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THE FEASIBILITY OF APPLYING SOLAR INDUSTRIAL PROCESS HEAT TO PAPER MACHINE DRYER SECTIONS

by
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The Bachelor of Science Degree

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REPORT TITLE: Application of Solar Heat To Paper Dryer Sections

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ABSTRACT:

Fossil fuel deficiencies and escalating costs are presented. The application of solar industrial process heat (SIPH) to the paper industry is examined with focus on cylinder dryer sections located at the dry end of a paper machine in a non-integrated mill. Drying theory, as it relates to SIPH, is discussed in detail. Very high steam temperatures are deemed unnecessary for good dryer efficiency. Factors favoring application are lisited, as are those U.S. installations similar to the type investigated. A fabric drying facility, using SIPH, is described with respect to the paper drying process. Inserted steam system configurations including instrumentation and process control features are described. The use of the SERI on-line Models Library, its components and applications are given. An experiment using a parabolic through prototype collector was performed and limited data made available. Results showed that the collector extraction efficiency was poor (8.5% at average peak noon), so calculation methods for thermal losses explained. A life-cycle economic analysis is performed with the conclusion drawn that SIPH in this form is not economically feasible, and its other positive aspects do not outweigh its high initial capital cost. The likelihood of using SIPH in other forms for other paper industry divisions, including bleaching, is examined.

Submitted by; Curtis J. Rollo

date submitted: 12-13-82

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Introduction

Based on what has been published recently, it appears that energy, or the lack of it, is still going to be a concern for a long time to come. In industry, especially, where a large portion of the total is consumed (37% of nation's gross energy demand[1]), it will become increasingly important to reduce energy consumption and thus cut costs in order to retain profit margins and in general run more efficiently. The paper industry is no exception. Energy demands and forecasts to the year 2000 are not promising for those industries which refuse to become innovative in using new and alternative fuel sources to reduce fossil fuel comsumption. Several organizations have compiled projections bases on their respective assumptions. Those researched include[2]:

Atomic Energy Commission	1974
Department of Commerce	1977
Council On Enviromental Quality	1974
Energy Research & Development Agency	1977
Federal Energy Administration	1976
Federal Power Commission	1975
Ford Foundation	1977
Hudson & Jorgensen	1976
Lawrence Livermore Laboratory	1976
Petroleum Industry Research Foundation	1977
Shell Oil Company	1976

Each projection specifically stated or noted that energy demands and costs, regardless of nuclear power (assumed to account for anywhere from 3% to 70% of the total), will continue to escalate. Projected increases range from 2 to 10 percent per year for oil, and though the price of coal is considered relatively stable, it too will increase according to predictions made.

The idea behind this thesis was not to prove that solar energy in the form of industrial process heat is, nor will be, the solution to tomorrow's industrial energy problems. An attempt was made to show that for a given paper mill, in a relatively cold climate, solar industrial process heat can be applied resulting in a net energy savings which is cost effective over the life cycle of the collector system. I am further limiting my application to the non-integrated mill situations since an excess of low grade heat might be available from the pulping process. A complete investigation of SIPH use in integrated mills is conducted nontheless.

Drying Theory

A steam condenses on a clean surface, a film of condensate forms, heat is transferred first from the steam to the condensate film, then through the film to the metal. If the steam is superheated its temperature will drop before it condenses, but condensation will occur at the same temperature as though it had been saturated at the same pressure. Researchers have established that with about 180°F superheat the rate of heat transfer to a given area is only about 3% more that for saturated steam at the same pressure.[3]

Typically, conventional main steam supply conditions are 140 psig @ 460°F. It has been shown, for example, that if this supply is throttled down to 15 psig with 180°F of superheat as mentioned there would not be a significant difference in drying conditions as opposed to a 15 psig saturated steam supply at 250°F.[4]

"In hot surface drying of paper, then, temperatures easily attainable with steam at reasonable pressures give the best results.[5]" As for the question of solar capability, the design to be presented has been applied successfully in a textile cylinder drying facility in Fairfax, Alabama. Steam generated there is comparable to that required by paper machine cylinder "can" dryer sections (figure 1).[6]

It is recognized that of the 30 million BTUs it takes to manufacture a ton of paper, about 40% is required in drying and finishing.[7] In focusing my attention on this major energy consumer in the paper industry it seems more likely that energy savings and thus financial benefits could be the final result.

General Factors:

Many types of SIPH (Industrial Process Heat) systems have been successfully applied in the U.S., but each type has its own set of operating conditions and design considerations. Many variables contribute to the practicality of a solar IPH system. Each of the factors listed are, to varying degrees, satisfied by the paper drying process within the paper industry.

Background: Solar IPH

Factors favoring the application of solar IPH systems:[8]

Enviromental Factors:

* High insolation levels-either total or direct, depending on the solar technology proposed.
* High ambient temperatures-to reduce thermal losses and to allow water to be used as heat transfer fluid.
* A pollution free microclimate-so as not to dirty or corrode collector surfaces.
* A pollution free macroclimate or area with strict air pollution regulations-where no additional air pollution emissions are allowed, and where such controls are a restraint on levels of production.

Process Factors:

* Lower temperature processes-so that the least expensive

type of collector, operating at high efficiency, can be employed.

* Continuous operation (24h/day, 7 days/week) where exact temperature control is not critical.

* Liquid heating applications as opposed to air.

* Easy retrofit of the solar system-so as to minimize costs.

* Inefficient present fuel usage, not easily rectified-so that energy delivered from the solar system replaces more than the equivalent BTU content of fossil fuel.

Economic Factors:

* High and rapidly escalating fuel costs.

* Uncertainties regarding fuel supplies.

* Industry has, or has access to, sufficient capital to finance investments in a solar energy system.

* Industry applies long payback periods or will accept low rates of return on energy investments.

* High federal, state, or local tax incentives for solar investments.

* Industrial operation is energy intensive, and energy costs represent a large fraction of value added.

* Cheap land or a strong roof is available close to the delivery point of the required energy.

* Low labor cost area-since solar installations are labor intensive.

* New plant-allowing a solar system to be incorporated from the beginning with savings on the conventional heating system.

Company Factors:

* The industrial plant wants to install a solar system and has an ethusiastic work force from top management down.

* The plant possesses a skilled maintenance and engineering work force-so as to run and maintain the solar system at maximum efficiency.

* Progressive management-which gives some recognition to the noneconomic and social values of solar energy, such as public relations, security of long term supply, and reduced air pollution, leading perhaps to less stringent

payback criteria for investments in solar systems.

- On a daily basis, loads that are constant or peak during daylight hours are preferred.
- Loads that run seven days per week will minimize or eliminate storage requirements.

The collector is the heart of any active solar energy system. It is vital to choose a collector that matches the process temperature requirement and maximizes energy delivered per dollar invested. Many collector types are available, but the types that have thus far been employed in the industrial process heat field are:[9]

1. Flat plate collectors - These are the most common type for applications below 70°C (160°F). This represents both liquid and air collectors.

2. Evacuated tobes - These have been used for applications below 175°C (350°F).

3. Linear concentrators - Parabolic trough collectors have been used extensively in industry for applications as high as 315°C (600°F).

Those applications in operation today which most closely approximate the needs of a paper drying section are listed (Table 1)[10]. From this table it can be seen that a parabolic trough collector has proven to be the most popular, if nothing else. There is however, computer software available which was used by Johnson & Johnson's pharmaceutical plant in Sherman, Texas to evaluate each possible configuration on the basis of life cycle costs per thermal BTU supplied. This set of programs will be discussed in detail later in this section. The successful application of such a system by Honeywell, Inc. to the process of cloth fabric drying in Fairfax, Alabama for the West Point Pepperell Company will be emphasized.

System Description

The Honeywell system is a retrofit, meaning it was built in addition to an existing system. This system design, to provide process heat for textile drying, consists of five major subsystems:[11]

1. the collector field
2. the high temperature water (HTW) pipe loop
3. the steam generator
4. the steam pipe loop
5. the process

Figure 2 is a simplified system schematic showing these five major subsystems.[12] The collector field contains concentrating collectors which utilize parabolic trough shaped mirrors and tubular receivers, and follow the sun by means of single axis tracking.

HTW Loop:

The HTW loop transports the collected energy to the steam generator in the form of 380°F (195°C) water. It is a closed loop system pressurized to 230 psig. Figure 2 also illustrates how the HTW loop connects the collectors, transports the high temperature water to the steam generator, and returns the cooled water back to the collector field. The HTW loop includes the expansion tank, air separator, and field flow pump.

Steam Generator:

The steam generator is an unfired package boiler that generates 76 psig process steam , fueled by the hot water from the HTW loop. Feedwater for the steam generation is taken from a steam condensate collection tank.

Steam Pipe Loop:

The steam pipe loop transports the solar generated steam to the process. Steam flow is controlled by a check valve that allows the solar system to displace fossil fuel generated steam when solar generated steam is available. Conversely, when solar steam is not generated, the existing steam system supplies the process steam.

Figure 3 shows the general routing of the steam lines in the steam loop.[13] Completing the steam loop is the feedwater line from existing condensate receiver. Figure 3 also shows the solar steam/conventional steam interface. The "T" which connects the solar steam line to the existing steam system is located on the 70 psi main manifold line. A flow meter in the solar line monitors the contribution from the solar system. The check valve is automatic in its acceptance of solar steam when available and use of conventional steam when necessary. Solar steam condensate is combined with the conventional steam condensate and carried to the condensate reciever. Solar boiler feedwater is then taken as needed.

The type of can dryer depicted is shown in Figure 1. This should look familiar to those in the papermaking business since it uses the same type of rotary joint plus syphon for condensate removal on paper machines. The steam inlet hose is attached in a similar fashion as well.

Certainly, one constraint which must be dealt with concerns installation of the solar system and its interface so that operation of the dryer section is not affected. The system described above is completely responsive to the requirement for integration with the drying operation without disturbing the plant's normal operation. The "T" shown in Figure 3 can easily be installed in 24 hours or when the facility is not in operation. Condensate line connections can be made at the same time. The feedwater system operates automatically by switching on a pump when the solar boiler needs water. Therefore, the complete solar system can be installed, tested, and hooked up to existing steam line with no effect on normal operations. Once operational a manual steam valve can be opened and the dryers will automatically use solar steam when it is available. It should be noted that the solar system can be completely isolated manually at any time using the manual valves. Other solar equipment integrated into this facility (ie. instrumentation, flow meters, chart recorders, pyroheliometer-for sun's energy data), will not disturb normal plant operation since most of it would be located on the roof. A collector support structure is necessary for this system since it is situated on the roof directly above the operation. Roof mounting can offer advantages of shorter pipe runs and a savings in land costs. In the paper making operation there is an large roof area existing overhead already, which might also be used to accomodate such collectors in a manner not unlike that used for textiles.

