OF 1

PROGRAMMER A. H. Litka DATE 3-76

REGISTERS	
0	n
1	
2	
3	V
4	
5	ΔT Evap
6	Q <sub>Load</sub>
7	
8	
9	

LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS
00 01	1		25 54	÷		50 74	-		75		
01 35	SUM		26 52	(		51 01	1		76		
02 00	0		27 01	1		52 53	)		77		
03 52	(		28 06	6		53 53	)		78		
04 01	1		29 64	X		54 58	RTN		79		
05 03	3		30 34	RCL		55			80		
06 00	0		31 03	3		56			81		
07 03	3		32 53	)		57			82		
08 00	0		33 94	=		58			83		
09 93	+/-		34 33	STO		59			84		
10 64	X		35 05	5		60			85		
11 57	SUBR		36 34	RCL		61			86		
12 04	4		37 00	0		62			87		
13 00	0		38 41	R/S		63			88		
14 84	+		39 42	RST		64			89		
15 01	1		40 52	(		65			90		
16 01	1		41 92	.		66			91		
17 09	9		42 02	2		67			92		
18 07	7		43 05	5		68			93		
19 04	4		44 64	X		69			94		
20 09	9		45 52	(		70			95		
21 53	)		46 02	2		71			96		
22 94	=		47 64	X		72			97		
23 33	STO		48 34	RCL		73			98		
24 06	6		49 00	0		74			99		

NOTES	
Display Shows n	

© 1976 Texas Instruments Corporation

APPENDIX 3



# SR-56 Coding Form

TEXAS INSTRUMENTS  
INCORPORATED

TITLE Process 1 Temperature Profile PAGE 1 OF 1

PROGRAMMER A. H. Litka DATE 3-76

LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS
00	92	.	25	74	-
01	05	5	26	01	1
02	54	÷	27	03	3
03	05	5	28	92	.
04	05	5	29	07	7
05	06	6	30	64	X
06	05	5	31	52	(
07	64	X	32	34	RCL
08	52	(	33	00	0
09	34	RCL	34	74	-
10	03	3	35	06	6
11	64	X	36	00	0
12	02	2	37	53	)
13	64	X	38	53	)
14	52	(	39	74	-
15	92	.	40	03	3
16	06	6	41	64	X
17	06	6	42	52	(
18	64	X	43	34	RCL
19	34	RCL	44	00	0
20	01	1	45	74	-
21	74	-	46	34	RCL
22	03	3	47	02	2
23	04	4	48	53	)
24	00	0	49	74	-

LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS
50	34	RCL	75	47	X≥t	80	33	STO
51	08	8	76	08	8	81	00	0
52	53	)	77	05	5	82	22	GTO
53	84	+	78	34	RCL	83	00	0
54	34	RCL	79	07	7	84	00	0
55	04	4	80	33	STO	85	34	RCL
56	94	=	81	00	0	86	05	5
57	52	(	82	22	GTO	87	41	R/S
58	33	STO	83	00	0	88	42	RST
59	05	5	84	00	0	89		
60	84	+	85	34	RCL	90		
61	34	RCL	86	05	5	91		
62	04	4	87	41	R/S	92		
63	53	)	88	42	RST	93		
64	54	÷	89			94		
65	02	2	90			95		
66	94	=	91			96		
67	33	STO	92			97		
68	07	7	93			98		
69	74	-	94			99		
70	34	RCL	95					
71	00	0	96					
72	94	=	97					
73	28	1x1	98					
74	12	INV	99					

LOC CODE	KEY	COMMENTS
75	47	X≥t
76	08	8
77	05	5
78	34	RCL
79	07	7
80	33	STO
81	00	0
82	22	GTO
83	00	0
84	00	0
85	34	RCL
86	05	5
87	41	R/S
88	42	RST
89		
90		
91		
92		
93		
94		
95		
96		
97		
98		
99		

LOC CODE	KEY	COMMENTS
25	74	-
26	01	1
27	03	3
28	92	.
29	07	7
30	64	X
31	52	(
32	34	RCL
33	00	0
34	74	-
35	06	6
36	00	0
37	53	)
38	53	)
39	74	-
40	03	3
41	64	X
42	52	(
43	34	RCL
44	00	0
45	74	-
46	34	RCL
47	02	2
48	53	)
49	74	-

