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SOLAR PRODUCTION OF INDUSTRIAL PROCESS STEAM FOR THE LONE STAR BREWERY

CONCEPTUAL DESIGN REPORT

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SOLAR PRODUCTION OF INDUSTRIAL PROCESS STEAM FOR THE LONE STAR BREWERY

By
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CONCEPTUAL DESIGN REPORT

Project No. 02-5476

Prepared for
Department of Energy

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I. INTRODUCTION

This document contains Southwest Research Institute's Conceptual Design Report for DOE Contract No. ET-78-C-03-2198. This report summarizes the work completed during the first three months of the project design effort. This project is being conducted as a team effort with the following participating organizations: Southwest Research Institute (SwRI), Lone Star Brewing Company, Industrial Systems, Inc., Jud Plumbing and Heating Company, Inc., and Trinity University. SwRI is the prime contractor; Lone Star Brewery is the industrial partner; Industrial Systems is the engineered equipment supplier including the solar collectors; Jud Plumbing is the mechanical contractor; and Trinity University is the solar system analysis subcontractor.

This report divides the project conceptual design activities into the following six chapters: Industrial Plant, Conceptual System Design, Collector Selection, Heat Transfer Fluid Selection, Site Fabrication, and Engineered Equipment. Included in the conceptual design chapter is an overview of the solar steam system and a brief discussion on the environmental impact of the project as well as the safety considerations of the system design. As explained in that section, the effect of the solar system on the environment is negligible, and the safety analysis of the system indicates the considerations to be taken to minimize any potential safety hazard due to contamination of the food product or to fire. Both of these potential hazards are discussed in greater detail in the Heat Transfer Fluid Selection chapter. As indicated in that chapter, both the question of product contamination and the question of potential fire hazards will be presented to the industrial partner's safety committee so that the selection of the heat transfer fluid meets with their approval.

II. INDUSTRIAL PLANT

A. Widespread Application

The industrial partner for this project is the Lone Star Brewing Company. The selection of Lone Star was made for the many advantages listed below. This plant has a large energy requirement which is mainly supplied by natural gas. Natural gas usage averages 12.7 Mcf per month. The brewing industry as a whole has an estimated yearly energy cost of \$235 million. Similar industrial applications for process steam consume an estimated 6.6 quads per year (6.6×10^{15} Btu). Therefore, the potential for widespread applications of the solar technology developed as a result of this proposed project to similar industrial sites is substantial.

B. Industrial Process Steam System

Lone Star Brewery has a steam requirement of 125 psi and 351°F at approximately 50,000 lbs/hr. This steam is manufactured by two 30,000 lb/hr steel shell-and-tube Keystone Boilers with heating surfaces of 3582 ft² and a maximum allowable working pressure of 200 psi. These boilers are fired by natural gas with diesel fuel burners installed for use as a supplement in the event of a natural gas curtailment. In addition to the Keystone Boilers, Lone Star also has a 50,000 lb/hr Erie City I.W.I. boiler with a heating surface of 4666 ft² and a water wall heating surface of 598 ft² that has a maximum allowable working pressure of 160 psi and is fired by natural gas. This boiler is also outfitted with two combination gas and oil burners which have a rating of 30,000 lb/hr. The steam pressure is controlled to a constant 125 psi, 24 hours per day. While the steam flow is not recorded directly, the load requirement can be gauged by variations in steam condensate temperature. A load time history is shown in Figure 1. In this figure, the maximum load of 60,000 lb/hr is represented by the 175°F steam condensate temperature, and the minimum load of 40,000 lb/hr is represented by the 150°F steam condensate temperature, with this value dropped to 6000 lb/hr on the weekend.

C. Solar System Interface

To illustrate how the solar steam generation system will interface with the present process, a simplified schematic drawing of the industrial process is shown in Figure 2. A more detailed sketch of the present steam generation system and the steam feedline from the solar-fired boiler is shown in Figure 3. A sketch of the present condensate return system, along with the condensate feedline to the solar-fired boiler, is shown in Figure 4. A block diagram of the solar steam system is shown in Figure 5. With the above figures for reference, a description of the interface between the solar steam system and the present industrial process follows.

Steam is presently generated by three boilers, each producing steam at a gage pressure of 125 psi and a temperature of 351°F. Boilers deliver

FIGURE 1. LONE STAR LOAD TIME HISTORY

LONE STAR BREWING COMPANY

This schematic drawing shows the various steps in the brewing process. Much of the smaller equipment has been omitted for the sake of clarity. Dry raw materials are conveyed to the cooker and mash tun, in which they are added to the correct amount of water. The proper amount of malt is drawn from the bin, weighed, cleaned, weighed a second time, crushed in the mill and finally weighed in the hopper and sent to the mash tun. At the same time a fixed quantity of corn grits is brought from storage, weighed and sent to the cooker. A small amount of malt is added to convert and liquefy the grits during the cooking process. When the malt has been properly steeped, the finished "cook" is rapidly dropped into it. The resulting

mash is pumped to the lauter tun which is so designed that the grains form a filter bed. The clear liquid containing fermentable and unfermentable sugars is drawn off the bottom and further extracted from the grains by spraying on hot water through what is called the sparging equipment. The resulting unfermented liquid collected in the brew kettle is called wort. In the kettle the wort is boiled with hops for flavor and clarity. The spent grains are carried away to be used as cattle feed. After settling for a time in the coolship, the wort is passed thru a series of coolers that reclaim most of its heat in the form of hot water for subsequent brewings. The wort then flows to the fermenting tanks, where the yeast is added. During fermentation

carbon dioxide gas is given off. The gas is compressed, stored and used to adjust gas volume to a very rigid standard and also as a counter pressure in the bottling plant in place of air. After leaving the fermenters the brew is cooled to a definite temperature and passes into the storage tanks. During the storage period the beer is carefully tested, and when properly aged is further cooled and filtered and is then sent to the finishing tanks, which are located in the shipping cellars. On leaving these, it is filtered. That portion being pumped to the bottling plant is further cooled; the draught brews pass on to the racking cellar where they are put in barrels.

FIGURE 2. SCHEMATIC OF INDUSTRIAL PROCESS

FIGURE 3. STEAM GENERATION SYSTEM

FIGURE 4. INTERFACE OF SOLAR SYSTEM WITH INDUSTRIAL PROCESS (CONDENSATE SIDE)

FIGURE 5. BLOCK DIAGRAM OF SOLAR STEAM SYSTEM

steam to a common header which feeds the various steam loads. Interface of the solar system with the existing process is to be accomplished by injecting the solar-produced steam into the main steam header that passes through the canning warehouse just below the collector field, thereby minimizing the piping runs between the collector field and boiler, and between the boiler and steam header. The piping which carries this steam will be connected to the plant steam header via a check valve and a gate valve provided in the solar steam line just before its point of connection to the header (Figure 3). The check valve in the solar steam line will serve to prevent plant-produced steam from flowing upstream in the solar line while solar steam is not being produced but, yet, will admit solar-produced steam to the plant header when it is available at the plant pressure of 125 psi gage. The gate valve in the solar steam line will allow positive manual shutoff of the solar line at any time required for maintenance or adjustment of the system. Interface being accomplished in this manner will allow all of the solar steam to be utilized in the plant processes and will diminish the loads on the existing boilers since their controls are such as to automatically limit their firing to produce a constant pressure at the steam header.

D. Process Utilization

The average steam requirement for the total plant is 50,000 lb/hr, but the steam requirement for the process downstream from where the solar-produced steam will be injected is 6000 lb/hr, seven days per week. The following assumptions were used for estimating the peak performance of a realistic system for this application: the weather is crystal clear with an intensity of 350 Btu/hr-ft², 90% of the total radiation is beam radiation, the collector has an efficiency of 70%, the collector area is 9450 ft², and 1000 Btu are required per pound of steam. With these assumptions during ideal conditions and no thermal losses in the remainder of the system, the maximum output from the solar collection system is 2084 lb/hr, which is 35% of the steam load downstream from where this steam will be injected, or 4% of the total plant load.

E. Building Configuration

The overall building configuration is shown in Figure 6. This aerial view shows the available roof area. To mount 9450 ft² of tracking solar collectors without significant shading requires about 24,000 ft² of roof area. The roof areas on the warehouse buildings (designated A and B in the upper left portion of Figure 6) are 24,240 ft² each, the next building to the right (Building C) has a roof area of 12,700 ft², Building D has 3040 ft², and Building E has a roof area of 5782 ft². Warehouse Building A has been selected as the most ideal location for the collector field. This location will place all 9450 ft² of collectors in one central location without any shading problem between rows and offers the collectors an unobstructed view of the sun all year long. The pipe run to the solar-fired boiler, which will be located in the warehouse equipment room directly below the collector field, will be about 20 ft. Some additional photographs of the industrial plant are shown in Figures 7, 8, and 9.

FIGURE 6. AERIAL PHOTOGRAPH OF LONE STAR'S INDUSTRIAL PLANT SITE LOOKING NORTHWEST

FIGURE 7. GROUND VIEW OF LONE STAR'S INDUSTRIAL PLANT SITE LOOKING TO THE WEST

FIGURE 8. GROJND VIEW OF LONE STAR'S INDUSTRIAL PLANT SITE LOOKING TO THE NORTH

FIGURE 9. GROUND VIEW OF LONE STAR'S INDUSTRIAL PLANT SITE LOOKING TO THE NORTH
AT THE WAREHOUSE WHERE THE PROPOSED COLLECTORS WILL BE INSTALLED

F. Climatic Conditions at Industrial Site

Lone Star Brewing Company's industrial plant is located in San Antonio, Texas. The location of this plant site on the edge of the Gulf Coastal Plains results in a modified subtropical climate, predominantly continental during the winter months and marine during the summer months. Normal mean temperatures range from 50.6°F in January to a high of 84.7°F in July. While the summer is hot, with daily maximum temperatures above 90°F over 80 percent of the time, extremely high temperatures are rare, the highest on record being 107°F. Mild weather prevails during much of the winter months, with below-freezing temperatures occurring on an average of about 20 days each year.

San Antonio is situated between a semiarid area to the west and the coastal area of heavy precipitation to the southeast. The normal annual rainfall is 27.54 inches. Precipitation is fairly well distributed throughout the year with heaviest amounts during May and September. Hail of damaging intensity seldom occurs, but light hail is frequent in connection with springtime thunderstorms.

Northerly winds prevail during most of the winter, while southeasterly winds from the Gulf of Mexico prevail during the summertime and may be experienced for extended periods during the winter. Rather strong northerly winds occasionally occur during the winter months in connection with "northers." No tornadoes have been experienced in the immediate area. Relative humidity averages above 80 percent during the early morning hours most of the year, dropping to near to well below 50 percent in the late afternoon.

San Antonio, popularly known as the place "where the sunshine spends the winter," has about 50 percent of the possible amount of sunshine during the winter months and more than 70 percent during the summer months. Skies are clear more than 35 percent of the time and cloudy about 30 percent. Air carried over San Antonio by southeasterly winds is lifted orographically, causing low stratus clouds to develop frequently during the later part of the night. These clouds usually dissipate before noon with clear skies prevailing a high percentage of the time during the afternoon.

The specific conditions that affect the operation of a solar steam system will be discussed here. Since the ambient weather conditions vary greatly from day to day, the only sound approach to characterizing these conditions is to determine the long-term average values. The pertinent data available from the local weather station are solar radiation measured on the horizontal, percentage of clear-day radiation received, daytime ambient design temperature as calculated from the mean and maximum temperature, and average wind speed. These four long-term average quantities were extracted from the U.S. Department of Commerce Weather Bureau "Climatological Data: National Summary" for the period of 1953-1974, and are listed in Table I. The long-term average daily total solar radiation for each month and each season are shown in Figure 10.

TABLE I. CLIMATOLOGICAL SUMMARY*

San Antonio, Texas

Lat. 29° 32'N

Long. 98° 28'W

El. 794 Ft

Climatic Parameter	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
$\bar{H}$, $\frac{\text{Btu}}{\text{day-ft}^2}$	980	1234	1528	1636	1895	2192	2288	2045	1724	1414	1076	871	1574
T_a , °F	54	58	66	74	79	85	88	87	82	74	63	56	72
% Possible	48	51	56	58	60	69	74	75	69	67	55	49	62
V, mph	9.0	9.8	10.4	10.7	10.2	10.1	9.3	8.5	8.5	8.4	8.9	8.6	9.4

where: $\bar{H}$ = Long-term monthly average daily total radiation on a horizontal surface, Btu/day-ft²;

% Possible = Percentage of clear day insolation received on the average day of the month;

T_a = Long-term monthly average daytime ambient design temperature, °F ($T_a = 0.3T_{\text{max}} + 0.7T_{\text{mean}}$); and

V = Long-term monthly average daily wind speed, mph.

* Extracted from U.S. Department of Commerce Weather Bureau "Climatological Data: National Summary" for the period 1953-1974.

FIGURE 10. SOLAR RADIATION AT INDUSTRIAL SITE

G. Energy Conservation Plan of Industrial Partner

Lone Star Brewery has pursued energy conservation for many years. The following indicate the major energy saving efforts that have been implemented in the past: the reclaiming of bottlewasher water for irrigating through an automatic yard sprinkling system; the lowering of hot water temperature in bottle and can warmers from 140°F to 120°F; the sterilizing time in pasteurizing units, product lines, bottle fillers, and can fillers has been reduced from four hours to two hours. The thermostat settings for space heating during the winter has been lowered from 78°F to 68°F, and settings for air conditioning during the summer have been raised from 68°F to 80°F. A comprehensive maintenance program including a shop with 60 craft employees has been initiated to keep equipment at peak efficiency. Plant personnel have recently completed a hot water reclaiming system to preheat brewing water from 80°F to 135°F with hot by-products at 198°F.