System Design

A well designed system is of prime importance. The major considerations are safety oriented and I will not go into great detail individually. Instead, a list of important elements and their respective function is given.[14]

a) Physical arrangement on roof should:
   * be parallel to roof beam structure

- optimize sun's energy collection with minimal modification to the existing structure.
- minimize shadow effect

b) Support structure

c) High temperature water loop design:

1. Piping
    - air trap & air eliminator used as purging devices
    - thermal expansion accounted for
2. Insulation
    - to control heat loss in the HTW loop
3. Interfaces
    - flexible hose should allow for thermal expansion and contraction of headers
4. Circulation pump
5. Expansion tank
    - accomodates for thermal expansion of water in the HTW loop
    - prevents boiling in the HTW loop under all normal operating conditions
6. Valves
7. Freeze protection
    - freeze protection may be accomplished by the addition of immersible heaters. As the fluid temperature drops below the set point temperature (35°F for H_2O), the electric heaters are activated. If severe freezing conditions are encountered, and the fluid temperature continues to drop, an alarm is triggered and the HTW fluid is drained. To lower this set point temperature (in colder climates) a heat transfer oil has been used. The use of these oils, though, places more stringent requirements in the selection of valves, pumps, and seals due to increased fluid viscosity.

d) System controller

- safe operation and (collector) field protection
- manual intervention capability

e) Unit controller functions

- acquire - act of finding sun's image and focusing it on the absorber tube
- track - to maintain focused image
- stow - "off duty" positioning
- self protect - ensures orientation limits have not been not been exceeded

f) Collector

- wind conditions
- collector pivot location
- collector stow position
- collector loads at support/roof interface
- absorber tubing
- motor/gear drive selection (for tracking mechanism)

System Operation

An operational sequence, which applies to most tracking parabolic solar systems is summarized in the following order of operation

A. Nighttime Status

1. Control in automatic
2. Collectors stowed
3. Pumps off
4. 110v supply on
5. 28v control supply on
6. Sensors active for control and data collection

B. Sun-up

1. When illumination is above preset level, and wind is below preset level, and system pressure is within limit; turn on field pump.
2. When field flow is verified; turn on collector field.

C. Unstow (Acquire)

1. Collector control transferred to unit controller
2. Collectors rotate to unstow
3. Tracking sensor monitors sun position
4. Unstow ceases when tracking sensor nulls.

D. Tracking

1. Collector tracks forward and/or reverse with control from tracker
2. Fluid in HTW loop is heated in receiver tube
3. Field flow pump transfers water around collector loop and to steam generator
4. Heat is transferred to water in steam generator
5. Steam is generated at process conditions and piped to manifold
6. Feedwater pump maintains liquid level with feedwater
7. Operation continues throughout the day with HTW loop collecting solar energy and transporting it to steam generator for production of process steam.

E. Stow (Sun-down)

1. Illumination drops below present level
2. Stow command sent from system controller
3. Collectors stow
4. Field flow pump turns off
5. System in nighttime status (A).

SERI On-Line Models Library:

On-line access to analytical models and related calculation tools for use by the nation's solar energy community is being provided through the scientific computational facility at the solar energy research institute at 1617 Cole Boulevard, Golden, Colorado, 80401. The user community includes several solar energy and energy research centers, laboratories, and contractors as well as universities and colleges engaged in related energy research. Many models are included in the on-line collection but those programs which are considered useful are listed:[15]

1. F-chart - Solar heating systems design
2. SOLCOST - Residential and commercial solar costing and design
3. EASE-2 - Economic analysis of solar energy
4. PROSYS - Process heat system performance model
5. ECONMAT - Solar system costing model

Utility programs for data conversion, insolation and angle calculations, return on investment computations, and financial charting are also available.

Access to the on-line models library is being provided through the SERI computer system. The system is accessible nationwide through the data communications value-added network Tymnet. Through the use of Tymnet (via Jordan College in Cedar Springs, MI), the user need only make a local call to access the SERI computer system.

After a user's request for access to the models library has been approved by SERI, the user is assigned a unique identification number. Once the desired model is selected, following log-on procedures, and run to the user's satisfaction, charges are tallied and printed.

Of course, resource ceilings are maintained for each user I.D. number to prevent unauthorized or unlimited usage. Costing policies are readily available.

A description of what seems to be the two most relevant and practical models available in the "library" is presented.

The PROSYS Computer Program:

This program is a tool which evaluates the abilities of various collector and system types to meet IPH demands at selected sites. PROSYS uses information from meteorological, industrial and collector data bases in its calculations of annual deliverable energy. The results are subsequently used in the economic analysis program ECONMAT. PROSYS is written in FORTRAN.

Program Logic:

The PROSYS program is designed to work with one "site" per computer run.[16] For each run the identifying site number and information for the typical industrial process, or specific plant, are input. The paper drying process can use a wide range of steam temperatures and pressures. The results of each collectors annual energy output in BTU/ft^2 are printed and recorded for each parameter input. Output also includes tilt and thermal effciency for use in the ECONMAT program.

The ECONMAT Computer Program:

Local fuel costs and labor rates are obtained from the data base called ECONMAT and collector costs are obtained from the data base COLDAT.[17] Performance results from the PROSYS execution are communicated to ECONMAT. The collector areas required to meet varying energy output levels are then calculated. In addition, costs are broken down to include the resultant collector cost, system cost, total cost, net present value, and cost per unit of heat energy are calculated for each combination and energy level. Ultimately ECONMAT will be a valuable tool for generating data and detailed information regarding fuel costs, system lifetime, tax rate, etc., yielding an accurate economic picture. To predict the performance of a solar IPH system the following information is necessary:[18]

- Solar insolation at the specific geographic location.
- Direct component of insolation (as opposed to the total, amount integrated over the spectrum of wavelengths).
- Solar collector performance.
- Thermal losses for respective systems.

Time does not allow the use of these computer programs for this project. The strategy behind them does not directly apply since the collector type to be evaluated is known, as are most of the other parameters. Even if the decision is made to install a SIPH system, complete backup with conventional fuel systems is mandatory in case any malfunctions, weather deficiencies, etc., are encountered. Solar systems lend themselves to retrofitting quite easily, and since existing mills have conventional drying systems already, backup is not a problem. New mills could incorporate SIPH also, reducing costs from the start.

Experimantal Procedure

Background

A small linear concentrating solar collector was constructed in hopes of producing high temperatures in the heat transfer fluid used, namely water. From the data accumulated several important aspects of collection were determined:

1) Collector performance; efficiency.
2) Combined radiation, convection and conduction losses for the linear absorber type employed.
3) Possible colllection based on improvements in reflector surface precision and elimination of losses using current technology available.

After determining the amount of solar radiation which may be extracted, a cost evaluation of the collector system studied is performed based on typical steam requirements in the dryer section of a paper machine.

Materials & Equipment

The collector built was intended to simulate engineering prototypes which have been industrially applied. Most installations of this type in the United States are so new that actual extensive data to determine performance is not available simply because it does not exist.

The parabolic trough collector surface was made by first constructing a supporting skeleton made from ¼ in. plywood. The parabolic curve was traced from a template drawn and cut out of cardboard. Next a flexible paperboard sample was adhered to the parabolic skeleton structure with a common wood glue. Aluminum foil was carefully placed on the parabolic trough surface so as to act as the reflector surface (higher reflectance side up).

A problem encountered at this stage was that the collector structure, as a whole, was too unstable when tipped on angle since only three support ribs were inserted along the five foot length of the collector. This rigidity is important since the collector operates as a tracking system and must be angled in accordance with the sun's position. To remedy, two additional structural ribs were inserted. A support system for the absorber was then designed and implemented (see Figure 4). The absorber type used was a "spiraled-concentric" cylinder concept not normally employed at all commercially. This spiral effect added some heat transfer fluid retention time inside a shorter length, larger diameter copper pipe in order that larger more accurately measured flow rates could be used to determine input and output temperatures and collector performance. The outer pipe was spray painted with a flat black acrylic paint to increase the absorbtance of the copper and to reduce the reflectance of the surface exposed to the sun's rays. Further knowledge of the absorber used will be gained in the following data discussion.

Results

Of the data collected, approximate peak noon* insolation values obtained will be used in the following calculations for determining the amount of heat extracted. Those measurements taken for each trial during collector operation and their respective average values at approximate peak noon are as follows:

T_a= Ambient surrounding temperature

T_o= Heat transfer fluid output temperature

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*"peak noon" infers maximum insolation available to collector on that particular day (see Data Table-Appendix).

T_i= Heat transfer fluid input temperature

Flow rate= total milliliters collected/total trial time (min)

The average data for two trials run consecutively at identical flow rates is given:

T_a= 55°F= 286°K

T_i= 56°F= 286.5°K

$\bar{T}_o$= 72.5°F= 296°K

Flow rate= 36 ml/min

The following calculations determine the amount of heat extracted by the heat transfer fluid. The basis for all calculations will be total BTU for entire absorber surface per hour.

$(\dot{m})(c_p)(T_o - T_i)\ (k)$= BTU/hr collected

Substituting measured values:

$$36\text{ grams } H_2O/\text{min})(1\text{lb}/453.6\text{ grams})(60\text{min}/1\text{hr})(1\text{BTU}/\text{lb}\cdot{}^{\circ}\text{F})(72.5-56^{\circ}\text{F})=78.6\ \frac{\text{BTU}}{\text{hr}}$$

extracted by heat transfer fluid. Note that retention time does not enter into calculation directly.