SR-56 PROCESS 1

MODEL DAY "A"

V = 350 Gal  
 V̇ = 350 Gal/Hr  
 ΔT = .5 Hr  
 Ġ = 1 Gal/Hr - Ft<sup>2</sup>  
 (UA)<sub>s</sub> = 3KJ/Hr-°C  
 T<sub>min</sub> = 80°C  
 T<sub>cut on aux</sub> = 88°C

Interval	N <sub>c</sub> =0		N <sub>c</sub> =6		N <sub>c</sub> =12		N <sub>c</sub> =20		N <sub>c</sub> =24		N <sub>c</sub> =26	
	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1
1	90	79.6	90	80.6	90	81.6	90	82.9	90	83.6	90	83.9
2	90	80.2	90	81.4	90	82.7	90	84.3	90	85.2	90	85.6
3	90	80.7	90	82.1	90	83.4	90	85.1	90	86.0	90	86.4
4	90	81.3	90	82.9	90	84.4	90	86.4	90	87.4	90	87.9
5	90	81.9	90	83.5	90	85.2	90	87.3	90	88.4	90	88.9
6	90	82.5	90	84.3	90	86.1	90	88.4	88.4	88.0	88.9	89.0
7	90	83.1	90	84.9	90	86.8	88.4	87.6	90	90.4	89.0	90
8	90	83.7	90	85.5	90	87.3	90	89.7	90.4	91.3	90	91.5
9	90	84.2	90	86.1	90	87.9	89.7	90	91.3	92.6	91.5	93.4
10	90	84.8	90	86.5	90	88.2	90	90.3	92.6	93.9	93.4	95.1
11	90	85.4	90	86.9	88.2	86.6	90.3	90.7	93.9	94.9	95.1	96.5
12	90	86.0	90	87.3	90	88.6	90.7	90.9	94.9	95.8	96.5	97.7
13	90	86.6	90	87.4	88.6	86.8	90.9	90.2	95.8	95.3	97.7	97.3
14	90	87.1	90	87.7	90	88.2	90.2	89.0	95.3	94.1	97.3	96.2
15	90	87.7	90	87.9	88.2	86.3	89.0	87.4	94.1	92.3	96.2	94.3
16	90	88.3	90	88.1	90	87.9	90	87.7	92.3	89.8	94.3	91.6
17	88.3		88.1		90		90		89.8		91.6	
Aux. (KJ)	5.33x10 <sup>5</sup>		4.2x10 <sup>5</sup>		3.19x10 <sup>5</sup>		1.74x10 <sup>5</sup>		1.12x10 <sup>5</sup>		9.12x10 <sup>4</sup>	
Start Up (KJ)	1.5x10 <sup>4</sup>		1.62x10 <sup>4</sup>		5.60x10 <sup>3</sup>		5.6x10 <sup>3</sup>		6.7x10 <sup>3</sup>		0	
ΣAux (KJ)	5.48x10 <sup>5</sup>		4.36x10 <sup>5</sup>		3.25x10 <sup>5</sup>		1.80x10 <sup>5</sup>		1.19x10 <sup>5</sup>		9.12x10 <sup>4</sup>	
Consumption (Gal)	10		8.0		5.9		3.3		2.2		1.7	
Savings (Gal)	0		2.0		4.1		6.7		7.8		8.3	
% Solar	0		20		41		67		78		83	



APPENDIX 4 -



# SR-56 Coding Form

TEXAS INSTRUMENTS  
CORPORATION

TITLE Process 2 Temperature Profile PAGE 1 OF 1  
 PROGRAMMER A. H. Litka DATE 3-76

LOC	KEY	COMMENTS
0	TGuess	
1	H	
2	Tamb	
3	Nc	
4	Ts,n	
5	Ts,n+1	
6	ΔTevap	
7	Used(TTank)	
8	QLoad	
9	Used(Tinlet)	