H. Visibility of Project

In addition to all of the above qualifications, we believe that the strongest reason for selecting Lone Star as the industrial partner is the unmatched visibility afforded to both the general public and the industrial community. Lone Star Brewing Company has over 400,000 visitors tour their industrial plant each year, and an additional 40,000 visitors use their party facilities. Plant tours are held from 10:00 AM to 5:00 PM, Monday through Friday, 12 months per year. The Engineering Department at Lone Star also holds special guided tours of their facilities at the request of groups within the construction and trade industries, brewing industries, or an industrial group with similar steam facilities. Groups that have recently toured Lone Star's plant are listed below.

- American Society of Heating, Refrigeration, and Air-Conditioning, Engineers' Local Chapter
- Plumbers and Pipefitters Local 142
- Refrigeration and Air-Conditioning Training Classes from local trade schools
- Mechanical Contractors Association of San Antonio
- Association of General Contractors of San Antonio

Arrangements have been made with the San Antonio Visitors and Convention Bureau to publicize the project to any incoming convention groups that may have an interest in process steam application. San Antonio has a \$300 million per year tourist and convention business with over 7.34 million people visiting the city a year.

In addition to the Lone Star-generated exposure mentioned above, SwRI will also provide significant visibility for this project. Last year SwRI grossed about \$30 million in contracts for over 300 industrial clients. This figure has steadily been increasing at a rate of 18% per year. A copy of the brochure developed for this program will be distributed to all of SwRI's project managers so that this effort can be brought to the attention of any of their industrial clients that may have an interest in such a project. The list of SwRI industrial clients represents a major portion of the nation's leading industries which have come to SwRI for solutions to a wide variety of industrial problems.

III. CONCEPTUAL SYSTEM DESIGN

A. General System Description

The conceptual design for this system is by choice a very simple one. We have striven to minimize operation and maintenance problems while, at the same time, providing a workable and economical system. The system schematic is shown in Figure 11. The design concept is to pump a nontoxic, non-corrosive heat transfer fluid through a collector field at 9450 ft² and then pass this fluid through the tube bundle of an unfired steam boiler. The steam produced in the shell of this boiler is then transported to the process steam header under the developed pressure and metered to this header by a standard check valve. Feedwater from the process deaerator, which is fed to the existing boilers by three boiler feed pumps in parallel to a common header, will be tapped for make-up to the solar-fired boiler. A more detailed description of each of the system components is included in the following chapters of this report.

B. Environmental Impact Assessment

1. Land Use at the Industrial Site

The industrial site itself is zoned for heavy industry, with light industrial designations immediately to the north and south. Scattered commercial activities border the industrial site on the west and southwest quadrants. Immediately east, across the San Antonio River, a mixture of open space, light industrial, heavy industrial, and single family residential land uses prevail. The open space use is Roosevelt Park, alleged to be the area where Teddy Roosevelt trained the "Rough Riders." This park is the entrance to the Missions of San Antonio Parkway, recently designated by Congress as a National Park and slated for significant open-space use development by the National Park Service. The increase in tourism associated with this type of development will further enhance the visibility of the project.

If the solar collector field were mounted on the ground, this land would need to be purchased or land for planned plant expansion would need to be purchased. Since the collector field will be roof-mounted, no long-range impact on land usage will be felt, and the surrounding valuable urban land can be used for more productive purposes.

2. Environmental Impact

a. Fire Hazard

Some of the typical heat transfer fluids used in high-temperature process systems have been known to possess a fire hazard when operated above the fluids' autoignition temperature. In addition to this condition, hazards have also been experienced when fluid leakages have saturated system insulation with fluids above their flash temperature. Clearly, care must be taken in the selection of any heat transfer fluids to consider the potential fire hazards.

FIGURE 11. SCHEMATIC OF CONCEPTUAL SOLAR STEAM SYSTEM DESIGN

b. Toxicity

Since this plant is a food industry, any contamination of the product or product packaging must be avoided. The fluids used in the solar system must, therefore, be tested for toxicity to assure that a system failure will not produce a health hazard. The heat transfer fluid must, therefore, be selected with toxicity in mind.

c. Air and Water Pollution

The only possible impact on the surrounding air and water table would be due to the leakage of the system heat transfer fluid. The quantity of this fluid will be small so that even if a system failure were to occur, no significant impact would be imposed on the surrounding industrial environment. As an additional safeguard, the volatility of most high-temperature heat transfer fluids is low, so the air pollution would be minimized. The contamination of the local water supply will be virtually impossible since the fluid used must be nontoxic to prevent the contamination of the food product produced at this plant.

d. Energy Usage

The impact of the solar steam system on the plant's energy usage will be positive. This effect is the main reason for considering the design of this type of system.

IV. COLLECTOR SELECTION

A. Collector Survey

1. Introduction

Since solar steam systems are not yet cost competitive, a concerted effort is being made in this design project to determine the most cost-effective system possible. The first step in this process is to select the most cost-effective collector, keeping in mind its performance, durability, maintainability, and installation cost. For a process steam system at 125 psi and 351°F we considered seven candidate collectors. These seven collectors are manufactured by:

- (1) Acurex Corporation
- (2) General Electric Company
- (3) Hexcel Corporation
- (4) Honeywell, Inc.
- (5) Jacobs-Del Solar Systems, Inc.
- (6) Solar Kinetics, Inc.
- (7) Suntec Systems, Inc.

Each of these units has certain advantages and disadvantages, and all are comparably priced. One must be careful, however, to determine what equipment is included in the purchase price, what equipment must be supplied by the installer, and whether or not the price of freight is included. The quality of construction for all these units appears good, with only small differences between units. These small differences, however, can have significant implications on performance and cost over the life of the system.

To determine, therefore, the most cost-effective collector for this application, the following procedure was used:

- A request for quotation was solicited.
- Sites visits were conducted.
- Installed system costs were estimated.
- The yearly collector performance was calculated.
- The cost per million Btu collected was determined and used as an indicator for selection.

The request for quotation was solicited in the form of a letter to each of the candidate manufacturers asking for the following information:

- Written quote for the purchase of 10,000 ft² of collector aperture including a maximum guaranteed escalation rate for the next year.

- Performance data so that collector output at 400°F average receiver temperature can be calculated for a typical weather year in San Antonio, Texas.
- Based on previous system installation, provide an estimate of the number of labor hours required for installing this size system by each labor trade, including special roof preparation required for wind and dead loads.
- Estimated maintenance schedule for the life of the collector field, along with the estimated life of the above collector system.
- Specify any unique features that would indicate a more economical system, a longer system life with lower maintenance, a higher thermal performance over the life of the system, greater durability, and overall quality of workmanship than other available collector systems.

Site visits were then made to at least one installation of each of the candidate collectors. The sites visited were:

- (1) Acurex Corporation - Campbell Soup Company in Sacramento, California, and Shallow Well Irrigation System in Willard, New Mexico.
- (2) General Electric Company - In-house test facility at the G.E., Valley Forge Plant in Philadelphia, Pennsylvania.
- (3) Hexcel Corporation - Indian Hospital in White River, Arizona.
- (4) Honeywell, Inc. - Honeywell General Office Building in Minneapolis, Minnesota.
- (5) Jacobs-Del Solar Systems, Inc. - Sandia Test Facility in Albuquerque, New Mexico.
- (6) Solar Kinetics, Inc. - Shallow Well Irrigation System in Willard, New Mexico, and Sandia Test Facility in Albuquerque, New Mexico.
- (7) Suntec Systems, Inc. - Sandia Test Facility and Sandia Total Energy System, both in Albuquerque, New Mexico.

Summaries of the evaluations for each of these site visits are included in Appendix A of this report.

The next step in determining the most cost-effective collector for this application was to estimate the installed system cost. This estimate includes the following:

- Purchase price of the collector.

- Estimated labor costs for collector installation.
- Estimated piping costs.
- Estimated roof modification for small as well as large collector modules.

In order to calculate total cost per Btu, the next item determined was the yearly collector performance, which was calculated using the SOCOSIM computer program developed at Trinity University (as described in Appendix B). This program uses weather data from the SOLMET weather tapes in conjunction with collector performance curves to calculate hourly operation for concentrating solar collectors.

Once the installed system cost was estimated and the yearly collector performance was calculated, then the dollars per million Btu's were calculated assuming a 10-year life for each collector system. This value was then used as an indicator to determine the most cost-effective collector available for this application. A summary of these values along with the estimated installed system cost and collector performance calculations are included after the detailed discussion of each of the candidate collectors.

2. Candidate Collector Units

a. Acurex Corporation Model 3001

The Acurex Model 3001 is a reflecting parabolic trough collector with a 6-ft wide aperture, a concentration ratio of 58, and a rim angle of 90° . This unit is constructed in 10-ft modules with vertical steel columns provided between modules to support the system weight of 5.9 lbs/ft². Eight of these modules are normally included in a single row with a single drive system in the center of the row. The drive system consists of a fractional horsepower gear motor which turns a large reduction worm and worm gear. Input to the motor is controlled by a shadow band tracker with two silicon photo cells. When the vertical axis of a collector is aimed at the sun, the output from the two cells is balanced and the motors deactivated.

The reflective surface of the parabolic trough is fabricated from ALZAK with a reflectance of 0.75. Once the sunlight is reflected from the surface, it passes through a Pyrex glass jacket and strikes the receiver tube. The receiver is constructed of a 1-1/4-in. mild steel pipe with a black chrome selective surface. The absorptance of this surface is 0.94, and the emittance is 0.18.

The principal advantage of this unit is that it has a fair amount of field experience. Also, the reflective surface of this unit is a relatively stable surface with very small degradation due to exposure. This reflective surface is also very hail resistant because of its 40-mil aluminum skin. The disadvantages of this unit are: low mirror reflectance, receiver tube breakage problems, rusting of the reflective casing, exposed worm gear, low system performance, leakage of the flexible hose connection,

and high purchase price. As will be shown later in this report, the cost-effectiveness of this particular unit is somewhat less than some of the other candidate collectors, because of its low performance and a high purchase price.

b. General Electric Company Model TC300

The G.E. Model TC300 solar collector is an evacuated tube design with a parabolic trough reflector. The reflector for this unit features a thin glass reflective surface which provides a concentration ratio of about 3. Three of these troughs are combined in parallel in a 45 in. x 16 in. module. Because this collector has a large acceptance angle no daily tracking is required; however, seasonal adjustments are required four times a year.

The material properties of this unit are: reflectance, 0.86; glass transmittance, 0.85; a receiver absorptance, 0.89; emittance, 0.07. An advantage of this type of collector is the elimination of any daily tracking requirements, however, since this unit is not yet in production, it was not considered further.

c. Hexcel Corporation Model 1655

The Hexcel Model 1655 parabolic trough tracking solar collector has the largest aperture of any other candidate collectors considered for this survey. This aperture is 9.75 ft with a rim angle of 72° and a concentration ratio of 72. Reflector panels of this unit are constructed from 3/8-in. aluminum honeycomb assemblies with 1/2-in. aluminum channel protecting the edges. The reflective surface is an aluminized second surface acrylic film, manufactured by the 3M Corporation, designated FEK-244. This surface has a reflectance of 0.84. The reflector support structure is constructed from welded steel tubing that, in combination with the honeycomb reflective backing, provides excellent rigidity against wind buffeting. The tracking system for this assembly is provided by the Suntek sun sensor manufactured by the Delavan Electronics Corporation. The sensing head consists of a shadow band with two phototransistors. The output from these sensors causes an imbalance in the bridge circuit by shading one of the transistors and is restored to balance when an electromechanical drive mechanism advances the position of the collectors so that the vertical axis of the collector is pointed directly at the sun. The drive mechanism is an electric stepping motor that drives the collector via a chain and sprocket assembly. The energy impinging on the reflector is collected by a black chrome coated receiver pipe with spiral internal grooves and an internal plug. The cover for this tube is a half cylinder of Pyrex glass with a back cover of double-layer metal shield coated with a reflective inner surface of ALZAK. The advantages of this unit are the high thermal performance, low weight, low purchase price, and excellent reflector rigidity. The disadvantages are high wind loads, exposed chain drive, potential for hail damage, degradation of plastic film, no flexible hoses are provided, and relatively high field installation costs.

d. Honeywell Corporation Model HCSC-4

The Honeywell collector Model HCSC-4 is a single-axis tracking parabolic concentrating collector. The reflector consists of 1/2 of a parabola. The design of this collector provides a low profile and is stowed in a low drag, mirror face down position. This stow position protects the mirror surface and reduces nighttime reradiation into space. The parabolic structure is a honeycomb sandwich construction to combine high strength and stiffness with light weight. The reflector is aluminized acrylic and is a product of 3M. The parabolic structure and reflective surface is manufactured for Honeywell, Inc., by the Hexcel Corporation. The mirror structures are constructed of 20-ft long modules allowing collector rows of 80 to 120 ft long. The tracking drive motor is mounted in the middle of each collector row. The thermal energy receiver consists of a black chrome coated absorber tube having a diameter of 1-1/4-in. and constructed of steel. The absorptance of the receiver tube is 0.94, and the emittance is 0.18. The absorber tube is mounted on a galvanized lightweight steel housing and is provided with a calcium silicate insulation on the back side of the receiver and a field-replaceable etched glass window in the front of the receiver tube to reduce thermal losses at the receiver. The tracking mechanical system is a Windsmith gear box, oil encased with a total enclosed fan-cooled motor. Each gear box is provided with a 5000-to-1 self-locking worm gear complete with brake and anti-backlash system. The motor is a fractional horsepower squirrel cage induction type. The controlled tracking system is a Delavan sun sensor modified by Honeywell. At the present time, this unit is not considered a production unit and will, therefore, not be considered further.

e. Jacobs-Del 24-In. Concentrating Collector

The Del collector is a parabolic trough concentrator composed of glass mirror segments. Each segment is a 2-ft long piece of sagged glass formed to the appropriate parabolic shape and back silvered. The silvering is protected from the weather by an inert, nonporous coating on the back side and by the glass on the reflecting side. These mirrors, which have a reflectance of 0.9, are fitted into a parabolic frame with an aperture of 2-ft and a rim angle of 110°. The parabola is composed of four mirror segments with some optical distortion at the edge of each mirror, or eight 1-in. distortion bands. These bands decrease the thermal performance from the theoretically predicted values.