Radiation, convection and conduction loss calculations become complicated and vary with absorber geometry. The basic equation for heat balance is:[19]

$$\alpha_o X t I = \epsilon_o \sigma T^4 - \epsilon_1 \sigma T^4 + (Nu + 1)(k/s)(T_o - T_1) + Q$$

where,

α_o = absorbtance of the pipe surface over the spectral passband of the energy input flux

X = surface optical flux concentration of flux (tI=flux intensity) reaching the absorber pipe

ϵ_o = thermal infrared emittance of the pipe surface 0 (outer surface of inner tube wall)

ϵ_1 = emittance of pipe surface 1 (inner surface of outer pipe wall)

σ = 5.72×10^{-8} J/m$^2\cdot$deg$^4\cdot$ sec (Stefan-Boltzman constant)

T_0 = absolute temperature surface 0 ($^\circ$K)

T_1 = absolute temperature surface 1 ($^\circ$K)

Nu = Nusselt number

k = Thermal conductivety of the medium

s = shape factor

Radiation loss

An assumption was made that no radiation is lost from surface 0 to surface 1 since the outer pipe temperature was greater than or equal to the output heat transfer fluid temperature at these relatively low temperature operating conditions. So, radiation is considered to be that of a single free horizontal pipe and $\epsilon_1 = \epsilon_0 \doteq 0.94$.[20]

$$Q/A = \epsilon\sigma(T_1^4 - T_a^4)$$

$$= .94\ (5.72 \times 10^{-8})(296\ ^\circ K^4 - 286\ ^\circ K^4)$$

$$= 53\ J/m^2\cdot sec$$

Absorber pipe area = 1.473 ft^2

53 J/m$^2\cdot$sec (1m^2/10.7639 ft^2)(3600sec/hr)(1BTU/1054.8J) x (1.473 ft^2)= 24 BTU/hr radiated from absorbed surface.

Convection loss

convection + conduction losses = $(Nu + 1)(k/s)(T_0 - T_1)$

To calculate the convective loss term, the value of the Nusselt number (Nu) for the geometry and physical conditions that apply to this design must be determined. Experimental data shows the variation of Nu with Raleigh number (Ra) for flat plates and for a horizontal cylinder (Figure 5).[21] The curve for the horizontal cylinder lies above the curve for the parallel plates. Some of the literature does not believe that this difference is real since the difference is approximately equal to π. If the diameter was used in the reduction of experimental data, rather than πD, the difference would largely disappear. The literature search leaves this question unanswered, but it is recommended that the student use the curve as indicated for calculations involving cylinders. This value incorporates the entire radiating surface of the cylinder.

The procedure then, to calculate the combined convection and conduction loss for linear absorbers and for concentric cylinders is to calculate the Rayleigh number, enter the graph for Nu versus Ra (figure 5) and add the conduction term.

Ra= Gr.Pr

Gr= Grasshof number = $gy\Delta TL^3\rho^2/\mu^2$

Pr= Prandtl number = $\mu c_p/k$

Ra= $(\rho^2 gy\Delta TL^3/\mu k)\ c_p$

= $a\Delta TL^3$, where a is the combination of the physical parameters of the medium involved in the convection phenomenon. In this case it is the modulus for air.[22]

g = gravitational accelleration

y = coefficient of thermal volume expansion of the gas

ρ = density of the gas

μ = dynamic viscosity of the gas

k = thermal conductivity of the gas

c_p= specific heat of the gas at constant presure

Substituting actual experimental values:

a_{air} at $100^{\circ}C = 130/cm^3 \cdot {}^{\circ}C$

L = distance of plate separation, in this case L = pipe diameter (cm)

$\Delta T = 72.5^{\circ}F - 55^{\circ}F = 17.5\ F^{\circ}$

An assumption made here is that the fluid actually flows through the large pipe at the measured flow rate. Thus convection loss occurs only from the outer surface of the large diameter pipe and no loss between coiled tubing and copper pipe occurs. This as mentioned is due to the fact that the coiled tubing and pipe are in contact. In other words, temperature of the pipe is the same as the tubing temperature.

$Ra = 130(10)(1.125in \times 2.54cm/in)^3 = 30{,}300$

This corresponds to a Nu = 7.0 as taken from relationship between Ra and Nu in the appendix.

23 $k_{air@20^{\circ}C} = .13\ BTU \cdot in/hr \cdot F^{\circ} \cdot ft^2$

24 s = shape factor = 2(Diameter of pipe) = 2(1.125in)/(12in/ft) = 0.1875

$$\text{convection plus conduction} = (7.0 + 1)(.13/.190)(72.5^{\circ}F - 55^{\circ}F) = 97\ BTU/hr \cdot ft^2$$

$$= (97\ BTU/hr \cdot ft^2)(1.473 ft^2/\text{absorber total area})$$

$$= 143\ BTU/hr.$$

The sum of the useful energy extracted by the heat transfer fluid itself and the radiation and convection & conduction losses is that total energy available to the absorber reflected from the collector surface.

78.6 BTU/hr	+ 24 BTU/hr	+ 143 BTU/hr	= 246 BTU/hr
useful energy	radiation loss	convection+ conduction loss	

Though 246 BTU/hr was available to the absorber surface, this represents approximately 33% of the insolation reflected from the collector surface itself since in the course of testing performance it appeared that the percent focus of the parabolic surface onto the absorber surface was about 33%. Therefore, the best estimate of the total amount of insolation reflected by the collector surface is 3(246 BTU/hr) $\doteq$ 738 BTU/hr. The reflectance of aluminum is equal to .80 or 80% reflectance. So, 738/.80 = 922 BTU incident on collector area (10ft^2), or 92 BTU/hr·ft^2 insolation. This corresponds to a value for mean daily solar radiation of approximately 550 BTU/ft^2·day.[25] Data available gives similar values for representative cities in the U.S. which are located along nearly the same °North latitude as Kalamazoo, MI where testing took place.[26]

Location	°North latitude	November MDSR(BTU/ft^2· day)
New York, N.Y.	42	546
Blue Hill, Mass.	42.5	601
St.Cloud, Minn.	46	646
Glasgow, Mont.	48	642
Spokane, Wash.	48	491

Discussion of Results

Based on the experimentation and problems encountered during construction one can begin to realize that equipment required in the manufacture of such a system commercially is unique to the solar industry. With current technology mirrored sagged glass can be formed in a parabolic mold to give focusing performances of 90 to 95 percent. Thermal sagging of glass is done by heating the glass to its melting point and allowing it to conform to the shape of the parabolic mold. The molded surface is perfected through the use of the latest laser technology. A laser beam tracer can detect errors in the surface of the mold so that they can be polished over in order that the best possible focus clarity is obtained (figure 6).[27] Costs for this type of mirrored parabolic reflector surface are relatively high at the present time and though engineering prototypes have already been built many industrial manufacturers of parabolic troughs are still working on their own designs to meet demonstrated performances and to enhance prospects for manufacturing troughs at reduced prices. This has not been accomplished as yet on a mass production scale. Furthermore, in order to eliminate high convective losses during winter months an evacuated glass tube envelope assembly has been designed and implemented widely (figure 7).[28] Examples of such an evacuated tube are shown in the photographs of commercial systems (figure 8).[29] In this way the absorber surface is not exposed to wind and cold surrounding air and convective loss is eliminated. The major technical problem with the evacuated absorber assemblies is in maintaining vacuum integrity under operating conditions over a lifetime of ten to twenty years. Once again, the major economic problem is in reducing the cost of these assemblies, most likely through automated fabrication techniques used for other products in the glass industry.

Radiation losses become increasingly significant as temperature differences between surroundings and absorber surface increase. Little can be done to eliminate radiation losses especially at elevated temperatures. Selective absorber surface coatings available prevent thermal infrared radiation via their inherent physical and thermal properties. However the problem exists as they can fail by overheating, e.g. black nickel at temperatures greater than 300°C.[30] Black chromium is in this same category. Cost of electroplating absorber surfaces range from three to five dollars per square meter.

It is believed that the collector tested could compare to those commercially manufactured only if its components were of similar quality. A precision system then is capable of generating steam under normal operating efficiencies of 40 to 60 percent, at 200 to 300°C with sufficient solar insolation provided. Geographical area is a factor which cannot be ignored and enters into collector efficiency calcuation indirectly. With relatively cold ambient temperatures prevailing during experimentation, collector efficiency was poor, 8.5% at average peak noon. The aim of this thesis was to apply solar industrial process heat in the form of steam to paper machine dryer sections with thoughts kept in mind concerning applications to other paper industry divisions.

Steam supply systems

Before the results of this experiment can be physically applied to paper machine dryer sections, a thorough knowledge of typical steam supply systems is essential. Two basic approaches to dryer steam and condensate system design are in general use. One recirculates most of the blow - through (the recirculation system), and the other uses blow-through steam from the higher pressure dryer sections as supply steam for lower-pressure sections (the cascade system). Since the recirculation system is more flexible, and is considered mandatory for modern machines producing certain grades of paper it will be considered a more likely candidate for supplemental SIPH because, in general, moisture content should be controlled at each of the following points on a paper machine:

breaker stacks, size presses and on machine coats as well as at the reel. This is most easily accomplished through the use of independent dryer groups as is the case with the recirculation system (refer to figure 9).[31]

The question arises as to where exactly the SIPH system can be inserted breaking the typical recirculating dryer system without disrupting its normal operation. The insertion could be made directly into the 200 psig mill steam supply, with reference to the figure above. Accurate valve positioners and instrumentation of the highest degree would be needed if, for example, the solar supplied steam is to be acknowledged by the pressure controllers, pressure transmitters and valve positioners. Expectation of controller reactions to variations in supply by amounts less than two percent might seem unfounded. But sensitive pressure control of this magnitude is readily available, and it is the author's belief that the use of solar process heat at the dryer section is technically feasible. This however is not to say that it is economically feasible and cost effective. It should be noted that since SIPH is unreliable, and when solar output diminishes the fluctuation in conventionally produced steam demand is such that the boiler efficiency remains unaffected.

Economic analysis

Main mill supply steam may contain as much as 150^{o}F of superheat to the dryer section. Remembering drying theory, the conditions desired are those for saturated steam at 200 psig (390^{o}F) and not 490^{o}F. In order to produce SIPH in the form of saturated steam at 200^{o}C (390^{o}F), a parabolic trough linear concentrating collector of the kind studied would be employed. An economic evaluation previously mentioned follows to determine cost effectiveness of a hypothetical SIPH system.