LOC	KEY	COMMENTS
TGuess = 85		
Ts,n = 90		
for First Entry		
1 → t		

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
00	34	RCL		25	06	6		50	52	(	
01	00	0		26	64	X		51	34	RCL	
02	74	-		27	34	RCL		52	00	0	
03	34	RCL		28	01	1		53	74	-	
04	06	6		29	74	-		54	34	RCL	
05	94	=		30	03	3		55	02	2	
06	33	STO		31	04	4		56	53	)	
07	09	9		32	00	0		57	74	-	
08	92	.		33	74	-		58	34	RCL	
09	05	5		34	01	1		59	08	8	
10	54	÷		35	03	3		60	53	)	
11	05	5		36	92	.		61	84	+	
12	05	5		37	07	7		62	34	RCL	
13	06	6		38	64	X		63	04	4	
14	05	5		39	52	(		64	94	=	Ts,n+1
15	64	X		40	34	RCL		65	52	(	
16	52	(		41	09	9		66	33	STO	
17	34	RCL		42	74	-		67	05	5	
18	03	3		43	06	6		68	84	+	
19	64	X		44	00	0		69	34	RCL	Ts,n+1
20	02	2		45	53	)		70	04	4	
21	64	X		46	53	)		71	53	)	
22	52	(		47	74	-		72	54	÷	
23	92	.		48	03	3		73	02	2	
24	06	6		49	64	X		74	94	=	TTank

SR-56 PROCESS 2

$\dot{V} = 350 \text{ Gal}$   
 $\dot{V} = 350 \text{ Gal/Hr}$   
 $\Delta T = .5 \text{ Hr}$   
 $\dot{G} = 1 \text{ Gal/Hr} - \text{Ft}^2$

$(UA)_s = 3 \text{ KJ/Hr-}^\circ\text{C}$

$T_{\text{min}} = 80^\circ\text{C}$   
 $T_{\text{cut on aux}} = 88^\circ\text{C}$

MODEL DAY "A"

Interval	Nc=0		Nc=6		Nc=12		Nc=16	
	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1	Ts,n	Ts,n+1
1	90	79.5	90	80.9	90	82.2	90	83.0
2	90	80.1	90	81.7	90	83.2	90	84.2
3	90	80.7	90	82.3	90	83.9	90	84.9
4	90	81.3	90	83.1	90	84.9	90	86.1
5	90	81.9	90	83.8	90	85.7	90	86.9
6	90	82.5	90	84.5	90	86.5	90	87.8
7	90	83.0	90	85.1	90	87.2	90	88.5
8	90	83.6	90	85.7	90	87.7	88.5	87.6
9	90	84.2	90	86.2	90	88.2	90	89.5
10	90	84.8	90	86.6	88.2	86.7	89.5	89.1
11	90	85.4	90	87.0	90	88.7	89.1	88.9
12	90	86.0	90	87.4	88.7	86.9	88.9	88.6
13	90	86.5	90	87.5	90	88.4	88.6	87.6
14	90	87.1	90	87.8	88.4	86.8	90	88.8
15	90	87.7	90	88.0	90	88.2	88.7	87.2
16	90	88.3	90	88.2	88.2	86.3	90	87.9
17	88.3		88.2		90		90	
Aux (KJ)	5.33 x 10 <sup>5</sup>		4.04 x 10 <sup>5</sup>		2.90 x 10 <sup>5</sup>		2.05 x 10 <sup>5</sup>	
Start UP (KJ)	1.5 x 10 <sup>3</sup>		1.6 x 10 <sup>3</sup>		5.5 x 10 <sup>3</sup>		5.5 x 10 <sup>3</sup>	
ΣAux (KJ)	5.48 x 10 <sup>5</sup>		4.20 x 10 <sup>5</sup>		2.96 x 10 <sup>5</sup>		2.10 x 10 <sup>5</sup>	
Consumption (Gal)	10		7.7		5.4		3.8	
Savings (Gal)	0		2.3		4.6		6.2	
% Solar	0		23		46		62	

EXTRA 100% RAG

APPENDIX 5



# SR-56 Coding Form

TEXAS INSTRUMENTS  
CORPORATION

TITLE Auxiliary Energy Summation

PAGE 1 OF 1

DATE 3-76

PROGRAMMER A. H. Litka

LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS	LOC CODE	KEY	COMMENTS
00	33	ST0	25			50			75					
01	01	1	26			51			76					
02	09	9	27			52			77					
03	00	0	28			53			78					
04	74	-	29			54			79					
05	34	RCL	30			55			80					
06	01	1	31			56			81					
07	94	=	32			57			82					
08	64	X	33			58			83					
09	01	1	34			59			84					
10	05	5	35			60			85					
11	92	.	36			61			86					
12	09	9	37			62			87					
13	64	X	38			63			88					
14	34	RCL	39			64			89					
15	02	2	40			65			90					
16	94	=	41			66			91					
17	35	SUM	42			67			92					
18	00	0	43			68			93					
19	41	R/S	44			69			94					
20	42	RST	45			70			95					
21			46			71			96					
22			47			72			97					
23			48			73			98					
24			49			74			99					