The reflector concentrates the sunlight onto a stationary receiver tube positioned at the focal point and center of rotation of the parabola, which is also the center of gravity of the unit. The fixed 1/2-in. diameter receiver is coated with a selective coating of black chrome which exhibits an absorptance of 0.94 and an emittance of 0.18. This hard-mounted receiver is completely fixed so that no flexible fluid connections are required. Thermal losses from this tube are decreased by a 1.5-in. diameter Pyrex glass tube with a transmittance of 0.9.

The drive system for this unit is a Delavan photoelectric sensor which controls a reversible motor and an enclosed worm gear assembly. This control unit provides stow as well as defocus features to provide a complete hazard avoidance system.

The advantages of this collector are its stationary receiver, its glass reflector, which provides high reflectance and long life, and low wind loads. The disadvantages are a low thermal performance due to low concentration ratio, high unit weight, and high installation costs.

f. Solar Kinetics T-700 Collector

The Solar Kinetics T-700 is a large aperture (7-ft) parabolic trough concentrating solar collector constructed of a rigid monocoque aluminum assembly which provides an excellent strength to weight ratio. The rim angle of this unit is 90° with a concentration ratio of 52. One of the unique features of this collector is the no-lash hydraulic tracking system. This system provides accuracy and durability with two tracking speeds, one for daily tracking of the sun and one for hazard stop operation. The hydraulic accumulator provides the capability to defocus the collector in the event of a loss of power or loss of fluid.

The parabolic reflector is a precisely constructed mirror surface covered with metalized acrylic film which combines weather resistance and high reflectivity. This film is FEK-244, manufactured by the 3M Corporation, with a reflectance of 0.84, a proven life of at least seven years, and a predicted life of over 10 years. The surface reflects the sun's rays onto a 1.63-in. diameter steel tube coated with selective black chrome and a Pyrex glass cover with an O-ring seal for dust and dirt protection. The absorptance/emittance ratio of this coating is 0.94/0.18. After the heat transfer fluid passes through this receiver tube, it is conveyed to the stationary plumbing via an insulated stainless steel flexible hose which allows rotation of the collector without any flow restriction. The reflector rotation is made possible by self-aligning sealed ball bearings which absorb structural loads and misalignment from shifting of the building support without any binding.

The advantages of the T-700 are the hydraulic tracking system, the O-ring receiver cover seal, the rigid reflector assembly, the excellent overall quality, the high thermal performance, and the low installation costs. The overall system was designed with low maintenance and minimal field installation requirements in mind. The only known disadvantage to the selection of this unit is the unknown durability of the acrylic reflective film.

g. Suntec SLATS Collector

The SLATS collector (Solar Linear Array Thermal System) is constructed of a fresnel trough reflector. This reflector consists of a field of curved rectangular mirrors that reflect sunlight into a narrow line image. The mirrors, resembling Venetian blinds, are steered by a linkage system to direct the sun's image onto a linear receiver. The mirror assembly is composed of ten 1-ft wide by 20-ft long segments orientated with the length dimension in the east-west direction and tilted at the latitude of the installation.

The concentration ratio of the unit is 38 with the glass mirror segments exhibiting a reflectance of 0.9. The receiver of this collector is composed of two absorber tubes constructed of 1-1/4-in. Schedule 160 steel tubing enclosed under a glass plate on the reflector side and an insulated box on the other three sides. Each absorber tube is electroplated with a black chrome selective coating.

The advantages of this unit are high mirror reflectance, stationary receiver, and a low thermal loss receiver. The disadvantages are a potential for breakage of the mechanically curved mirrors, large number of moving mirror segments, low thermal performance, high purchase price, and high installation costs.

3. Survey Summary

Of the seven candidate collectors discussed above, only five were determined to be production units. This determination was made when two of the seven either could not provide a quote on the purchase price of 10,000 ft² of collectors (in the case of the Honeywell unit) or a single module could not be supplied for the exposure test unit until a special production run could be made (in the case of the G.E. unit). The physical and performance characteristics of the remaining five collectors are summarized in Table II. The performance characteristics are given in the form of the absorptance coefficient and the loss coefficient which are indicated in the following equation:

$$\eta = F(\tau^{-\alpha})_e - U_1 \Delta T / I$$

where η = Efficiency
 $F(\tau^{-\alpha})_e$ = Absorptance coefficient
 U_1 = Loss coefficient
 ΔT = Temperature difference between the average fluid
 temperature and the surrounding air temperature.
 I = Direct normal solar radiation

The performance characteristics for each of the five candidate collectors is shown in Figure 12. These data were then used in the SOCOSIM computer program (a discussion of which is included in Appendix B of this report) to calculate the yearly output of 10,000 ft² of collector aperture with 80-ft long rows and a row spacing of two apertures. A summary of the results of these computer programs is shown in Table III. This table shows the collector output for each month of a typical San Antonio weather year.

To make a selection of the most cost-effective collector, the next step in the process was the estimation of the collector installation costs. This was accomplished by requesting quotes for the purchase of 10,000 ft² of each of the candidate collectors. These quotes had to be based on an assumed number of rows and row lengths. It will be shown later that the cost per square foot is effected by the number of collectors

TABLE II. PHYSICAL AND PERFORMANCE CHARACTERISTICS
OF THE CANDIDATE COLLECTORS

	<u>Acurex</u>	<u>Hexcel</u>	<u>Del</u>	<u>Solar Kinetics</u>	<u>Suntec</u>
Mirror Width	6 ft	9 ft	2 ft	7 ft	10.7 ft
Mirror Length	10 ft	20 ft	8 ft	20 ft	20 ft
Rim Angle	90°	72°	110°	90°	Fresnel
Reflectance	0.75	0.84	0.90	0.84	0.90
System Weight	5.9 lb/ft ²	3.5 lb/ft ²	7 lb/ft ²	3.7 lb/ft ²	-
Receiver Width	1.25 in.	1.5 in.	0.5 in.	1.63 in.	3.4 in.
Receiver Absorptance	.94	.94	.94	0.94	0.94
Receiver Emittance	.18	.18	.18	0.18	0.18
Drive Mechanism	Worm & Worm Gear	Chain & Sprocket	Worm & Worm Gear	Hydraulic	Chain & Linbase
Tracking System	Acurex	Delavan	Delavan	Delavan	Suntec
Concentration Ratio	58	72	48	52	38
Absorptance Coefficient	0.63	0.69	0.72	0.7	0.68
Loss Coefficient	0.093	0.088	0.046 ₁ 0.040 ₂ -0.002 ₃	.075	.119

*Loss coefficients for the Del collector are
for a third-order correlation, i.e.,

$$\eta = 0.72 - 0.046 (\Delta T/I) - 0.040 (\Delta T/I)^2 + 0.002 (\Delta T/I)^3$$

FIGURE 12. INSTANTANEOUS COLLECTOR PERFORMANCE

TABLE III. COLLECTOR PERFORMANCE SUMMARY IN MILLIONS OF
BTU's FOR A 10,000-FT² COLLECTOR FIELD
OPERATING AT 400°F

<u>Month</u>	<u>Acurex</u>	<u>Hexcel</u>	<u>Del</u>	<u>Solar Kinetics</u>	<u>Suntec</u>
Jan	75.6	89.0	71.1	102.8	54.9
Feb	98.4	114.8	104.6	129.5	82.6
Mar	174.4	201.6	192.2	220.6	158.1
Apr	195.6	225.1	214.5	242.6	186.8
May	210.1	242.4	228.2	260.5	205.2
Jun	259.2	297.1	289.6	316.9	256.6
Jul	296.9	339.2	337.3	360.6	295.8
Aug	255.7	292.3	288.7	311.9	251.3
Sep	201.1	230.3	225.9	248.6	188.8
Oct	155.3	178.8	168.5	196.8	136.3
Nov	104.6	120.3	110.5	134.6	85.4
Dec	<u>71.2</u>	<u>83.7</u>	<u>68.6</u>	<u>96.4</u>	<u>50.9</u>
Total	2098.1	2414.6	2299.7	2621.8	1952.7

per row since the longer the row the less drive hardware required per square foot. In addition to the purchase price of the collectors, the installation costs, roof modification costs, and piping costs were all estimated and combined to obtain the total installed cost of the collector field. A list of these costs for each of the collectors is shown in Table IV.

There are two different methods for determining the most cost-effective collector. The first method is to compare the ratio of installed collector costs to thermal efficiency for the different collectors as a function of the collector operating parameter*, as shown in Figure 13. This method shows that the collector manufactured by Solar Kinetics is the most cost-effective collector available under all conditions. The second method compares the total dollars per million Btu's for each collector by estimating the total Btu output of each collector over its predicted life and estimating the installed costs for each collector. This was done by assuming a ten-year life for each of the five collectors. A list of cost per million Btu is shown in Table V. This method also indicates that the Solar Kinetics collector is the most cost-effective candidate collector. It must be pointed out, however, that it was assumed that the maintenance and operating costs of all of these collectors is essentially the same. Since there is no reason to expect the maintenance and operating costs of the Solar Kinetics T-700 to be any greater than any of the other candidate collectors, this unit was selected for this application.

B. Solar Kinetics T-700

The Solar Kinetics T-700 has been chosen as the most cost-effective concentrating solar collector for the present application outlined above. This collector unit is a parabolic trough collector manufactured in 10-foot and 20-foot long modules. These modules are connected together to form rows of 80 to 120 feet. Each row tracks the sun about an axis just below the vertex of the parabolic trough. The tracking actuator is located at the center support pylon and mirror modules are connected through the use of flanges and shafts mounted to self-aligning pillow block ball bearings. The connecting drive pins are also the receiver tube stands and at each inner bearing there is a load bearing universal joint to eliminate any bind in the tracking rotational axis.

The mirror module is constructed using the well developed and tested Solar Kinetics "monocoque-stressed skin" technique. This form of fabrication provides the best strength to weight ratio and the parabolic shape provides excellent torsional rigidity.

The 1-5/8-in. carbon steel receiver tube is plated with black chrome and covered by a Pyrex (7740) glass tube. The entire assembly is mounted to the receiver tube stand through a unique, fully adjustable clamp.

* Deffenbaugh, D. M., and Carper, H. J., "Cost-Effective Selection of Flat-Plate Solar Collectors," Proceedings of 1977 Flat-Plate Solar Collector Conference, 1977. (A copy of which is included in Appendix C.)

** Information on this product extracted from manufacturer's literature courtesy of Solar Kinetics, Inc.

TABLE IV. ESTIMATED INSTALLED COLLECTOR FIELD COSTS PER FT²

<u>Collector Manufacture</u>	<u>Purchase* Price</u>	<u>Installation Cost</u>	<u>Roof Modification</u>	<u>Piping Cost</u>	<u>Total</u>
Acurex	23.85	2.50	3.00	3.00	32.35
Hexcel	19.50	3.00	3.00	3.00	28.50
Jacobs-Del	20.50	3.20	4.00	6.00	33.70
Solar Kinetics	19.00	2.00	3.00	3.00	27.00
Suntec	23.00	2.80	3.00	3.00	31.80

* Including freight, tracking system, and flexible hose connection.

FIGURE 13. COST-EFFECTIVE INDICATOR FOR THE CANDIDATE COLLECTORS

TABLE V. ESTIMATED DOLLARS PER MILLION BTU FOR A 10,000-FT²
COLLECTOR FIELD ASSUMING A 10-YEAR LIFE

<u>Collector Manufacture</u>	<u>Total Unit Cost, \$/ft²</u>	<u>Yearly Collector Output, 10⁶ BTU</u>	<u>\$/10⁶ BTU</u>
Acurex	32.35	2048.1	15.42
Hexcel	28.50	2414.6	11.80
Jacobs-Del	33.70	2299.7	14.65
Solar Kinetics	27.00	2621.8	10.30
Suntec	31.80	1952.7	16.29

The receiver tube is fully floating with linear as well as rotational freedom. Each end is terminated with an expansion bellows which is connected to a flexible insulated hose. The hose assembly is connected to the pylon support at each end of the row where it connects to either a crossover pipe or the manifold plumbing.

The air annulus in each receiver assembly is plumbed together and an outlet fitting is provided at the center to allow air expansion through a dessicator.

The reflective surface is an aluminized second surface acrylic sandwich bonded to the mirror sheet metal surface. This film has demonstrated up to 84% specular reflectivity and excellent weather resistance for seven years.