Some basic assumptions for the proposed installation are as follows:

1. Average collector efficiency = 50% (actual value probably lower in the high parasitic heating requirement zone in the midwest)
2. MDSR = 850 BTU/ft^2 (actual value probably lower based on published values for similar latitudes)
3. Collector area = 10,000 ft^2

These assumptions (1 & 2) provide for a 10-20% cushion for collector performance. In other words, actual average collector efficiency is probably ten percent less, as is MDSR, resulting in a net 20% overestimate for extracted heat as useful energy.

Proceeding:

$$\begin{aligned}\text{solar system output} &= (\text{eff.})(\text{MDSR})(\text{Area})\\ &= (.50)(850\ \text{BTU/ft}^2\cdot\text{day})(10{,}000\,\text{ft}^2)\\ &= 4.25\ \text{million BTU/day}\end{aligned}$$

This corresponds to approximately 1.53 billion BTU/yr, a savings of $5600 /yr at $4.00/MM BTU in fuel cost.

On the basis of 100 TPD paper production using the recirculation system described, with average steam to dryer conditions of 35 psig (280°F), the solar fraction of the total required is calcuated. Latent heat of this steam = 924 BTU/lb steam. Average steam suppied to each of the 61 dryers = 525 lbs/dryer · hr.[31]

$$\begin{aligned}Q &= (924\ \text{BTU/lb})(525\ \text{lb/dryer}\cdot\text{hr})(61\ \text{dryers})\\ &= 29.59\times10^{6}\ \text{BTU/hr required}\end{aligned}$$

Average solar fraction supplied:

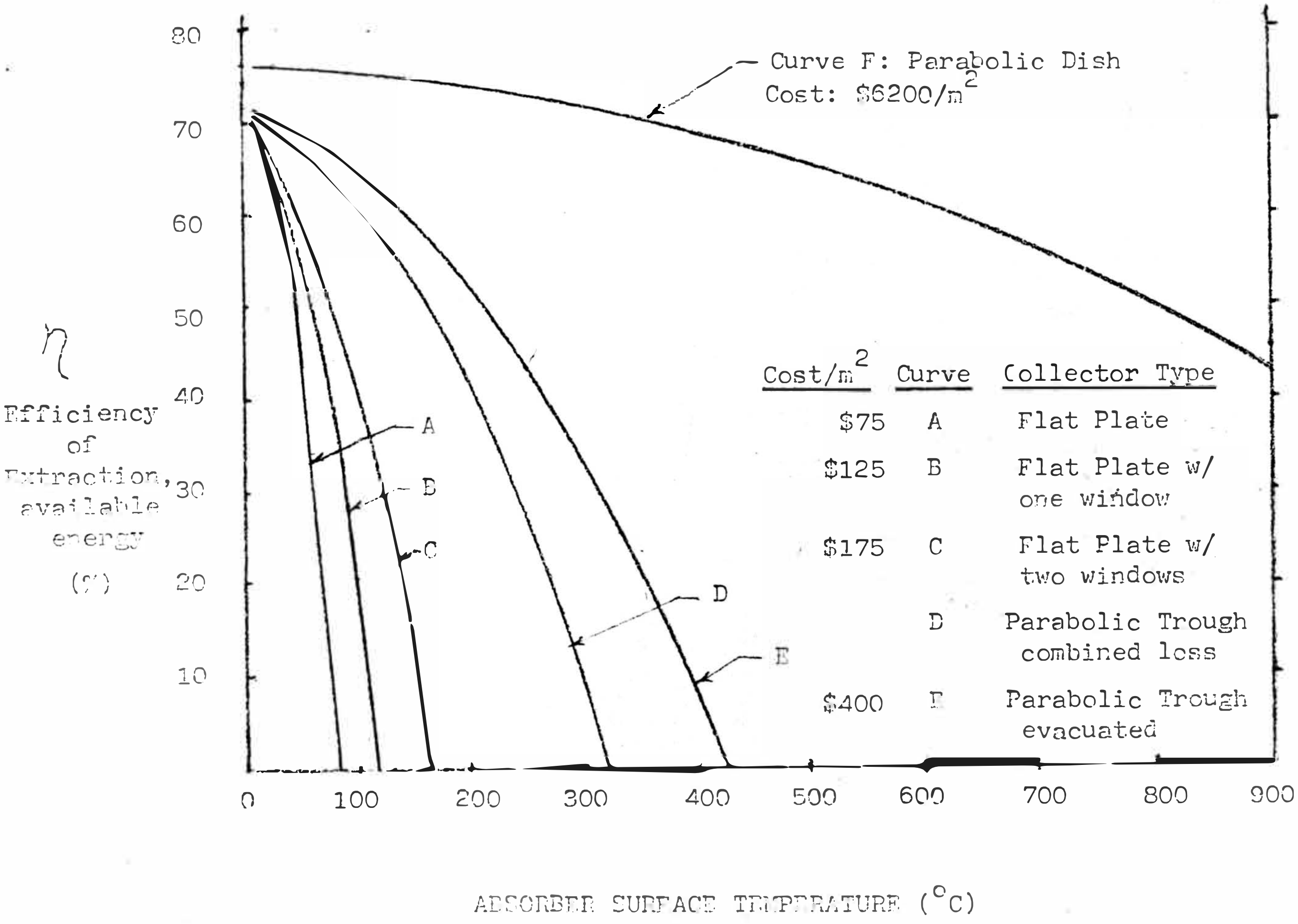
$$4.25\times10^{6}\ \text{BTU/day} = 1.771\times10^{5}\ \text{BTU/hr (solar)}$$

$$\frac{1.771\times10^{5}\ \text{BTU/hr (solar)}}{29.59\times10^{6}\ \text{BTU/hr (total required)}}\times100\% = 0.599\%$$

$$= 0.60\%\ \text{of total}$$

Initial and Operating Costs	$\$/ft^2$
Site (roof) preparation	1.69
Collectors and Absorbers	20.76
Mechanical equipment (fans, pumps, etc.)	7.59
Structural Cost (pylons)	.99
Electrical and Controls	7.79
Total	38.83 ($418/m^2$)
Operating, Maintenance Replacement, and Insurance	.50

This example confirms general cost estimates for such an installed collector system.[33] Normal operating efficiency of 50% corresponds to an output temperature of 200-250°C on the figure below.



Graph of the relationship between the efficiency of heat extraction of the available sunlight arriving at the collector for variations of flat plate and Parabolic trough types.

With a 20 percent investment tax credit, using straight line depreciation, the payback period approaches 30 years. However, if fossil fuels escalate in cost at an annual rate of 5 percent payback period shortens to 25 years, which approximates the lifetime expectancy of usefulness for today's highest quality parabolic trough collector types (at $\doteq \$40/\text{ft}^2$). ([illegible]).

Conclusions

It follows logically, if the payback period only equals the life expectancy and does not exceed it, it would certainly be considered basic business sense not to invest in a venture requiring a huge capital investment and giving so little hope for financial reward. Thus based on current installed solar equipment costs, existing and future tax laws, projected conventional fossil fuel costs and the results obtained experimentally; the present cost of conventional fuels ($/BTU) is less than, or equal to the annualized total cost of the solar energy system (conventional and solar cost). Therefore, at this time, the optimum energy system based on total system costs, consists of a 100 percent conventional fuel system. As conventional fuel prices continue to escalate and solar equipment costs decrease, the economics of solar relative to conventional will improve.

Furthermore, another problem which needs to be addressed regarding poor results taken in November, concerns radiation losses to low temperature surroundings during the winter months. Antifreeze protection of the absorber equipment need be implemented from the start adding additional initial cost. The heat required by this defrosting mechanism supplied by the collector itself and is considered a high parasitic heating load requirement (consuming up to 10 percent of output energy), as compared to warmer climate areas of the country where little or no heat load exists. Thus efficiency is reduced even further in northern climates.

Recommendations

Some areas of special interest to the paper industry where SIPH may be considered feasible, though certainly not proven cost effective by any means, and the reasons for its positive prognosis are discussed and left open for future work.

Pulp Mill

It has been implied throughout this project that application of a SIPH system where a chemical pulping facility exists, or will soon, would certainly prove to be inappropriate. Further investigation into the alkaline chemical recovery process, for example, reveals that the recovery furnace is the base of the mills energy supply. An example of a mill's total energy balance has been worked out so that one can see without a doubt that enough steam is generated for suppling the majority of the branch energy requirements, namely digester, black liquor evaporator system and the paper dryers. Additionally, electricity can be generated with a turbine which can be sold back to the utility companies indirectly compensating for some of the energy required by the furnace itself. Even so, there remains some steam generated that goes unused by the major energy consuming units named. This energy is available to use in other areas of the mill. In the example provided in the appendix, 28 lbs saturated steam per 100 lbs black liquor solids at 135 psig and 360°F where h = 975 BTU/ft^2· lb, is generated.[34] This converts to 8.1 x 10^5 BTU/A.D. ton pulp produced. Since significant amounts of hot fresh water are important and required for effectiveness of the bleaching process, this would seem to be a reasonable place to use the additional heat. In order to determine heating requirements, the total amount of water throughput per A.D. ton and temperatures needed must be known. Use of filtrates from bleach washers reduces steam consumption and in recent times has helped to limit the water consumption in the bleach plant to between 15,000 and 20,000 gallons per A.D. ton.[35] Assuming 15,000 gal/A.D. ton required to be heated to 150°F from average mill water temperature equal to 45°F. Calcuations show that 12,500,000 BTU required/A.D. ton bleached pulp or 8.75 x 10^{11} BTU/yr for a 200 TPD production rate for the bleaching process alone. This quantity required greatly exceeds the quantity of left over steam from the recovery furnace. There is the possibility, then, that bleached kraft mills might have a use for solar industrial process heat in the form of hot water. Referring to the efficiency versus output temperature curve (p.26), a liquid heating flat plate collector would be the type chosen for heating water to 150-200°F (less than 100°C). Bleaching is the kind of process which lends itself favorably to SIPH application since the solar supplemental process heat would represent only a small fraction of that required so as not to affect conventional water heater operation. The idea of using SIPH in an integrated pulp and paper facility is not as far from the realm of possibility as one might think.