REGISTERS	
0	Σ Aux. (KJ)
1	Ts', n+1 (<88°C)
2	n (Gal)
3	
4	
5	
6	
7	
8	
9	

NOTES	
(Ts, n+1-1) = Ts', n+1	
Enter T's, n+1	
R/S	

## FOOTNOTES

<sup>1</sup>F. A. Henglein, Chemical Technology (Oxford: Pergamon Press, 1969), pp. 604-607.

<sup>2</sup>Earl V. Anderson, "Output of the 50 Top Chemicals Drops Sharply," Chemical and Engineering News (May 3, 1976):34-37.

<sup>3</sup>Robin Wood, "Solvent Recovery - Now Practical for the Smaller Firm?" Manufacturing Chemist and Aerosol News (January 1974):29-31.

<sup>4</sup>U. S. Environmental Protection Agency, Environmental Information Bulletin, No. 11226R, May 1975 (Washington, D. C.: Government Printing Office, 1975), pp. 1-3.

<sup>5</sup>"Cancer Link Shown for Trichlorethylene," Chemical and Engineering News 54 (April 5, 1976):4.

<sup>6</sup>"Aldan Rubber Pioneers Solvent Recovery System," Rubber World 170 (July, 1974):74-76.

<sup>7</sup>"Solvent Recovery System Proves a Speedy Payout," Rubber World 165 (February, 1972):44.

<sup>8</sup>Chamberlain Manufacturing Corporation, Chamberlain Solar Collector Panels (Illinois: Chamberlain Manufacturing Corporation, 1974), p. 5.

<sup>9</sup>J. Duffie and W. Beckman, Solar Energy Thermal Processes (New York: John Wiley & Sons, 1974) pp. 34-37.

<sup>10</sup>PPG Glass Division Technical Report, Baseline Solar Collector (Pittsburgh: PPG Technical Services, 1974), p. 9.

<sup>11</sup>F. Ayres, Mathematics of Finance, Schaum's Outline Series (New York: McGraw Hill Book Company, 1963), pp. 73-79.

<sup>12</sup>Eugene L. Grant and W. Grant Ireson, Principles of Engineering Economy (New York: The Ronald Press Company, 1970), pp. 109-129.

## BIBLIOGRAPHY

- "Aldan Rubber Pioneers Solvent Recovery System." Rubber World 170 (July, 1974):74-76.
- Anderson, Earl V. "Output of the 50 Top Chemicals Drops Sharply." Chemical and Engineering News (May 3, 1976):34-37.
- Ayres, F. Mathematics of Finance. Shaum's Outline Series. New York: McGraw-Hill Book Company, 1963.
- "Cancer Link Shown for Trichlorethylene." Chemical and Engineering News 54 (April 5, 1976):4.
- Chamberlain Manufacturing Corporation. Chamberlain Solar Collector Panels. Illinois: Chamberlain Manufacturing Corporation, 1974.
- Duffie, J. and Beckman, W. Solar Energy Thermal Processes. New York: John Wiley & Sons, 1974.
- Grant, Eugene and Ireson, W. Grant. Principles of Engineering Economy. New York: The Ronald Press Company, 1970.
- Henglein, F. A. Chemical Technology. Oxford: Pergamon Press, 1969.
- PPG Glass Division Technical Report. Baseline Solar Collector. Pittsburgh: PPG Technical Services, 1974.
- "Solvent Recovery System Proves a Speedy Payout." Rubber World 165 (February, 1972):44.
- U. S. Environmental Protection Agency. Environmental Information Bulletin, No. 11226R, May, 1975. Washington, D. C.: Government Printing Office, 1975.
- Wood, Robin. "Solvent Recovery - Now Practical for the Smaller Firm?" Manufacturing Chemist and Aerosol News, (January, 1974):29-31.