Solar tracking is effected through the use of a solid state electronic differential shadow bar device. Accurate tracking has been accomplished with this device. The tracking actuator developed at Solar Kinetics is unique in that it eliminates backlash in the tracking system. Backlash becomes a serious problem with most mechanical trackers since continued wind buffeting wears gears and mechanical drives.

1. Collector Features

a. Short Focal Length

The true test of a parabolic trough collector's efficiency is not the instantaneous efficiency at solar noon, but rather the all-day efficiency curve. In the early and late hours of the day, (for an east-west orientation) losses are experienced due to the cosine effect of the angle of the sun, but in addition to those losses, rapidly increasing focal lengths cause reflective errors greater than the diameter of the receiver tube. These losses are unavoidable when focal lengths are chosen which require mirror accuracy beyond reasonable construction limits.

b. Light Weight

This unit module (20 ft) weighs approximately 3.7 lb per ft² of aperture area. This includes the mirror, receiver tube, pylon and bearing assembly.

c. Reflective Surface

The reflective surface is 3M's FEK-244 with average specular reflectivity of 84%. Solar Kinetics has conducted weather testing for two years on 3M 5400 and 18 months on FEK films with less than 4% specular loss and no other unsatisfactory changes have been observed. The samples were tested in Dallas, Texas, from ambients of 10°F to 110°F, which included snow and hail.

d. Hail Resistance

Twenty-five percent of the reflective surface is T-6 aluminum extrusion which is hail proof. The balance of the surface is T-6 x 0.040 in. aluminum sheet which provides far greater protection than 0.040-in. ALZAK which was accepted by Sandia's solar pumping facility (1) as hail resistant. ALZAK (2) is not tempered and has a much lower yield than T-6 heat treated aluminum.

e. Flow Friction

A receiver tube plug was omitted although a slight increase in performance can be experienced due to fluid velocity increase. This increase is offset by increased pumping loads. The T-700 requires less than 4 psi per 100 ft of collector when pumping 5 gpm of Therminol 66 @ 200-450°F. Lower flow friction allows longer pumping runs and eliminates problems in plumbing large collector layouts.

f. Angular Misalignment

This feature, not found on other parabolic trough collectors will prevent tracking drive loads which develop due to shifting of the pylon base. Installation misalignments also will not cause a bind on the tracking drive mechanism. Should the ground or building under the T-700 shift, the collector will continue to operate at misalignments of up to 5°.

g. Receiver Tube

The reflective surface focuses sunlight onto the receiver tube which is O.D. 16-gauge steel tubing. The selective surface is black chrome on a nickel substrate with absorptivity of .94 and emissivity of .18. The receiver tube is insulated by a 2-in. I.D. Pyrex glass tube. The annulus between the receiver and the glass jacket can be evacuated or filled with Argon gas. Each annulus is connected in series to enable evacuation or gas purging. Should a vacuum leak contaminate the annulus with moisture, the tube can be purged without removal of assembly. Receiver removal can be accomplished by loosening two fittings.

h. Material of Construction

The use of precision machined, cast, aluminum bulkheads, extruded aluminum edge formers, and monocoque sheet metal construction was based primarily on the desire to provide long unit life in the initial stages of solar energy equipment development. The torsional rigidity of this structure is exceptionally high and quality control for the components of this system of construction can be effective through known techniques. The T-700 should withstand wind loads in excess of 90 mph at any focal position.

(1) Sandia Laboratories, Solar Irrigation Project at Willard, New Mexico.

(2) Aluminum Company of America chemically polished and oxidized aluminum.

i. Production

Of the initial design considerations, ease of production increase was considered heavily. Assembly of the T-700 mirror section is accomplished entirely through the use of hand tools and does not require elaborate jigs or fixtures. Production rates can be altered without large expenditures.

j. Solar Tracking

The T-700 can accept analog signals from any type tracking demand control system whether it be microprocessor with precision shaft encoders or differential shadow bar devices. We have chosen the latter as being the most cost-effective. This system has been found to perform well on clear as well as cloudy days. Hydraulic tracking actuation has been chosen for several reasons. All mechanical tracking mechanisms will develop backlash when exposed to continuous wind buffeting loads. Hydraulics eliminates this type of backlash as well as providing a slight cushioning effect to sudden loads. Repair and maintenance to the hydraulic components need not cause lengthy down time since the components can be readily replaced and repaired in the shop. Tracking speeds are adjustable by the operator. Slow speed is independently adjustable through the use of bypass solenoid valves. Long-run trough windup can be eliminated by positioning several actuation assemblies (@ 100 ft) and plumbing the hydraulics in parallel. Each collector row is controlled by an electronic solar position indicator which generates analog signals for direction. When sunrise provides sufficient insolation for system startup, a light switch located at the central control panel provides power to the electronic trackers and each row will track from its inverted "stow" position. Tracking continues until the shadow cast from the shadow bar on the tracker is equal on both of the light-sensitive transistors. As the sun moves, the tracker maintains this shadow "deadband" and accurate tracking is accomplished. A hazard-stow relay is provided which will drive the row to the "stow" position should any of the field contact closure devices cause the circuit to the hazard relay coil to lose power. Loss of AC power, nightfall, over temperature fluid condition, high winds, rain, or insufficient flow will cause the collector to defocus by eliminating the automatic tracker and providing a direct stow signal to the drive pylon.

k. Maximum Operating Temperature

Heat transfer fluids are suggested since high pressures are avoided. Teflon hoses and insulators are used on the T-700 and this material limits the operating temperature to 500°F. Replacement with alternate insulators and all metal hoses allows temperatures up to 650°F.

l. Maintenance

The narrow aperture of the T-700 increases ease of maintenance. The greatest number of hours required for maintenance will be the cleaning of the reflective surface and glass receiver tube cover. All cleaning operations can be accomplished from ground level. The receiver tube assembly may be removed by four bolts and two hydraulic

fittings. The mirror may be removed by eight bolts. The tracking drive system is modular and all components may be replaced with a minimum of down time. Hydraulic repair kits are relatively inexpensive. Solar Kinetics has developed a complete cleaning maintenance program involving in-house developed chemicals. It is proposed to clean the surface with high-pressure washers including special antistatic, chelating agents along with rinse agents to prevent spotting. Mechanical cleaning of the acrylic surface on the FEK film is to be avoided due to scratching and resultant reduction of specular reflectivity.

2. Collector Characteristics

A photograph of the Solar Kinetics collector is shown in Figure 14. The photo illustrates the high quality of construction of this collector unit. The rigidity of the reflector frames and the structural supports all indicate that this unit is one that will last. A pictorial representation of four collector rows in parallel is shown in Figure 15 with a typical spacing and row length. A list of special features of this collector is shown in Table VI. The technical specifications for the T-700 collector are enumerated in Table VII. Figure 16 gives an indication of the scale of these collector units. A plot of thermal efficiency versus average collector temperature is shown in Figure 17 and indicates a thermal efficiency of over 60% at temperatures out to 400°F. An efficiency versus direct normal insolation plot is shown in Figure 18 for 200°F and 500°F. The pumping loss through a 100-ft receiver and two hose assemblies is shown in Figure 19 with a Therminol T-66 fluid at 390°F. The pylon and support stud details are shown in Figure 20. Wind load calculations for the T-700 are outlined in Figure 21 and Table VIII.

3. Installation Instructions

The installation procedure for the T-700 consists of the following steps:

- Installation and alignment of the support pylons.
- Fastening and alignment of the mirror modules.
- Installation and adjustment of the receiver tube assembly and hoses.
- Connection of the electrical controls and hydraulic power supply plumbing.

The installation and alignment of support pylons should be the initial step in the field installation. The roof mounted support pads shall be prepared to accept the pylon bolt pattern and spacing. The double nut technique is used to fasten the bottom of the support pylons and allow for adjustment and alignment. The pylons should be installed and aligned with a standard transit or other suitable optical instrument. Care should be taken to obtain a true line of sight through the center of the axis of rotation. While the parallel alignment of each row is desirable, the

FIGURE 14. SOLAR KINETICS HIGH-TEMPERATURE CONCENTRATING COLLECTOR

FIGURE 15. T-700 SOLAR COLLECTOR PYLON BASE LAYOUT

TABLE VI. T-700 SPECIAL FEATURES

High Efficiency
High Outlet Temperatures
High Strength to Weight Ratio
Monocoque Construction*
High Wind Load Resistance
Hydraulic Tracking with Zero Backlash*
Adjustable Tracking Speed
Adjustable Stow Speed
Angular Misalignment Compensation
Ease of Assembly (Lower Installation Cost)
Ease of Maintenance (Lower Maintenance Cost)
Sealed Receiver Gas Annulus (Longer SS Life)
Vacuum or Gas Purging of Receiver Annulus
Quality of Workmanship
Long Life Durability
Large Module Requires Fewer Support Structures
Low Cost Mirror Film Replacement
Corrosion Resistant Materials
Company Owned Transportation Equipment

*PATENTS PENDING

TABLE VII. T-700 TECHNICAL SPECIFICATIONS

Module Width	94"
Module Length	10' or 20'
Mirror Width	86"
Solar Area ft ²	72 or 144
Mirror Reflectance	0.84
Mirror Shape	90° Parabolic
Max. Height (vertical)	100"
Mirror Orientation	E/W or N/S
Max. Tracking	210°
Stow Angle	45°
Rotation Axis Height	53"
System Weight	3.7 lbs./ft ²
End Pylon Static Load	260 lbs.
Center Pylon Static Load	520 lbs.
Pylon Base Mount Bolts	4-1" @ 12" c-c
Pylon Spacing c-c	246" & 126"
Row Spacing c-c	13'-4"
Max. Row Length	120'
Receiver Tube	1-5/8" Carbon Steel
Selective Surface	Black Chrome
Absorbtivity	0.94 - 0.97
Emissivity (400°F)	0.12 - 0.18
Receiver Cover	Pyrex Glass (7740)
Cover Transmissivity	0.91
Annulus Size	0.25"
Annulus Medium	Argon or Vacuum
Pumping Loss (T-66)	4 psi/100' @ 5 gpm
Plumbing Connections	1" Std. Pipe
Max. Operating Temp.	500°F
Max. Operating Pressure	250 psi

FIGURE 16. RELATIVE SCALE OF THE T-700

FIGURE 17. T-700 SOLAR COLLECTOR
EFFICIENCY VS TEMPERATURE

FIGURE 18. T-700 SOLAR COLLECTOR
EFFICIENCY VS INSOLATION
@ 200°F AND 500°F

FIGURE 19. T-700 PUMPING LOSS THROUGH 100-FT RECEIVER AND TWO HOSE ASSEMBLIES

FIGURE 20. T-700 PYLON AND SUPPORT STUD DETAILS

$+L_f$ = lift force

$-L_f$ = down force

θ = pitch angle

Y = yaw angle

D_f = drag force = C_d (psf)(area)

L_f = lift force = C_l (psf)(area)

T_m = torque = C_{mw} (chord)(psf)(area)

Bolt force = $\frac{D_f(H) + T_m}{2(X)} + \frac{L_f}{4}$

θ	Y	C_d	C_l	C_{mw}
-45°	0°	1.4	1.0	0.1
0°	0°	1.0	0	0
60°	0°	0.78	-1.5	0.14
120°	0°	0.5	0.1	-0.28
120°	40°	0.78	0	0.55
180°	0°	1.6	0	0
225°	0°	0.78	0	-0.2

Unit	$\frac{Ft^2}{Area}$	in. H	in. X	Chord
T-700(10)	72	53	12	7.0'
T-700(20)	144	53	12	7.0'

FIGURE 21. T-700 WIND LOAD CHARACTERISTICS

TABLE VIII. T-700 WIND LOAD CALCULATIONS

PSF = 22 @ 90 mph

H = 53" or 4.4'

X = 12" or 1'

ASSUME:

 $\theta = -45^\circ$ (stow)

Pylon = Drive unit

 $D_f = C_d$ (psf) (area) = 1.4 (22)(144) = 4,435 lbs. $L_f = C_l$ (psf) (area) = 1.0 (22)(144) = 3,168 lbs. $T_m = C_{mw}$ (chord) (psf) (area) = 0.1 (7)(22)(144x3) = 6,653 ft. lbs.

$$\text{Bolt Force} = \frac{D_f(H) + T_m}{2(X)} + \frac{L_f}{4} = \frac{(4435)(4.4) + 6653}{2(1)} + \frac{3168}{4}$$

Bolt Force = 13,876 lbs.

Pylons = all others

 $D_f = 4,435$ lbs. $L_f = 3,168$ lbs. $T_m = 0$

$$\text{Bolt Force} = \frac{(4435)(4.4) + 0}{2} + \frac{3168}{4} = 10,549 \text{ lbs.}$$

 $\theta = 120^\circ$

Pylon = Drive

 $D_f = 0.78$ (22)(144) = 2,471 lbs. $L_f = 0$ $T_m = 0.55(7)(22)(144x3) = 36,590$ ft. lbs.

$$\text{Bolt Force} = \frac{2471(4.4) + 36,590}{2} + \frac{0}{4} = 23,731$$

Assume Wind Loads for Fields to be 67% of Stand Alone Collector Wind Tunnel Data Extensions:

Maximum $D_f = 3,000$ lbs.Maximum $L_f = 2,100$ lbs.Maximum $T_m = 24,500$ ft. lbs..