Some other processes of possible special interest where SIPH could concievably be applied successfully, and which propose possible avenues for future work are listed in what is considered their order of significance:

1. Secondary fiber pulping: SIPH to heat water to be used in pulpers.
2. Deinking of secondary fibers: SIPH to heat water to be used in this process.
3. Pocket ventilation: SIPH to preheat air used in aiding mass transfer in dead pockets of can dryer sections.
4. Through-air drying: SIPH to preheat air to be used in tissue making operations.
5. Corrugating process: SIPH to form low pressure steam required by the corrugating machines.
6. Groundwood bleaching: SIPH to heat water.

Any one of these processes might be used to use SIPH cost effectively, however each would be a study in itself and a precise quantitative and qualitative knowledge of process variables as well as a complete investigation into the individual process would be required.

Concerning future work with the collector constructed at WMU one might want to apply an insulating layer across the surface of the collector in order to at least partially eliminate convective losses. This would simulate as best as is possible, the glass tube surrounding the most concentrating collector absorbers though the space would remain unevacuated. To remedy this a small electrical fan might be positioned at one end of the collector while the other end is sealed with the insulator creating a partial vacuum.

Summarizing, it has been concluded on the basis of a life-cycle cost economic analysis that the use of SIPH in the form of process steam is not feasible in the paper industry today and cannot be considered a viable alternative to conventional fuel as yet. However its desirability is a function of conventional fuel cost escalation and, just as importantly, of mirrored collector fabrication technology and commercial glass forming techniques. Advancements in this area are being made. One of these is the recent development of thin film glass which eliminates aberations of focus still encountered with normal, thicker thermally sagged glass techniques. Until these improvements are made, or fossil fuel costs increase steadily, solar energy in the form discussed will not be used by the paper industry.

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APPENDIX

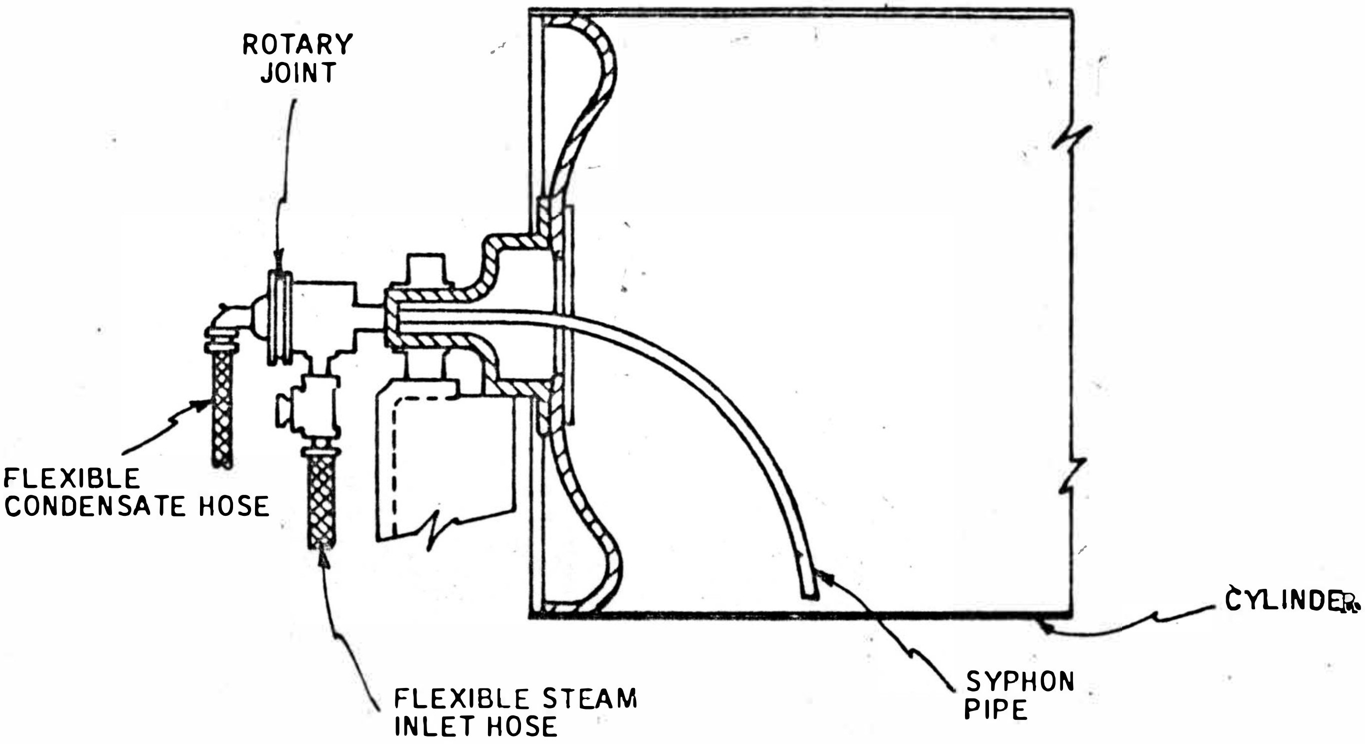

Figure 1: Cylindrical can dryer used at textile drying facility.

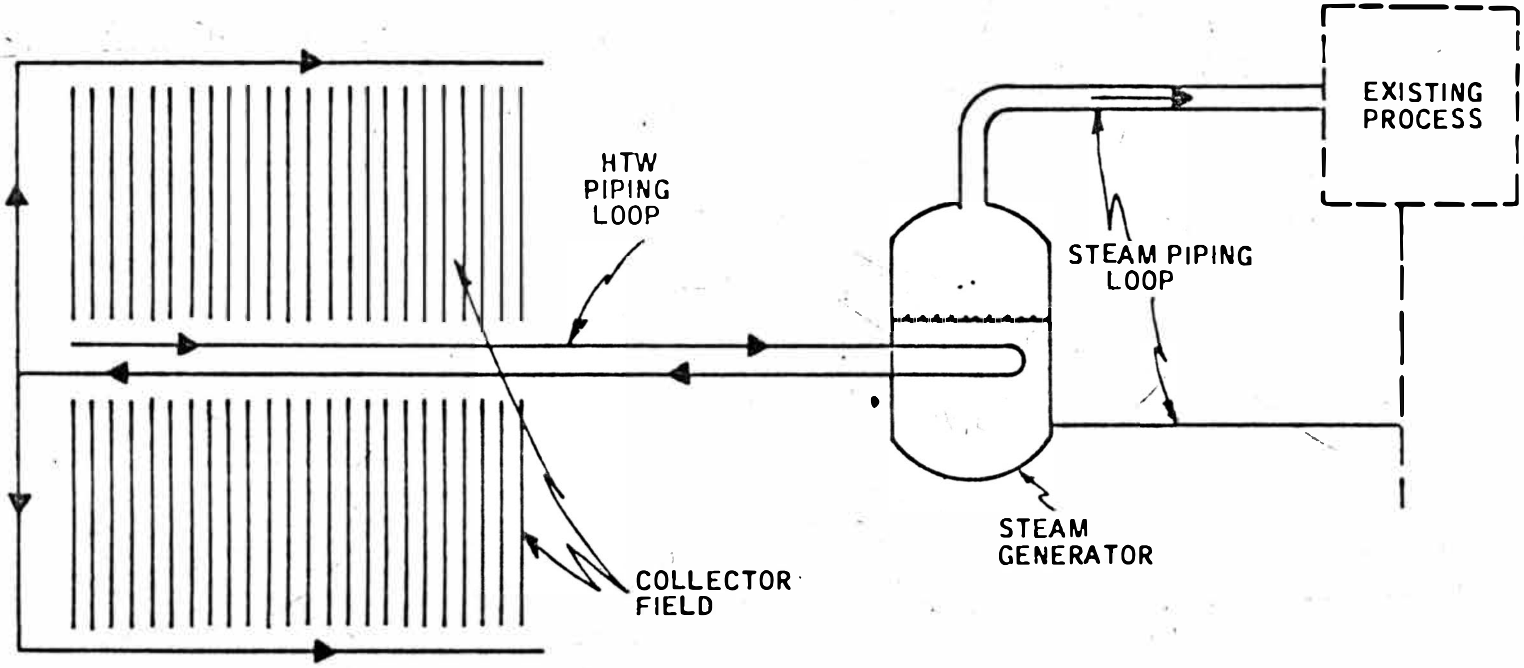

Figure 2: Basic operational schematic of suggested solar industrial process heat system.

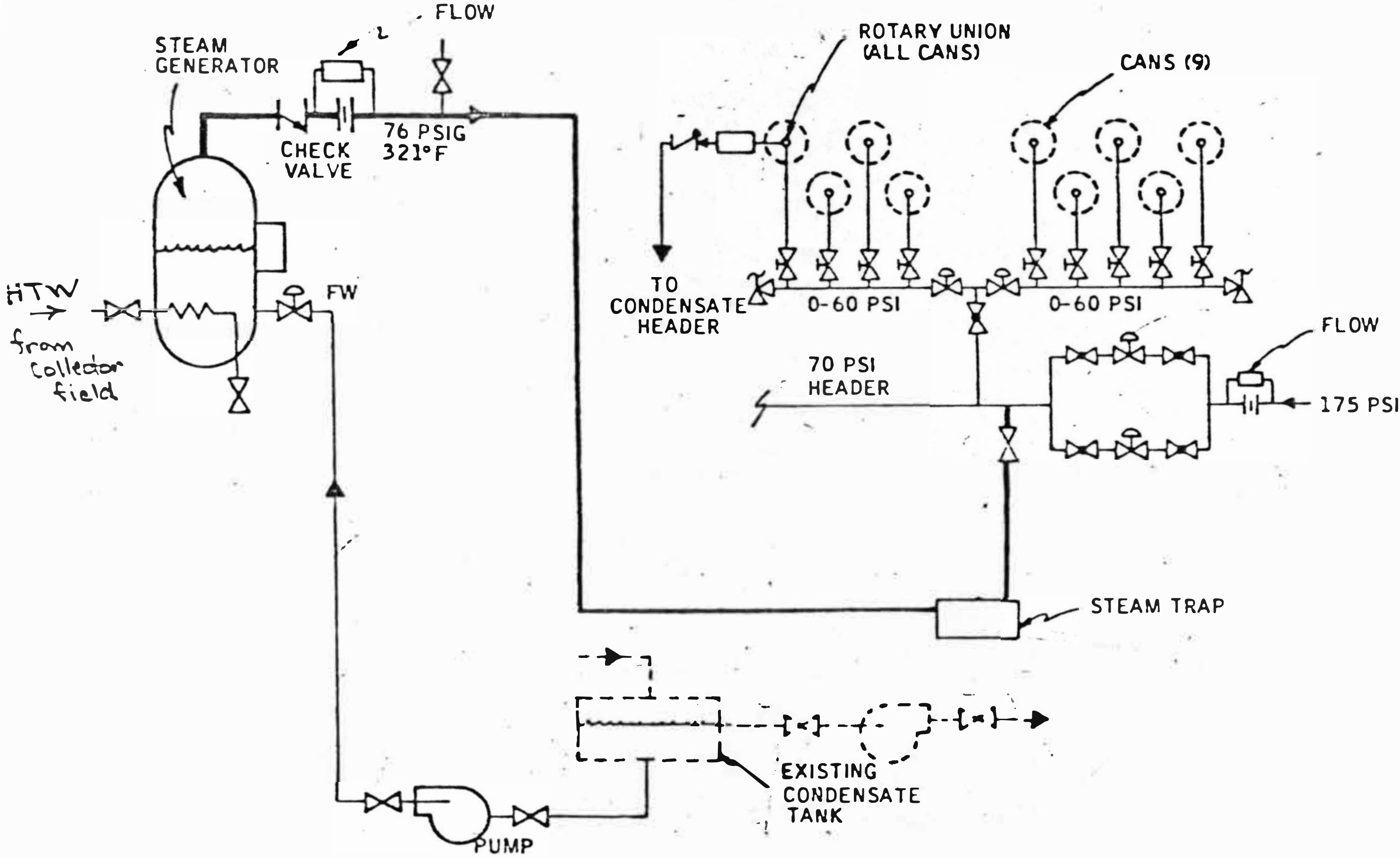

Figure 3: Schematic showing solar steam supply/conventional steam supply interface and instrumentation.

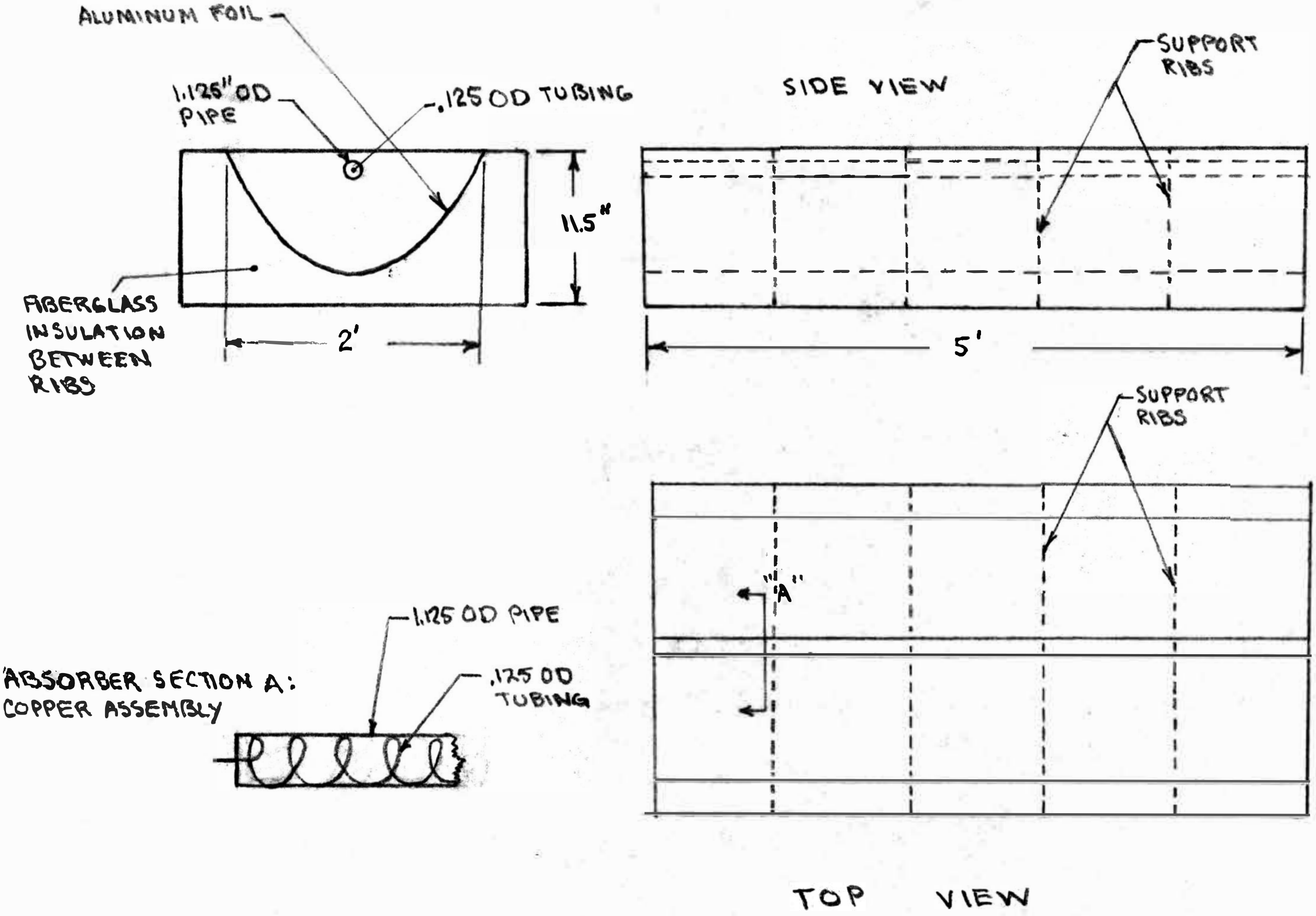

Figure 4: Drawing depicting prototype parabolic collector and copper absorber assembly.

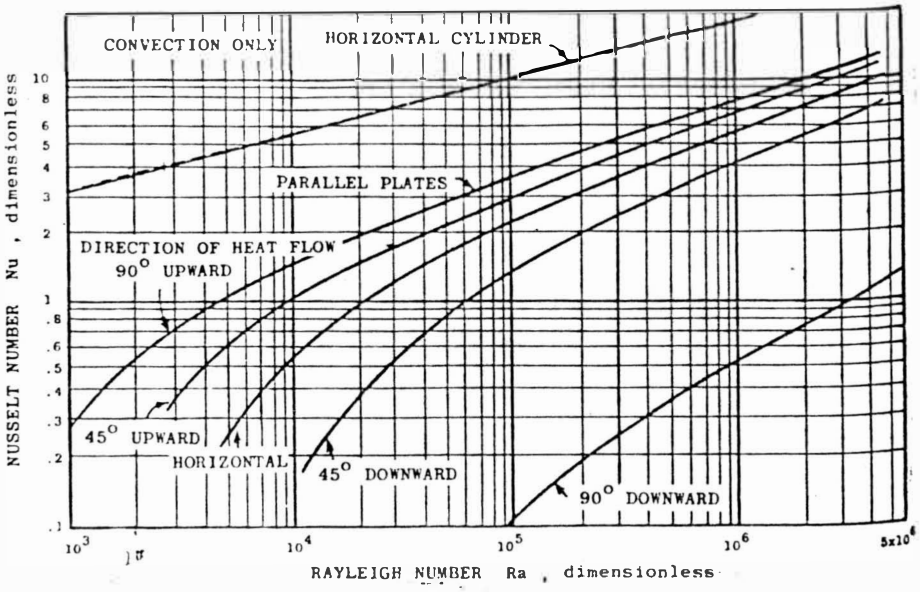

Figure 5: Generalized graph of heat flow between parallel plates and for horizontal cylinders after subtracting the conduction loss, from Tabor (1958).

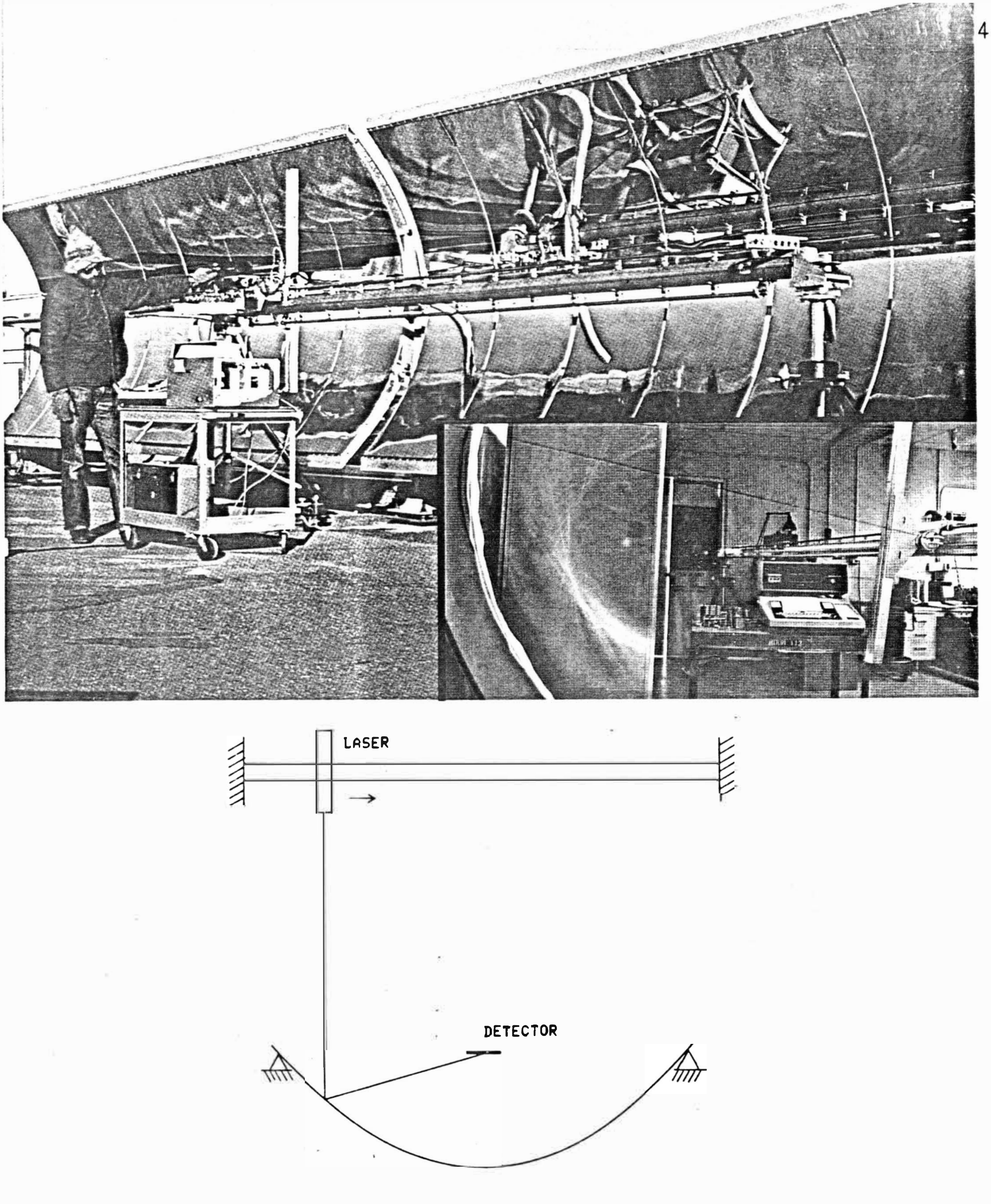

Figure 6: (Top) Photograph showing Laser Ray Tracer in operation. (Bottom) Laser Ray Tester geometry.