Maximum B.F. = 16,000 lbs.

exactness of orientation is not critical. Also exact levelness of the row is not critical but is suggested that the pylons be shot level and straight to the next row whenever possible. When the pylons are aligned and tightened to the foundations the mirror modules are ready for installation. The drive pylon should be in the stow position and filled with hydraulic fluid to prevent rotation.

The mirror modules are installed to the drive pylon first and then to the end of each row. An intermediate bearing assembly is bolted to one end of the mirror module with the receiver tube stand on the mirror side. The module is then lowered into position and the bearing bolted to the first standard pylon while the other end is bolted to the drive flange. The procedure is repeated for each module out to the end of the row where an end bearing assembly is attached to the end pylon. Care should be taken to align the modules rotationally. The bolt holes are sufficiently oversized to provide some adjustment. The counter-weights may be bolted to the end of each mirror module before or after installation. The counter-weight attaches with two 1-in. bolts and weighs approximately 90 lbs.

The third step in the installation of the collector field is the installation and adjustment of the receiver tube assembly and hoses. The center receiver tube stand is attached with four bolts and the intermediate receiver tube stands are inserted through the mirror module body and fastened with a nut on the back side. Receiver stands are at 10-ft spacing and the receiver adjustment brackets are installed into each stand with one bolt and two nuts. The bolt allows height adjustment while the slotted bracket provides side adjustment. Each bracket should be adjusted to put the center of the receiver at the center of the focus. That point is in the center from each edge of the collector and 22.157-in. up from the bottom of the mirror. A simple pattern or fixture will allow rapid adjustment. Each receiver tube connects to the next with a union that tightens with two wrenches. The glass jacket "O" ring retainer slips over the receiver and is spaced every 10-ft to correspond to the stand and bracket. Two glass tubes are suspended on each receiver tube by the silicone "O" rings, and the entire assembly is clamped to the bracket. The two center receiver tubes should be installed to the special union attached to the central receiver tube stand and then out to the end of each row. The hoses are fastened to the tube with a union and the expansion bellows are clamped in place. The lower end of the hose assembly is attached to the end pylon with the hose bracket. Each receiver assembly should be pressure tested for leaks at this point.

The last step in the collector field installation process is the connection of the electrical controls and hydraulic power supply plumbing. The shadow bar tracker bracket is bolted onto the collector next to the drive pylon. The shadow bar sensor is bolted to the bracket and aligned lengthwise with the collector. The hydraulic power supply is plumbed in parallel to each drive pylon and connected to the hydraulic fittings at the bottom of each control box. Stainless steel tubing is suggested and manifold tubing size should be considered for long runs to avoid pressure drop. Stainless tube of 3/4-in. diameter is usually adequate for lengths up to 200 feet. Cold weather conditions should be

considered and appropriate hydraulic fluid used. The manifold tube size should be selected based on the pressure drop during cold weather operation. The control wiring should be routed to each drive pylon control box and appropriate connections made. After all plumbing connections have been accomplished and fluid is flowing through the receiver, the collector automatic focus command may be given. The angular adjustment of the shadow bar tracker is then changed until the receiver is focused to the center of the reflected light. Slight "tweaking" adjustments may be made at each bracket for fine focus. Caution should be taken never to focus the receiver without fluid flow.

The estimated labor-hours required to perform the above installation are as follows:

	Labor-Hours	
	Per Row	Per System*
Align and install one row of pylons (6)	8	120
Install five mirror modules	8	120
Install five counter weights	3	45
Install hydraulic lines-per row	1.6	24
Connect hydraulics at drive pylon per row	0.5	7.5
Install receiver assembly-per row	4	60
Install two hose assemblies	2	30
Assemble tracker components (control) per row	4	60
Focus receiver assy. - per row	2	30
Shake down per row	2	30
System shake down (9450 ft ²)		24
Wire control panel-per system		24
Plumbing of hydraulic power supply		12
Miscellaneous Wiring		6
Total		592.5

4. Mirror Cleaning Instructions

As with any optical system, solar collectors operate best when components of the system are clean. The Factory recommends periodic rinsing of the mirror surface and receiver cover with deionized water. If weather conditions permit, exposing the mirror surface to mild rainfall will also reduce dust accumulations. Depending on conditions, the following detergent cleaning procedure should be used biannually or quarterly. Clean with a pressure washer with a nozzle pressure of 400-800 psi. The Malsbary C-310 is recommended. Detergent use solution should be 0.1-0.3% active detergent at the washer nozzle. This detergent level creates a moderate sudsing action. Excessive detergent solution should be avoided. The detergent should be a non-ionic bio-degradeable type such as Union Carbide UCON 15-5-9, Rhom & Haas Triton X-100, or Jefferson Surfonic N-95. These detergent liquids are non-drying for thorough rinsing. Under no conditions should any detergent solution be allowed to dry on the mirror before rinsing. A deionized water rinse should immediately follow the pressure wash. The Factory does not recommend any phosphate or silicate based detergent systems. There should be no mechanical agitation of the mirror surface, i.e., no mopping or wiping of the mirror. In addition, the pressure wash spray should be kept near a 90° angle with the mirror and the spray not directed at low

* Assuming 15 rows

angles against the edges of the applied film. The water temperature should not exceed 120°F. The receiver cover should be hand wiped using good glass cleaning practice.

5. General Maintenance Instructions

At yearly intervals the pillow block bearings and universal joints should be greased with a lithium base short fibre bearing grease. Sufficient grease should be injected to cause a slight flow past the bearing seals. Glass tubing should be inspected monthly for clearance with the receiver tube brackets. The glass should not contact any metal portion of the bracket or clamp. Aluminum shields should cover the O-ring portion of the assembly. The phototransistors in the tracking sensor heads should be wiped free of dust with a soft cloth at quarterly intervals. Batteries supplied are calcium chloride type and are maintenance free. The terminals should be checked occasionally for corrosion and cleaned if required. Hydraulic fluid level should be checked monthly. The hydraulic fluid filter should be changed yearly.

6. Materials Degradation

The durability of the materials of construction for the T-700 collector is excellent with the possible exception of reflector coating. This coating is an acrylic film manufactured by the 3M Corporation. The estimated degradation of absorber coating, transparent absorber cover, and the reflector surface are shown in Figure 22 as a function of years exposed to ambient weather.

C. Optimum Collection Field Size

The collector field will be located on the roof of the canning warehouse as indicated by the A in Figure 23. A close-up view of this roof is shown in Figure 24. The dimensions of this roof are 201-ft - 8-1/2-in. by 100-ft with the longer dimension oriented in the east/west direction. The roof is constructed with bar joist running in the north/south direction spaced on 13-ft - 4-in. centers. These bar joists are supported by I-beam girders at the north and south walls plus a single girder down the middle of the building supported on columns.

It was determined that a savings in support structure cost could be made by placing the collector rows directly over the roof bar joists. To investigate the cost-effectiveness of this arrangement, roof support structure modifications were designed for four different cases. These test cases are summarized in Table IX. In addition to the row spacing trade-offs, it was also determined that the purchase price of the Solar Kinetics T-700 was effected by row length and module length. The cost per square foot was greater for the 10-ft modules than the 20-ft modules, so a trade-off was conducted to determine if a 90-ft long row with four 20-ft long modules and one 10-ft long module was more cost-effective than an 80-ft long row with four 20-ft long modules. The trade-off analysis was conducted by first calculating the yearly thermal performance of each of the four test cases and then estimating the total system cost including

FIGURE 22. MATERIALS DEGRADATION ESTIMATES

FIGURE 23. AERIAL PHOTOGRAPH OF LONE STAR'S INDUSTRIAL PLANT SITE LOOKING SOUTHWEST

FIGURE 24. A VIEW LOOKING DOWN AT THE ROOFTOP OF THE WAREHOUSE WHERE THE PROPOSED COLLECTORS WILL BE INSTALLED

TABLE IX. ESTIMATED SUPPORT FRAME COSTS FOR DIFFERENT
COLLECTOR FIELD CONFIGURATIONS

<u>Number of Rows</u>	<u>Row Length</u>	<u>Row Spacing</u>	<u>Collector Field Size, ft²</u>	<u>Total Estimated Cost</u>	<u>Support Cost Per Square Foot</u>
15	90'	13'-4"	9,450	\$27,540	\$2.91
15	80'	13'-4"	8,400	\$23,540	\$2.80
16	90'	12'-5½"	10,080	\$29,680	\$2.94
16	80'	12'-5½"	8,960	\$25,280	\$2.82

pumps, pipes, and heat exchangers. The cost of the collectors was found to change with row length which made the cost per square foot rise slightly above the value quoted in the original quotation. This collector was, therefore, re-evaluated with respect to the other candidate collectors and was still found to be more cost-effective. The 80-ft rows were quoted at \$20.50/ft² and the 90-ft rows were quoted at \$20.80/ft². If the 90-ft long row cost is used to re-compute the dollars per million Btu over a ten-year life, this value was raised from \$10.30/MBtu to \$10.98/MBtu which is still below any of the remaining candidate collectors.

The next step in this analysis was to estimate the below roof component and construction cost which includes the pumps, piping, unfired boiler, and labor to install this equipment. These costs are estimated to be about \$30,000 which is added to the above roof cost to obtain the total estimated system cost. A summary of the total yearly energy collected and the total estimated system costs along with an estimated \$/MBtu over a ten-year life are shown in Table X.

This analysis shows that the most cost-effective collector field configuration is the one with fifteen 90-ft long rows on 13-ft - 4-in. centers to give a total aperture area of 9450-ft². It should also be pointed out that the possibility of proposing a ground mount system was investigated but the cost of purchasing the land was greater than the estimated difference between a ground-mounted support structure and a roof-mounted support structure. The roof-mounted support structure also provides a lower cost for system piping and insulation. The thermal performance of the total system is also increased due to a decrease in thermal losses in the piping system as well as a decrease in operating expense due to a decrease in pump horsepower because of a lower required head. One last item concerning the roof-mounted system, the cost of the roof modification and support structure is estimated to be \$2.91/ft² while the difference in purchase price between candidate collectors is as much as \$4.85/ft² in the original quotes; therefore, the argument over roof-mount versus ground-mount is insignificant if the remainder of the system design is not optimized.

The next step in the system optimization will be the determination of the collector field piping arrangement (series versus parallel versus series/parallel). This analysis will be conducted to optimize the size of the collector field pump and the size of the solar-fired boiler. This optimization will be conducted in the detailed system design phase of the project and the results of which will be included in the 80% design review report.

TABLE X. TRADE-OFF ANALYSIS FOR DIFFERENT COLLECTOR
FIELD CONFIGURATIONS.

<u>Collector Field Size, Ft²</u>	<u>System Cost Per Square Foot</u>	<u>Yearly Collector Performance, 10⁶Btu/Yr</u>	<u>\$/10⁶ Btu*</u>
9,450	31.88	2369.7	12.713
8,400	31.87	2103.8	12.725
10,080	31.72	2466.0	12.966
8,960	31.67	2189.2	12.962

* For a ten year life and a
cost for the pump, piping
and heat exchange of \$30,000.

V. HEAT TRANSFER FLUID SELECTION

A. Fluid Survey

Numerous heat transfer fluids are available with physical properties applicable to this application. However, the selection of the collector field heat transfer fluid for this project must consider that the industrial process is a food industry. It is, therefore, required that the toxicity of the different fluids also be evaluated in any selection process, and that once a fluid is selected, this fluid must then be submitted to the industrial partner at Lone Star Brewery for approval. If an acceptable heat transfer fluid cannot be found, then a pressurized water system will be incorporated even though it is estimated to be more costly.

A survey was conducted and 23 heat transfer fluids were identified. A listing of these fluids, along with the physical characteristics, cost, and toxicity of each, are shown in Table XI. The price per gallon is based on quotes for supplying the fluid in quantities of 400 gallons. The list of candidate fluids can be shortened initially by observing the useful temperature range assuming an unpressurized system. The useful range must extend from about 20°F to 500°F, so that the number of potential candidates is reduced from 23 to 11. The physical properties of the fluids that impact on the design of the fluid handling system are viscosity, density, thermal expansion, specific heat, freeze point, flash point, and autoignition temperature. The first four of these properties will determine the equipment sizing of the pump, heat exchanger, and expansion tank, while the last three are items effecting safety. The final two items in the table are indicators of fluid toxicity.

The term LD₅₀ signifies that 50% of the animals in a controlled test who were given the specified oral dosage died. For example, a 150-lb (70 kg) animal having an LD₅₀ of 15 g/kg would require the oral ingestion of 1050 g or 1.3 quarts to be fatal. The National Academy of Sciences Committee on Hazardous Materials has correlated these values of LD₅₀ with different levels of toxicity for human beings. The levels are as follows:

Nontoxic	-	LD ₅₀ > 15 g/kg
Practically Nontoxic	-	5 g/kg < LD ₅₀ < 15 g/kg
Slightly Toxic	-	0.5 g/kg < LD ₅₀ < 5 g/kg
Moderately Toxic	-	50 mg/kg < LD ₅₀ < 500 mg/kg
Toxic	-	LD ₅₀ < 50 mg/kg

These designations are included in the last column of Table XI.

If only fluids that are classified as nontoxic or practically nontoxic are further considered, the list of candidate fluids is shortened to seven fluids.

TABLE XI. HEAT TRANSFER FLUID PROPERTY SUMMARY

Fluid Specification	Supplier	Unit Cost (\$/gal)	Useful Temperature Range (°F)	Viscosity (cS)				Density (lb/gal)	Thermal Expansion (1/°F)	Specific Heat (Btu/lb-°F)	Freeze Point (°F)	Flash Point (°F)	Autoignition Temp. (°F)	LD50 (g/kg)	Toxicity
				0°F	100°F	200°F	400°F								
BRAYCO 888	Bray Oil Co.	4.56	-100 to 550	500	6.29	1.91	.5	6.7 @ 60°F	-	0.55	-80	325	-	-	-
Dowtherm A	Dow Chemical Co.	3.61	60 to 750	-	2.49	1.05	.42	7.54 @ 400°F	.00048	.5 @ 400°F	54	255	1150	4.0	Slightly Toxic
Dowtherm C	Dow Chemical Co.	3.70	-20 to 700	-	13.6	2.86	.71	8.02 @ 400°F	.00047	.48 @ 400°F	<20	305	1030	4.0	Slightly Toxic
Dowtherm LF	Dow Chemical Co.	3.60	-25 to 600	23.4	2.94	1.02	.42	7.47 @ 400°F	.00053	.514 @ 400°F	<-25	260	1020	4.0	Slightly Toxic
Dowtherm J	Dow Chemical Co.	5.46	-100 to 575	2.0	.824	.471	.20	5.90 @ 400°F	.00065	.545 @ 400°F	<-100	145	806	4.0	Slightly Toxic
Siltherm 444	Dow Corning Corp.	21.12	-50 to 350	55	15.0	7.3	2.9	7.0 @ 300°F	.00060	.42 @ 392°F	-50	450	-	0.5	Slightly Toxic
Drewsol	Drew Chemical Co.	15.25	-28.5 to 230	-	16.0	5.8	-	9.27 @ 200°F	.00020	.87	-28.5	None	-	-	-
Caloria HT-43	Exxon Corp.	1.41	15 to 600	-	40.0	7.0	1.5	7.16 @ 60°F	.00029	.60 @ 400°F	15	425	750	10.0	Practically Nontoxic
H-30-C	Marks Enterprises	5.00	-40 to 620	310	17.0	4.3	-	6.96 @ 100°F	.00045	.50	-40	370	-	34.6	Nontoxic
H-30	Marks Enterprises	5.40	-40 to 560	1,500	29.0	5.5	-	6.96 @ 100°F	.00033	.57	-40	310	-	34.6	Nontoxic
Sunsafe 100	NPD Energy	3.78	0 to 222	-	1.52	.55	-	8.75 @ 60°F	.00028	.87 @ 60°F	0	None	-	0.5	Slightly Toxic
Sunsafe 130	NPD Energy	5.32	-30 to 230	-	2.24	.75	-	8.92 @ 60°F	.00030	.80 @ 60°F	-30	None	-	0.5	Slightly Toxic
Sunsafe 200	NPD Energy	3.85	0 to 218	-	1.94	.58	-	8.59 @ 60°F	.00030	.92 @ 60°F	0	None	-	30.0	Nontoxic
Sunsafe 230	NPD Energy	5.46	-30 to 225	-	3.27	.91	-	8.67 @ 60°F	.00034	.86 @ 60°F	-30	None	-	30.0	Nontoxic
Therminol T-44	Monsanto	3.20	-60 to 425	125	2.7	1.3	.85	7.67 @ 100°F	.00045	.476 @ 100°F	-80	405	705	13.0	Practically Nontoxic
Therminol T-55	Monsanto	3.15	0 to 600	1,400	26.9	4.85	1.03	7.32 @ 100°F	.00049	.472 @ 100°F	-40	350	675	15.8	Nontoxic
Therminol T-60	Monsanto	1.30	-60 to 600	65	4.9	1.75	.62	8.33 @ 100°F	.00046	.450 @ 100°F	-90	310	835	13.0	Practically Nontoxic
Therminol T-65	Monsanto	3.85	0 to 650	50,000	30.0	4.3	.97	8.34 @ 100°F	.00039	.380 @ 100°F	-18	355	705	10.2	Practically Nontoxic
Sun-Temp	Resource Tech. Corp.	3.75	-40 to 500	563	12.0	2.48	.90	7.5 @ 72°F	.00040	.56	-40	380	824	44.9	Nontoxic
Thermia 33	Shell Oil Co.	1.87	20 to 550	-	50.0	7.2	2.0	7.33 @ 60°F	-	.56 @ 300°F	+10	455	-	-	-
Sunsol 60	Sunworks	5.83	-20 to 228	38	6.7	-	-	8.64 @ 60°F	-	-	-20	-	-	-	-
UCAR 17	Union Carbide	3.90	0 to 350	57	10	-	-	9.4 @ 68°F	.00034	.56 @ 68°F	0	260	-	-	-
PAO-13C	Unifroyal	7.50	-40 to 400	5,000	100	14	2.5	6.90 @ 68°F	.00042	.50 @ 68°F	-55	555	N.A.	32.0	Nontoxic

On a subjective basis, the factory representatives for each fluid were consulted and they suggested the Marks H-30-C over H-30 and the Therminol T-55 over T-60 and T-66 so that the candidate fluids are:

1. Caloria HT-43 @ \$1.41/gal (practically nontoxic)
2. Marks H-30-C @ \$6.00/gal (nontoxic)
3. Therminol T-55 @ \$3.15/gal (nontoxic)
4. Sun-Temp @ \$3.75/gal (nontoxic)

The Caloria HT-43 is the only one of the above fluids that is classified practically nontoxic, but the price of this fluid is so attractive that it will be included in further analyses. The next step in the selection process is the submission of test samples of each of the four fluids to the Lone Star Brewery for evaluation. This evaluation process has not yet been completed, so a tentative selection will be made to continue with the design process. Of the fluids that are classified as nontoxic, the most cost-effective selection is the Therminol T-55 at \$3.15/gal. This fluid will, therefore, be used for design purposes until the chemical evaluations are completed.

B. Therminol T-55*

1. Physical Properties

Therminol T-55, marketed by the Monsanto Company, has an operating range of 0°F to 600°F and a pour point of -40°F. This fluid offers good viscosity characteristics with minimum pumpable temperatures of -5°F for a centrifugal pump and -10°F for a positive displacement pump. A list of physical properties for Therminol T-55 is given in Table XII, and a list of property variations with temperature is given in Table XIII. The pressure drop characteristics for this fluid are shown in Figure 25, plotted as Δp in psi per 100 ft of pipe at a fluid temperature of 600°F versus flow rate in gallons per minute. For calculations on the heat exchanger, Figure 26 shows the convective heat transfer film coefficient in Btu/hr-ft²-°F at a fluid temperature of 600°F as a function of flow rate in gallons per minute.

2. System Design, Safety, and Handling

Therminol T-55 is designed for use in nonpressurized, indirect heating systems, where it delivers efficient, dependable process heat with no need for high pressures or costly venting equipment. Since this fluid is not classified as fire-resistant, the use of protective devices will be considered during the detailed system design process. To minimize fluid oxidation, the fluid expansion tank will be blanketed with an inert atmosphere and a pressure relief valve. This fluid offers long service life within its recommended operating temperature range. A thermal life prediction test has been conducted which indicates a life of 45 years for continuous 24-hr per day use when used in systems operating below 500°F. Therminol T-55 is noncorrosive to metals commonly used in the design of process heat systems; therefore, no special materials are required when

* Information on this product extracted from Therminol Fluid Heat Systems, A Design, Operating, and Maintenance Guide for Low-Cost, Low-Pressure Heat Transfer, Monsanto Industrial Chemical Co.

TABLE XII. THERMINOL T-55 PHYSICAL PROPERTIES

Composition	-	Synthetic Hydrocarbon Mixture
Appearance	-	Clear Yellow Liquid
Operating Range, °F	-	0° to 600°
Pour Point, °F	-	-40°
Moisture Content	-	250 ppm, maximum
Viscosity, cs		
• at minimum operating temperature	-	1610
• 100°F	-	26.9
• at maximum operating temperature	-	0.60
Specific Gravity		
• at minimum operating temperature	-	0.915
• at 100°F	-	0.878
• at maximum operating temperature	-	0.691
Coefficient of Thermal Expansion, %/°F	-	.00049
Specific Heat, Btu/lb-°F		
• at 0°F	-	0.420
• at 100°F	-	0.472
• at maximum operating temperature	-	0.718
Thermal Conductivity, Btu/hr-ft °F		
• at 0°F	-	0.0813
• at 100°F	-	0.0784
• at maximum operating temperature	-	0.0630
Heat of Vaporization, Btu/lb	-	84.4
Flash Point, COC, °F	-	350°
Fire Point, COC, °F	-	410°
AIT, °F	-	675°
Boiling Range		
• 10%, °F	-	635°
• 90%, °F	-	734°
Minimum Pumpable Temperature, °F		
• Centrifugal Pump, 300 cp	-	25°
• Centrifugal Pump, 2000 cp	-	5°
• Positive Displacement Pump	-	10°

TABLE XIII. VARIATIONS OF THERMINOL T-55 PROPERTIES AS A FUNCTION OF TEMPERATURE

Temperature (°F)	Density (lb/gal)	Specific Heat (Btu/lb-°F)	Thermal Conductivity (Btu/hr-ft-°F)	Viscosity		Vapor Pressure (torr)
				Absolute (lb/hr-ft)	Kinematic (cSt)	
0	7.57	0.431	0.0764	3070	1400	
50	7.41	0.453	0.0749	263	122	
100	7.26	0.476	0.0733	56.6	26.9	
150	7.10	0.498	0.0717	20.3	9.86	
200	6.95	0.521	0.0701	9.77	4.85	0.2
250	6.79	0.543	0.0684	5.62	2.86	0.7
300	6.64	0.566	0.0666	3.64	1.89	2.3
350	6.48	0.588	0.0647	2.55	1.36	6.9
400	6.33	0.611	0.0627	1.90	1.03	18.2
450	6.17	0.633	0.0606	1.47	0.82	43
500	6.02	0.656	0.0583	1.19	0.68	93
550	5.86	0.678	0.0559	0.98	0.58	187
600*	5.71	0.700	0.0533	0.83	0.50	352
650	5.55	0.723	0.0505	0.72	0.45	626

* Maximum recommended bulk temperature: 600°F.

FIGURE 25. PRESSURE DROP DATA FOR THERMINOL T-55 UNDER TURBULENT FLOW CONDITIONS INSIDE CLEAN ROUND TUBING AND PIPING

FIGURE 26. HEAT TRANSFER COEFFICIENTS FOR THERMINOL T-55 UNDER TURBULENT FLOW CONDITIONS INSIDE CLEAN ROUND TUBING AND PIPING

selecting piping, pumps, and heat exchangers. This heat transfer fluid is nontoxic by ingestion in single doses and by single dermal applications according to NAS classifications. It is a slight eye irritant and produces only a trace of skin irritation on prolonged contact. Although no special handling precautions appear necessary, as with any industrial chemical, good industrial practices and personal hygiene should be observed in handling to minimize exposure. In case of contact, flushing eyes or skin with plenty of water is required. Because of its low volatility, T-55 does not present an inhalation hazard at ambient temperatures such as those encountered in transferring cold fluid from shipping containers to the heat transfer system. Vapor emitted by T-55 heated to elevated temperatures may be mildly irritating and cause discomfort on prolonged exposure. In heat transfer installations, the fluid will be used in a closed, nonpressurized system free from leaks and with the expansion tank vent trapped so as to condense any vapors. Consequently, there should be little or no opportunity for worker exposure to vapors.

3. Toxicity

Therminol T-55 has an oral LD₅₀ of 15.8 k/kg to albino rats and a dermal LD₅₀ of 7.94 g/kg to albino rabbits. According to NAS classifications, this fluid is nontoxic by ingestion in single doses and by single dermal applications.

The undiluted product is a slight irritant to rabbit skin (average score of 1.0 on a scale of 8) but practically nonirritating to the rabbit eye (average score of 6.0 on a scale of 110). A group of male rats survived a six-hour exposure to air near saturation with vapor of this material at room temperature. They exhibited no adverse signs during the exposure and subsequent ten-day observation period.

Groups of 20 male and 20 female albino rats were fed diets containing levels of 100 ppm, 300 ppm, or 1000 ppm Therminol T-55 for 90 days. A similar group of rats of both sexes served as controls. During the study no differences in behavior, survival, final body weight, body weight gain or food intake between test and control animals were noted. No adverse alterations in hematology (hematocrit levels, erythrocyte, hemoglobin, and total and differential leukocyte counts), blood chemistry (blood urea nitrogen, fasted blood glucose concentrations and serum alkaline phosphatase and glutamine-pyruvic transaminase activities), or urinalyses (glucose and albumin concentrations, pH, specific gravity and microscopic examination) were noted.

On termination of the feeding study, 15 animals of each sex were sacrificed and autopsied by gross examination. Weights of liver, kidney, spleen, gonads, heart, and brain of each rat were determined and recorded. A microscopic examination of tissues and organs (approximately 32 per animal) from ten rats of each sex from both the control and 1000 ppm Therminol T-55 group was conducted. There was no relevant gross or microscopic pathology and no significant differences between test and control animals in either organ weights or their ratios to body or brain weights.

Separate groups of White Leghorn chickens (4 males and 20 females per group) were fed diets containing 30 ppm, 100 ppm, or 300 ppm of T-55 for 12 weeks, after which the birds were returned to a Therminol-free diet for an additional four weeks. A similar group of 24 birds served as controls. No abnormalities in body weight gain, food consumption, survival, or behavioral reactions were noted. No adverse effects in egg production or egg quality (defects, breakage, weight, shell thickness, specific gravity) related to ingestion of Therminol T-55 were noted. No differences in the viability (hatching of chicks during the study) or body weight gain in the F_1 generation (chicks) were seen. No relevant gross pathological abnormalities were determined for either the parents or the F_1 generation birds.