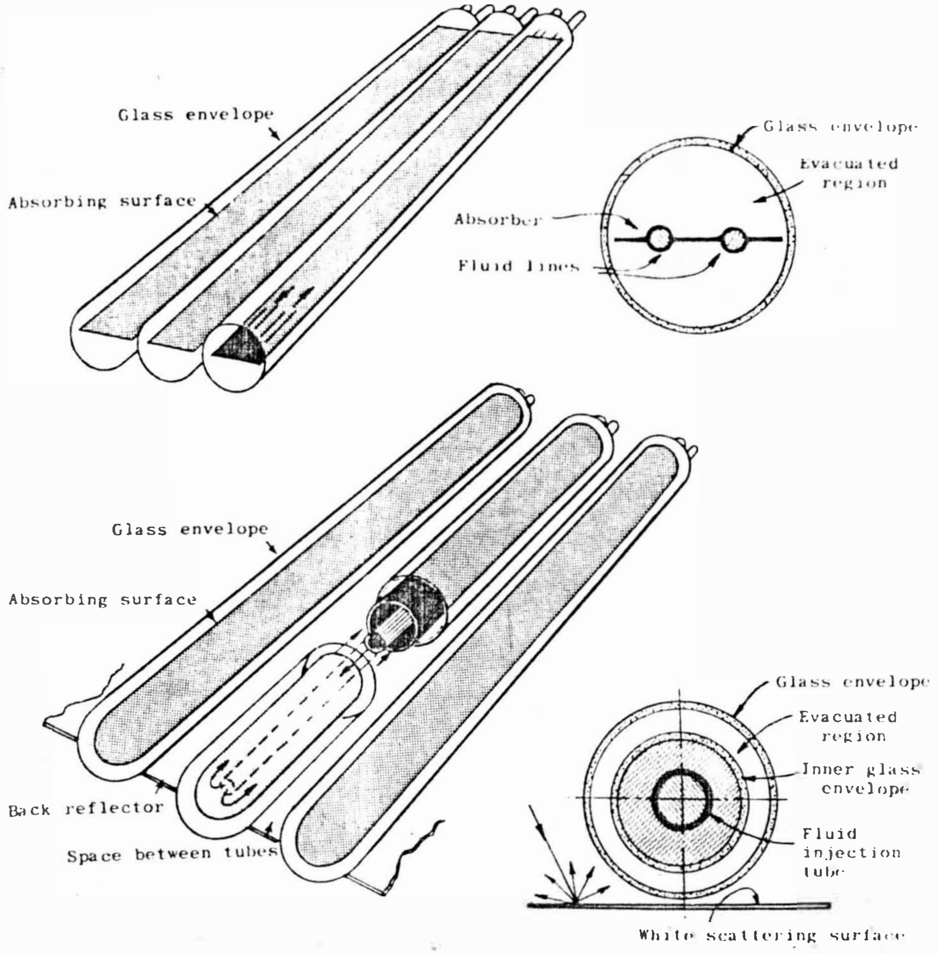

Figure 7: Two designs for evacuated solar collectors. The top configuration is used by Corning and the bottom by Owens-Illinois.

Figure B (a): Evacuated parabolic trough at Dalton, GA

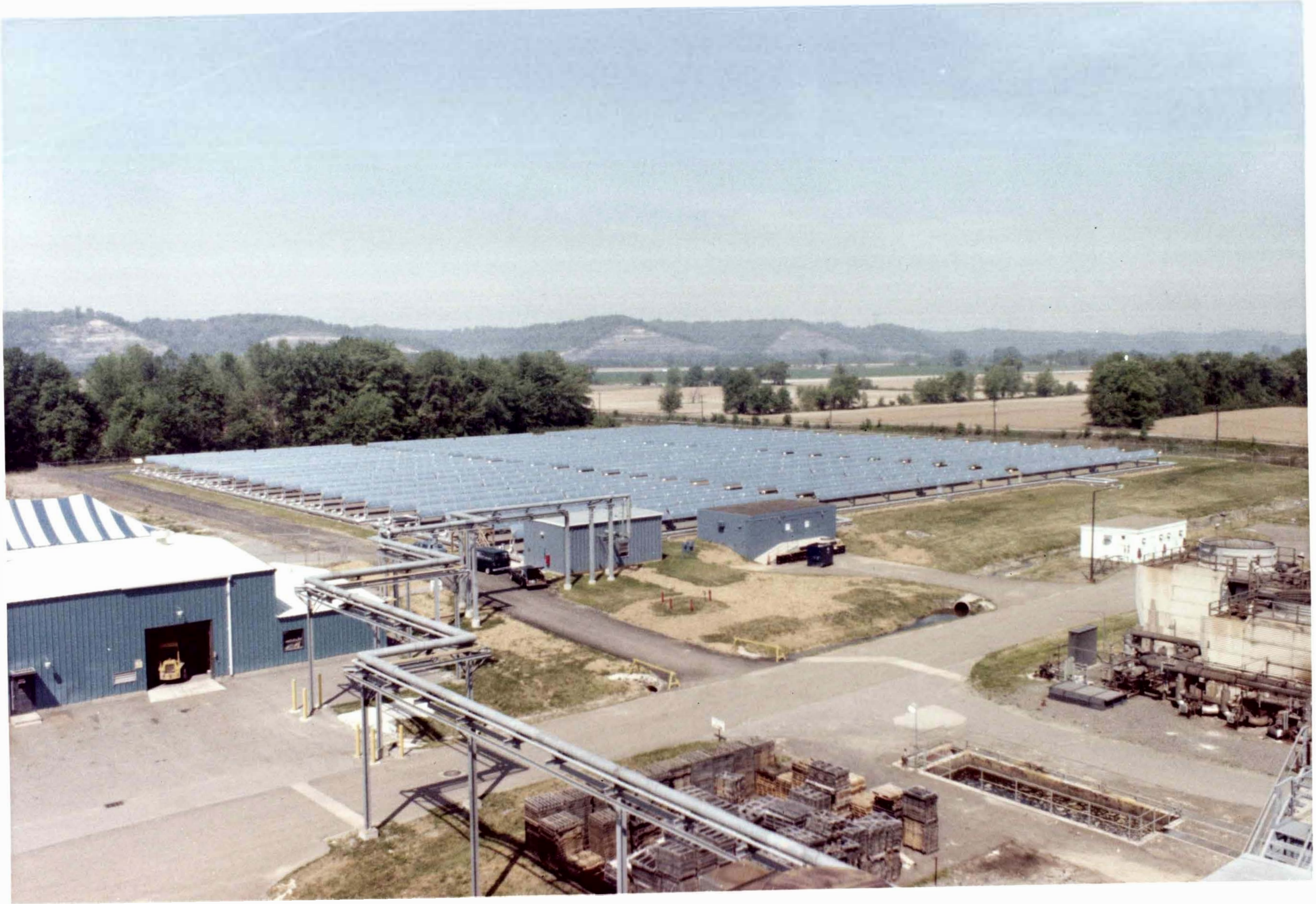

Figure 8 (b): Parabolic trough installation (evacuated) at Haverhill OH.