4. Fouling and System Cleanout

While Therminol T-55 has a select-stable chemistry, conditions can develop to precipitate fouling of heat exchangers, pumps, and valves which may require a system cleanout. The most common causes of Therminol system fouling are:

- Overheating the heat transfer fluid
- Contamination by process chemicals or other heat transfer fluids
- Oxidation of the heat transfer fluid

Therminol T-55 can be affected by oxidation conditions. Should extensive oxidation occur by air contacting hot fluid, a carbonaceous residue will form and adhere loosely to the system heating surfaces requiring cleanout of the system. Thermal breakdown of T-55 is less common than oxidation of these fluids, but can create carbonaceous deposits within the system. Contamination of Therminol by process fluids or other heating media may contribute to fouling of the system. Incompatibility of the chemistries involved dictate changing to fresh fluid and reclamation or disposal of the contaminated fluid.

Four methods of "cleaning" a system are recommended, depending upon the degree of fouling or incompatibility of the contaminant in the system:

- (1) Draining of old fluid and recharging with fresh fluid. This method is the easiest and least expensive. Solids in the fluid can be removed by a hot and rapid draining. Addition of new fluid provides a small degree of cleaning action on slightly fouled heating surfaces.
- (2) Fluid flush. This method involves flushing the system with a small amount of the Therminol to be used to fill the system. Isolation of system components is desirable to avoid using large quantities of flushing fluid. This method is effective for new systems where surfaces are not heavily fouled.

- (3) Solvent cleaning. This method is useful to clean or flush a lightly soiled system. Chlorinated solvents are to be avoided. Typical solvents used are:

- Xylol
- Kerosene
- Benzene

- (4) Chemical cleaning. This method is effective in cleaning heavily fouled heating surfaces. The following chemicals should be used:

- Oakite cleaning products
- Caustic soda and soda ash

The following cautions are recommended for chemical cleaning:

- Mechanical agitation by high velocity flow or air injection is necessary to loosen difficult soils.
- Cleaning products must be completely removed from the system prior to charging with fresh fluid.
- All water must be completely removed to preclude startup pumping problems.
- Certain metals in the system (copper and aluminum) may be affected by the cleaning agents used.

VI. SITE FABRICATION

A. Piping and Valves

The piping system will be constructed of Schedule 40 seamless carbon steel pipe (ASTM A 53, Type S, Grade B, material). This piping will be assembled by welding and using standard weight weld fittings (ASTM A 234, Grade WPB material, USAS B-16.9 dimensions). All flanges will be USAS 300-lb forged steel (ASTM A 181 material, USAS B-16.5 dimensions). Extreme care will be taken to provide a leak-free system, even at the flanges, since the high temperatures encountered in this application will produce internal stresses which could cause leaks at flange joints. The 300-lb welding neck flanges will be used to reduce the possibility of flange face warping during welding and compression of spiral-wound gaskets. A leak-free system is more critical at higher temperatures due to a possible fire hazard in insulation materials. The subject of potential fire hazards will be discussed under the following section on pipe insulation.

The valves specified for this application will also be 300-lb butt-welded to reduce the need for flange connections. Since there are a number of possible valve suppliers, no manufacturer will be specified at this time, but will be selected during the detailed system design. The most important consideration, however, for the selection of valves is the temperature and pressure rating of the valve seals or packing.

Various types of packing are used to seal valve stems in high-temperature systems. Flexible metal or solid graphite packing is recommended due to its proven life in similar applications. Graphite or Teflon impregnated, short fiber asbestos gasketing has been used on previous systems, but leak-free service is not always achieved at higher temperatures with this type packing. Generally, five rings of packing are required on valve stems to assure a reasonable seal. The use of metal bellows stem seals on valves is a possibility and would, of course, provide absolute leak-free service, but this type seal is more expensive than the conventional flexible stem packing discussed above.

B. Insulation

Fires have occurred in insulation materials that have been soaked with heating fluids at apparent temperatures of 500-600°F, which is well below the autoignition temperature of most commercial heating fluids. Tests indicate that magnesia, calcium silicate, and silicate-bonded asbestos insulations are subject to this problem. While the exact mechanism by which such fires occur is not fully understood, the most probable explanation is that a slow exothermal oxidation reaction between hydrocarbon-type heating fluids and air inside the voids of the insulation starts at about 500°F. Such a reaction is believed to occur because the combination of the large heating fluid surface exposed on the insulation fibers, poor heat dissipation conditions, and the formation of low flash point oxidation products, can cause a temperature buildup in the saturated insulation mass resulting in ignition of the material when exposed to air.

Calcium silicate, asbestos, and magnesium oxide insulation can saturate with almost their original weight of leakage fluid. This saturation when spread over the large surface area within the insulation at high temperature can give rise to oxidation of heating fluid and the formation of lower boiling, more combustible, decomposition products. Subsequent ignition of the fluid within the insulation system can result.

An alternate insulation, cellular glass, tends to resist saturation by the heat transfer fluid and is, therefore, a safer insulation to use. Cellular glass is not normally the most economical insulation for most applications because of its higher installation cost and its tendency to crack when thermally shocked. The use of cellular glass insulation does not insure that insulation fires will not develop, but the amount of fluid that can saturate the insulation system and be oxidized is greatly reduced.

The insulation system must be designed to minimize fire problems in the event of fluid leakage. The following precautions will be taken to minimize the fire hazard potential in insulation systems.

- Every precaution will be taken to install and maintain a leak-free piping system. The number of flanges will be held to a minimum.
- On horizontal runs of pipe with welded joints and proper flange fittings, standard high-temperature insulation such as calcium silicate and magnesium oxide will be used.
- On vertical runs of piping where occasional leak sources can develop at flanges and valves, protective, tight-fitting caps will be installed below flanges and valves to divert any fluid leakage to the outside of the insulation system.
- Valve stems will be installed horizontal so that any stem leakage does not enter insulation.
- On those sections of piping where control valves and instrument fittings are attached and where leakage is a potential problem, cellular glass insulation or metal shielded insulation will be installed to minimize or eliminate any potential saturation of leakage fluid into the insulation system.
- On jacketed vessels where leakage due to metal failure can occur, a heavy gauge metal foil barrier will be installed between the jacket surface and the insulation system.

It should be pointed out, however, that even though these precautions will be taken, the operating range of the system will be below 500°F so that no

fire hazard is anticipated. As with the toxicity situation discussed before, before any firm specification with respect to fluids can be made, all of the potential fire aspects will be reviewed with Lone Star Brewery's Safety Committee.

C. Installation Techniques

The following is an outline of the installation techniques to be conducted during the field construction of the system.

The roof of the building which will support the collectors will be prepared by cutting through built-up roofing to steel members underneath. Structural attachments which will accept collector bases will then be installed. The roof will be repaired with pitch pockets at collector support penetrations and the pitch pockets stripped in to existing roofing.

During the wait for collectors, steam and feedwater piping will be run from the location of the solar-fired boiler to the collector area. New piping within the building areas will be supported from building structures using roller clevis hangers to allow pipe movement. Where piping is run across the roof of the building, it will be supported by structural steel supports tied in to building roof structures in the same manner as collector supports. Pipe hangers for roof-mounted piping will be roller bracket hangers.

Anchors fashioned from structural steel members will be installed at the proper points to confine and direct pipe expansion. Piping guides will be installed around piping on either side of expansion members.

After steam and feedwater piping is run to the collector field areas, it will be capped and pressure tested to prove its integrity. Following the pressure test, the piping will be insulated.

Upon arrival at the job site, the collectors will be installed by the following process:

- Support members will be set in place on structural attachments previously installed, utilizing a motor crane of sufficient reach.
- Reflectors will be set in place on supports, aligned, and secured.
- Continuing to use the motor crane, the receiver tubes and covers will be carefully set using a specially improvised sling to avoid damage to tubes or covers. As tubes are set and aligned, they will be attached using compression tube fittings to form continuous lengths of tubing. Tubes and covers will be secured in place.

- Following installation of receiver tubes and covers, the crane may be dismissed and piping connections made to flex connections at each end of collector rows.
- Following piping connections, each row of collectors will be pressure tested.

When the heat exchanger is received at the site, it will be set in place and all piping connections made. Following piping connections and pressure testing, the heat exchanger and its associated piping is to be pressure tested.

Following receipt of the collector fluid pump at the site, it will be set in place on a concrete foundation adjacent to the heat exchanger and securely bolted down. Collector fluid connections and seal cooling piping will be installed and tested. Electrical wiring connections will be made to the pump at this time.

As accessory items such as the compression and storage tank and steam separator are received, they will be installed, tested, and insulated. The entire system should be pressure tight at this time, and trim such as thermometers, gauges, relief valves, flow control valves, and air release valves may be installed.

Following trim installation, all controls, control wiring, interlock wiring, and data acquisition instruments are to be installed, together with their associated piping and wiring. Collector tracking mechanisms and their wiring should be installed at this time and all wiring checked.

Following final checkout, the collector loop will be filled with the high-temperature heat transfer fluid and a reserve amount of fluid placed in the compression/storage tank.

The collector fluid pump will then be started, checked for rotation, and the fluid circulated while venting air from the system until it is free of all entrained air. All operating controls will be set and checked at this time and carefully monitored for proper operation. After satisfactory operation is achieved, the system may be operated under close supervision and careful attention paid to operating parameters and to the functioning of safety devices.

In order to minimize installation costs of factory-fabricated equipment requiring particular care in final installation, the following procedure has, in our experience, worked well:

- When purchasing equipment, arrange for the services of a trained factory man to be available for the first week of the installation period. At the same time, arrange for the same man to return to the job at completion.

- Installation labor is to be performed by a local contractor under the initial supervision of the factory technician.
- The factory technician is to return to job on completion of machinery installation and either certify that it is properly installed or request the necessary changes to allow him to make such a certification.

Factory personnel cannot install equipment as economically as can local contractors with good mechanics. Additionally, factory personnel are away from home and are living on expenses paid by the customer. It is desirable, however, to maintain the responsibility of the factory for proper installation.

VII. ENGINEERED EQUIPMENT

A. Pump and Seals

The selection of the type of pump and pump size will be determined after the collector field optimization study is completed, as was explained in the collector selection chapter of the report. The optimization process will determine the best collector field piping arrangement to provide the most cost-effective combination of the engineered equipment, both collector field pump and solar-fired boiler. As a prerequisite of the pump selection, the following comments on pump seals and pump types are outlined.

1. Seals

Certain conditions can develop within the seal environment of a high-temperature heating system that will increase the incident of seal failure. The most critical conditions that affect the service life of pump seals are heat, pressure, corrosion, cavitation, and product characteristics. The heat transfer fluid can have an effect on, or be affected by, any or all of the above conditions. Other conditions such as shaft deflection, bearing wear, vibration, and poor installation can also affect the life of a seal, but these problems are usually minimized by proper pump selection for the intended service, careful installation, and proper maintenance.

a. Heat

Excessive temperature at a mechanical seal face can lead to premature failure. The seal environment should not normally exceed 300°F for most heat transfer fluid applications. Common seal face materials, such as carbon, Stellite, and tungsten carbide require some degree of fluid film lubrication. High temperatures decrease lubricity and the resulting friction and heat buildup can promote abnormal face wear. Excessive temperatures can also cause vaporization of fluid at the seal face resulting in no lubrication and/or mechanical damage to face materials such as carbon. Most heat transfer fluids are low vapor-pressure high-boiling compounds that do not normally vaporize over their use range. However, some thermal decomposition products of these fluids are lower boiling components and could cause vaporization conditions at the seal face. Dead-ended stuffing boxes provide little chance for fluid circulation and are frequently collection zones for abrasive or corrosive system dirt that can damage the seal faces. In addition to stuffing box and seal gland cooling to control seal temperatures, many high-temperature pump suppliers offer a seal flush system which provides a cooled, filtered supply of the pumped fluid to the seal faces. Seal flush systems have minimized mechanical seal face wear in many high-temperature applications.

b. Pressure

Hydraulic seal face loading depends on the stuffing box pressure and type of seal used. Generally, a single-inside, unbalanced, or

partially-balanced seal is used in high-temperature applications. Excessive face pressure, either hydraulic or installation imposed, can reduce face lubrication, increase frictional heat buildup, and cause face distortion resulting in reduced seal face life. Pressure surges and hydraulic shock created by automatic valving within the system can also have a damaging effect on seal life. While not a common problem, proper valve selection and operation of the system hydraulics can minimize this type of overload on the seal faces.

c. Corrosion

Many heat transfer fluids can create--through decomposition or contamination--a corrosive environment at the mechanical seal. Even though most heating fluids are miscible, when added together, certain chemical incompatibilities can result in a corrosive environment at the seal. Acidic conditions can result in the formation of acidic metal salts which can be abrasive to seal faces when present in the fairly quiescent environment of a dead-ended pump stuffing box. When corrosive conditions develop along with corrosion by-products that affect seal characteristics, the system fluid should be changed to a fresh charge. A flush of the corrosive system may not necessarily resolve the problem since fresh fluid can loosen existing system soil. A more effective cleanout of the system may be necessary to remove the corrosive products along with other system soils. The seal flush mentioned above can also be effective in minimizing excessive seal wear by removing harmful corrosive deposits.