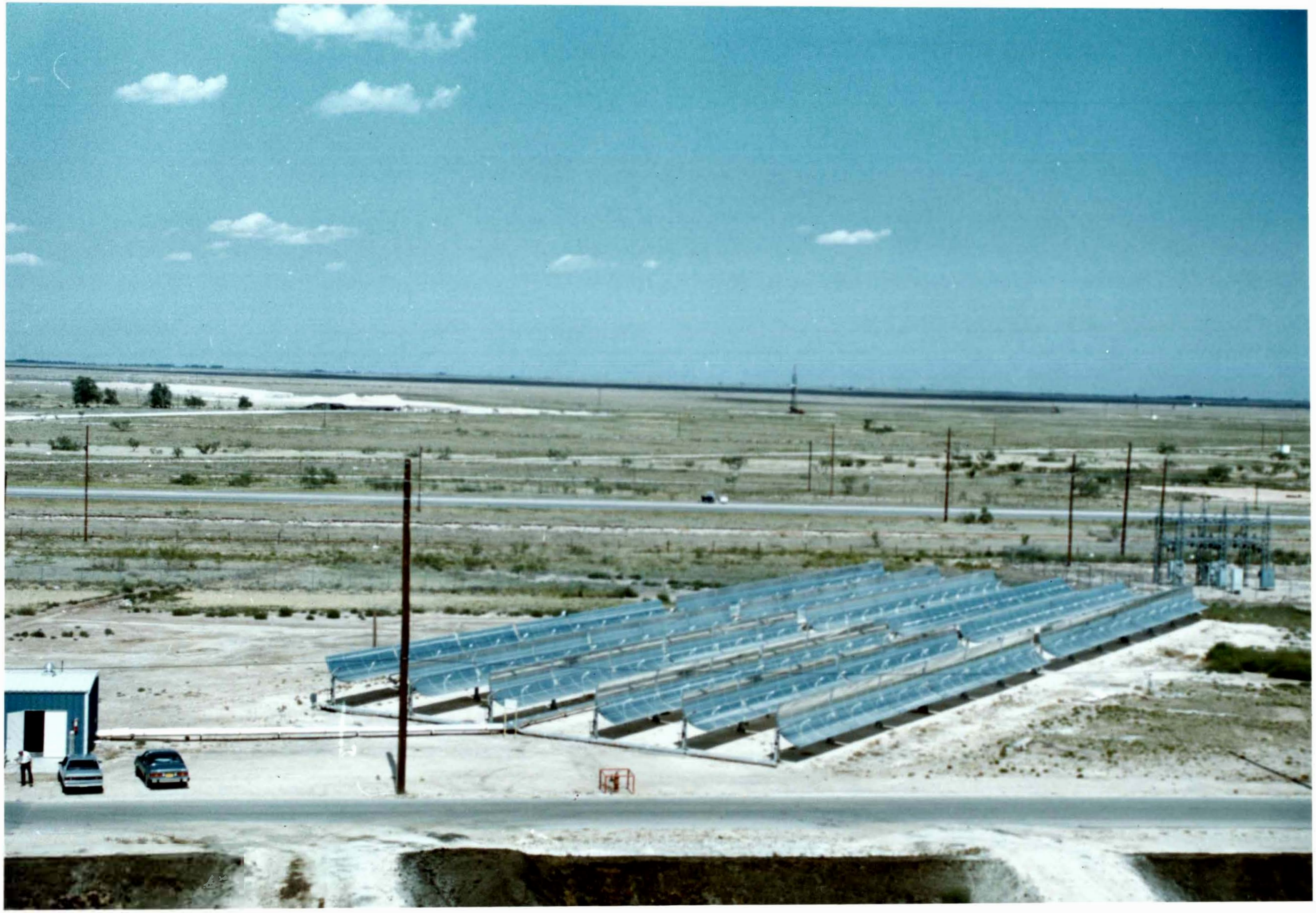

Figure 8 (c): Evacuated parabolic trough installation at Lovingston, N.M.

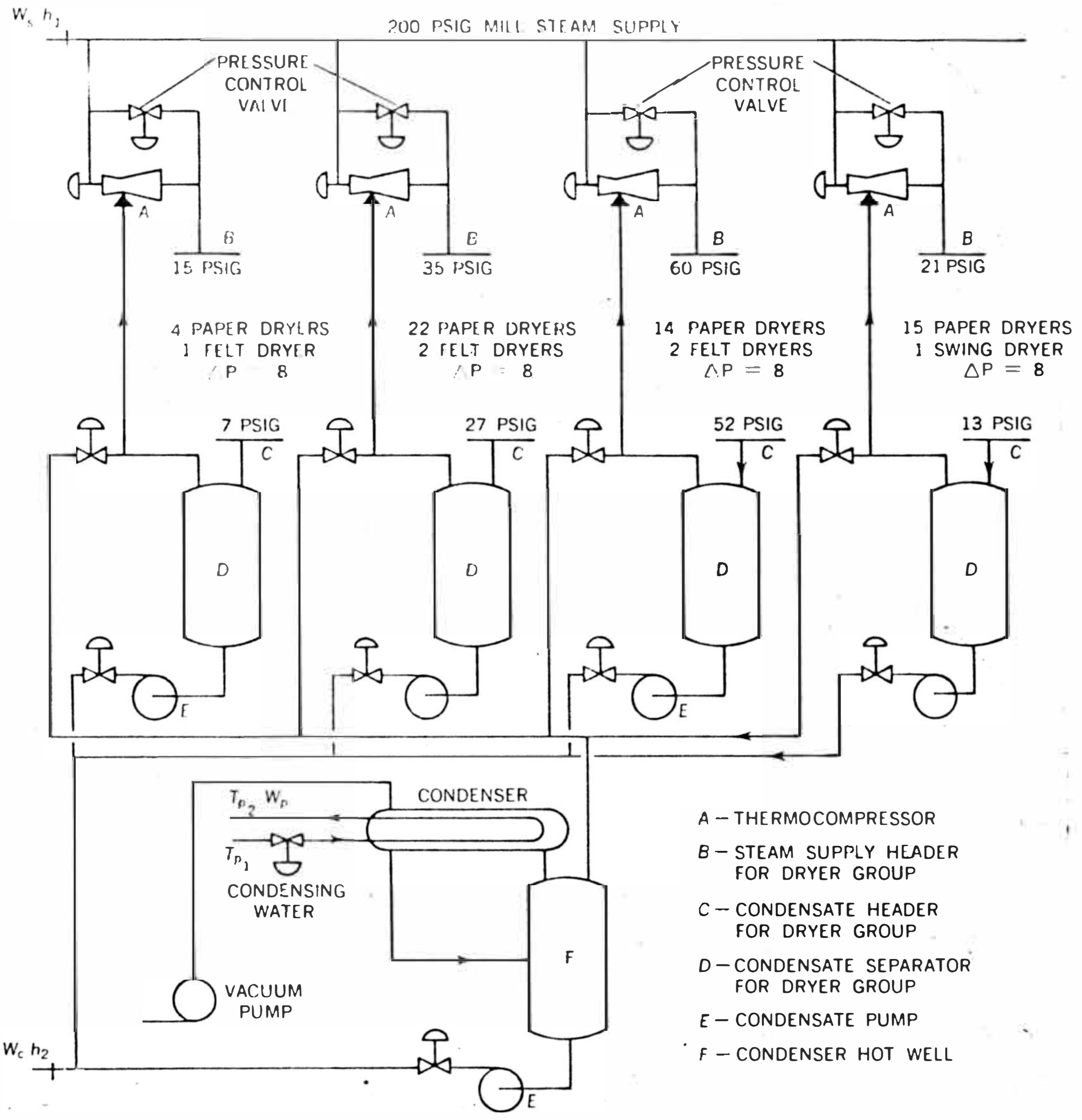

Figure 9: Recirculation-type steam supply/condensate system for a multicylinder dryer section.

Table 1: Selected U.S. solar industrial heat projects - trough installations.

Location	Process	Industrial Partner/ Contractor	Collectors	Size (m^2)/ Steam Conditions
Pasadena, Calf.	Commercial laundry	Home Laundry/ Jacobs-Del Solar Systems	Parabolic trough	603.5/0.86 MPa 171°C
Sherman, Texas	Gauze bleaching	Johnson & Johnson/ Acurex Corp.	Parabolic trough	1,070.2/0.86 MPa 174°C
Fairfax, Alabama	Fabric drying	West Point Pepperell/ Honeywell, Inc.	Parabolic trough	772.3/0.58 MPa 158°C

DATA TABLE

Measured variable Trial	Time	T ambient (^{o}F)	T_{H_2O} in (^{o}F)	T_{H_2O} out (^{o}F)	Flow rate (ml/min)	BTU/hr
1	11:20am	50	55	69	53	98.8
2	11:30am	51	55	70	49	96.7
3	11:40am	53	56	70	46	85.7
4	11:47am	54	56	72	39	82.0
5	12:00noon	55	56	74	36	79.4
6	12:11pm	55.5	56	71	36	71.4
7	12:33pm	56	57	76	22	53.9
8	12:42pm	56	57	79	17	48.5
9	12:49pm	57	58	80	20	58.3
10	1:04pm	57	58	83	17	56.3
11	1:24pm	56	57	72	24	47.6
12	1:36pm	57	56	72	31	65.6
13	1:43pm	56	54	63	89	93.9
14	1:55pm	56	54	60	80	74.1
15	2:10pm	56	54	61	72	66.7

Formula for computing BTU/hr extracted by heat transfer fluid.

$BTU/hr = (\dot{m})(Cp)\ (\Delta T)k$

where, $\dot{m}$ = ml/min = g_{H_2O}/min

$Cp = 1\ BTU/lb \cdot {}^{o}F$

$\Delta T = {}^{o}F$

$k = 60/453.6 = 0.1323$

General overall integrated paper mill steam - heat balance :

Datum: $H_2O_{(1)}$ 250°F

Basis: 100lb. Black liquor solids

1. Heat for steam available = 418,200 BTU

2. For Boiler:

H_{feed} = 218.5 BTU/lb @ 250°F

H_{exit} = 1360.5 BTU/lb @ 435 psig, 700°F

lbs steam = $\frac{418,200}{(1360.5 - 218.5)}$ = 366.2 lbs

3. For 35 psig steam extracted:

a. 2240/(30) = 74.7 lbs to evaporator

b. [1800/(30)] (.9) (.07) = 4lb H_2O to reel

c. 54 lb O.D. (960/40) = 81 lb H_2O

d.. Dryer section evaporates 81-4 = 77lbs

e. Steam requirement = 77lb (1.5 lb steam/lb H_2O) = 115.5 lb to dryers (estimate)

4. BTUS in the steam:

H = 1174 BTU/lb @ 35 psig

Total = (1174 - 218.5) (115.5 + 74.7) = 181,740 BTUs

5. Summing:

366.2 - (115.5 + 74.7) = 176 lb 135 psig steam
H = 1194.1 BTU/lb - 218.5 = 975.6 BTU/lb @ 135 psig

for digester: $\frac{26,987,000 \text{ BTU/cook}}{975.6 \text{ BTU/lb}}$ (1 cook/8 tons)(1/30) = 115.3 lbs

6. To air heater (furnace)

a. dry air: (7.0 BTU/mole·°F)(300-80°F)(518.65 lb/29 lb per mole)
= 27,542 BTUs

b. Combustion air: 8.1/lb·mole (220)(6.74/18 lb per mole)
= 667 BTUs

667 + 27,542 = 28,209 BTUs TOTAL HEAT AIR

28,209/975.6 = 28.9 lb steam to air heater

7. To Liquor Heater:

(1194.1 - 48)(2.99 lb) = 3,430 BTUs added at Liquor Heater

3,340 BTU/975.6 BTU per lb = 3.4 lb steam to Liquor Heater

TOTAL 135 psig steam consumed:

3.4 + 28.9 + 115.3 = 147.6 lbs

Available = 176 lbs steam
leaving 28.4 lbs unused

8. BTU converted to KWH by Turbine:

176 lb (975.6) = 171,700 BTU

Converting,

418,200 - (171,700 + 181,740) = 64,760 BTU

TOTAL (@ 72% efficiency) = 64,760 (.293 w•hr/1000 BTU) (.72)

= 13.7 KWH