d. Cavitation

Cavitation, the formation and collapse of vapor pockets from fluid near its vapor point or from low boiling components in the fluid, does not normally have a direct affect on pump seals. However, frequent or continuous cavitation at the pump can bring about pressure variation, shaft deflection, vibration, or mechanical shock that will damage seal components. An effect similar to cavitation, entrained gases, or rapid liquid to vapor phase change, can produce a chattering effect on the seal causing face damage and leakage. System design, with attention to NPSH requirements of the pump, usually corrects cavitation problems. Many heat transfer fluids form lower boiling components on thermal or oxidative decomposition that can result in cavitation conditions. Some heat transfer fluids can form low boilers from thermal damage. Venting a slip stream of pumped fluid to a nitrogen or CO₂ inerted, outside vented expansion tank will relieve low boilers from the fluid. Any vented material should be collected for proper, nonpolluting disposal. Inerting prevents oxidation damage to the fluid during the venting operation. The seal flush system mentioned above provides a continuous venting of the stuffing box in addition to cooling the seal area with filtered fluid.

e. Product Characteristics

Characteristics of the heat transfer fluid, such as system dirt pickup, decomposition products, chemical compatibility, sludge formation,

oxidation resistance, vapor pressure, and lubricity can have an affect on pump seal performance. Abrasive particles are a major contributing factor to seal failure, particularly particles under 200 mesh size. These particles, other than rust and scale usually found in the piping system, can be thermal decomposition products such as salts, oxides, and tars; carbonaceous oxidation products from certain types of fluids; dirt from the environment external to the seal; or combinations of these. Rust and scale usually found in the pipework are frequently loosened by heat transfer fluids and circulated throughout the system. Filtration is effective in removal of these particles. Decomposition products from certain fluids can create conditions that are detrimental to seal performance. Highly acidic decomposition products, for example, cannot only catalyze further decomposition of the fluid, but establish a corrosive seal environment discussed earlier. Oxidation products from many fluids develop into abrasive carbonaceous deposits that can seriously affect seal face wear. Air contact should be minimized with those fluids having oxidative instability. Cold or inerted (nitrogen) expansion tanks will reduce oxidation problems and potential seal problems from oxidation residues. Many fluids are chemically incompatible with one another in heating applications. Certainly, any change of heating fluid or top up with another fluid should be thoroughly evaluated to preclude seal and other system problems. Most heat transfer fluids are capable of forming high boilers and tars on thermal decomposition. These tars have a sludge-like characteristic and tend to be abrasive to the seal faces. This sludge-like deposit has been observed as an uneven coating on mating seal faces which prevents sealing of the surfaces and results in leakage. Virtually all heat transfer fluid systems generate dirt or debris that can affect seal performance. In summary, a clean and cool pump seal environment is a prerequisite to satisfactory seal service in high-temperature heating systems.

2. Pumps

There are three candidate types of pumps recommended for this application: a centrifugal pump, a canned centrifugal pump, and a positive displacement gear pump.

a. Centrifugal Pump

The characteristics of this class of pump are such that a relatively steady flow over a large capacity range is possible. When operated at elevated temperatures, however, a number of design requirements must be considered. Among these requirements are pump shaft sealing, pump alignment in relation to thermal expansion, and stuffing box cooling efficiency.

The successful sealing of the pump shaft in high-temperature services requires not only special pump design features but also careful packing or mechanical seal application.

Provision for maintaining pump alignment under the difficult strains of high-temperature service is a major part of a successful

application. Therefore, any pump selected must provide rigidity and guard against thermal distortion to assure long and trouble-free service of shaft bearings, coupling parts, and pump seals. The major design features required to accomplish the above are:

- Centerline casing support must allow thermal expansion about the pump centerline without disturbing alignment.
- Suction and discharge connections must equalize pipe loads and prevent center forces and resulting distortion.
- The bearing housing and cradle spacing must be constructed of a high-strength steel stress-relieved to guard against uneven expansion during temperature changes.
- If a bearing housing cooling jacket is provided, it must provide for full annular flow to equalize housing temperatures, eliminate distortion, and keep bearing accurately aligned.
- The pump support must be rugged enough to resist thermal expansion piping loads and hold the pump firmly in place.

Of equal importance to alignment is the provision of a livable environment for the shaft sealing materials in the pump stuffing box.

- An efficient stuffing box cooling jacket should be provided to concentrate the cooling where it is needed to keep packing or mechanical seal parts at long life temperatures and extract as little heat as possible from the pumped fluid.
- A single piece pump shaft of high-strength steel should be used to limit shaft deflection at the mechanical seal face.
- To minimize shaft end play, adjustable angular contact thrust bearings should be used.
- Mechanical seal glands should be water cooled to prolong seal face life.

b. Canned Centrifugal Pump

One solution to the problems inherent in sealing centrifugal pumps is a sealess pump known as a canned pump. Because the canned pump combines pump and motor in a single leakproof unit, there is no leaky stuffing box, no seals or packing to adjust, no external lubrication required, and no seal misalignment problems. Fluids cannot leak out, nor can they be contaminated by in-leakage.

The canned pumps have only one moving part--a rotor and impeller assembly which is driven by the rotating magnetic field of the induction motor. Bearing lubrication and motor cooling for these units are provided by the pumped fluid circulating in the rotor chamber. The fluid is isolated from the stator windings by a nonmagnetic, corrosion-resistant liner placed in the stator air gap and welded to the end bells. It is kept at the proper temperature for cooling by (1) a thermal barrier provided by a necked-down area between the pump casing and motor section, and (2) by the constant circulation of the rotor chamber fluid through an integral heat exchanger by means of an auxiliary impeller mounted on the rotor shafts. The only drawback to this type of pump is the higher cost of the unit, but for a total system design, this type of pump may be more cost-effective if a seal cooling system is deemed necessary.

c. Positive Displacement Gear Pump

This type of pump has the characteristic advantage that high heads can be produced at low flows for cold weather start-up. All of the considerations for pump sealing outlined above for centrifugal pumps are also applicable to this type of pump. The basic operating characteristic of this pump is that it traps the fluid and pushes it around the closed casing, instead of "throwing" the fluid as in a centrifugal pump, thereby producing a smooth flow even with wide changes in viscosity.

B. Solar-Fired Steam Boiler*

The solar-fired steam boiler will be a liquid-to-steam exchanger, commonly known as an unfired boiler. This exchanger will have the solar-heated Therminol on the tube side and the steam condensate from the water treatment plant supplied to the shell side for steam production. The unit selected from this application is a Patterson-Kelley Series 380 steam generator, as shown in Figure 27.

The selected steam generator is a skid-mounted unit. It has lifting lugs for hoisting into place, and it can also be moved on rollers or by sliding. It requires no special foundation. Once in place, it needs only to be hooked up. All controls are connected and pretested. The shell is already covered with 2-in. high-density fiber insulation which is protected by a heavy zinc-plated sheet steel jacket. A discussion of different design features follows.

* Information on this product extracted from manufacturer's literature courtesy of Patterson-Kelley Co.

HIGH-TEMPERATURE WATER-TO-STEAM SERIES 380
UNFIRED STEAM GENERATOR

Figure 27

1. Shell

The tank or shell is amply proportioned to store a large volume of water at saturated steam pressure. Intermittent feedwater injection has little or no effect on steam output. Plenty of area is available for steam disengagement at rated capacity. Water entrained in emerging steam is removed at the steam separator, which utilizes inertia forces at sharp changes of flow direction. The shell is designed, constructed, and stamped to requirements of the ASME Code, Section VIII, for Unfired Pressure Vessels. Reinforced manholes are provided in all units. Units for service at pressures higher than 50 psig are fully x-rayed and stress relieved after fabrication. They are ASME stamped for a maximum steam generating pressure of 150 psig.

2. Heat Transfer Section

Tube bundles for circulating high-temperature heat transfer fluids are all of the single tube sheet U-tube design. They are all capable of operating without damage in the event the steam generator is run absolutely dry. They have the complete flexibility to withstand sudden injection of cold feedwater while they are at steam-generating temperature. Standard 3/4-in. O.D. tubing is used in the tube bundle. It is arranged in a square pattern on 1-in. pitch so that tube exteriors can be cleaned mechanically without difficulty. Generously thick tube supports maintain tube alignment in the bundle. These full disc supports rest on tracks inside the shell. Whenever the bundle must be pulled for inspection or service, the supports slide on the tracks. The bundle stays properly aligned, and the job of handling it is very much simplified by this convenient arrangement.

3. Standard Fittings and Controls

The Series 380 package is supplied completely equipped with accessory components of proven excellence. Connections for the heat transfer fluid are all standard ASA flanged nozzles in 2-in. size and larger. The pressure control system delivers a pneumatic or electrical call-for-heat signal to the heat transfer fluid regulator valve. A pressure gauge is supplied and installed on the front of the shell. Liquid level controls deliver electrical or mechanical action to the feedwater pump or valve. Because the Series 380 can tolerate wide fluctuations in water level, a modulating feedwater system is not necessary. An ASME gauge glass assembly is installed to permit visual inspection of water level. Thermometers are installed in the high-temperature heat transfer fluid piping or steam gauges on steam supply piping to monitor performance of the unit. Safety valves are provided and installed per ASME Section I Boiler Code. Blow-off valves in the ASME tandem arrangement are installed on the bottom of the shell.

4. Steam Controls

A properly sized and selected steam regulator valve is furnished for the system pressure and generator capacity required. It may operate pneumatically, electrically, or hydraulically. Bypass connections can also be installed. Necessary strainers and steam traps are installed.

5. Heat Transfer Fluid Controls

Heat transfer fluid will be available at ample pressure to take care of circulation through the Series 380 heat transfer section. Control requirements are satisfied by a two-way or three-way V-port valve that operates automatically in response to generator steam pressure.

VIII. SUMMARY

The conceptual system design, as outlined in this report, consists of pumping Therminol T-55 through a 9450-ft² collector field of Solar Kinetics T-700 parabolic trough concentrating collectors and then passing this fluid through the tube bundle of a Patterson-Kelley Series 380 unfired steam generator. The steam produced in the shell of this boiler is then transported to the process steam header in the warehouse directly below the collector field under the developed pressure and metered to this header by a standard check valve. Feedwater from the process deaerator, which is fed to the existing boilers by three boiler feed pumps in parallel to a common header, is tapped for make-up water to this boiler.

The selection of the Solar Kinetics T-700 was made after an exhaustive review of the concentrating solar collector market. This collector was determined to be the most cost-effective unit available. In addition to this selection, a review of the potential heat transfer fluids to be used was conducted, and the Therminol T-55 was selected upon considerations of freeze protection, toxicity, cold weather start-up, boiling temperature, viscosity characteristics, and fire protection. Considerations for both installation and selection of the remaining system equipment has also been discussed. The actual selection of this equipment will be made after an optimization study has been conducted to determine the most cost-effective combination of collector field piping, collector field pump, and solar-fired boiler size. This optimization study will be conducted as the next task in the design process.

An environmental impact assessment and a system safety analysis are also included as a part of this Conceptual Design Report.

APPENDIX A

SITE VISIT EVALUATIONS

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATION

I. Thermal Performance

A. Efficiency Vs Operating Conditions (on-site data)

Not available at this time

B. Efficiency Degradation with Age (from on-site data)

Not available at this time

C. Fill Factor (aperture area per gross field area)

0.29

D. Tracking Accuracy Requirements to Optimize Performance

0.25°

II. Structural Characteristics

A. Static Weight (dead load)

5.90 lbs/ft²

B. Wind Loads

?

C. Support Structure Tie-In Technique

A-Frame--Four bolts through dash pot at Campbell Soup

D. Collector Support Spacing

10 ft

SITE VISIT EVALUATION (CONT'D)

III. Installation Requirements (labor and materials)

A. Plumbing Connections

Rotary joint with metal hoses

B. Roof Reinforcement and Support Structure Installation

Pylon or A-frame type of support

C. Constraints Caused by Special Fluids

High pressure water

D. Tracking Control System

Acurex Model 3001-03 control, shadow band sensor

E. Modular Assembly and Site Equipment Requirements (hoists or crane, slings, etc.)

This modular assembly only required a simple hoist or crane

IV. Maintenance History

A. Reflective Surface Optical Durability

Manufacturer claim only a 1% loss per year, but not enough data is available to verify this.

B. Absorptive Surface Optical Durability

Appears to be good

SITE VISIT EVALUATION (CONT'D)

C. Receiver Tube Cover Sealing Problems

Glass breakage problem observed at Willard, a new assembly has been installed.

D. Mechanical Durability of Tracking System

Appears to be continuously hunting, durability is questionable.

E. Mechanical Durability of Movable Plumbing Connections

Poor--has been changed at Willard

F. Hail Resistance

Yes

G. Cleaning System

Water hose

H. Drive System Enclosure

None, open. worm + worm gear, next installation will have a new system

I. Ability to Replace On-Site the Reflective Surface and Receiver

Tube Cover if Damaged

Yes

SITE VISIT EVALUATION (CONT'D)

J. Self-Aligning Bearings for Reflector Systems

Yes--self-aligning pillow block bearing

K. Leakage Problems

Yes--very definite problem at Willard

L. "Stow" Position Difficulty

Slow

V. Overall Quality of the System

A. Installation

Seems to be fair in most areas, but there are some definite problems

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

Alzac on 40 mil aluminum

2. Receiver (image size, cover, back insulation, etc.)

Black chrome

3. Support Pylons (rigidity, tie-in, bearings, etc.)

Seems adequate

4. Tracking System (feedback system, drive system, etc.)

Continuously hunting, tracking system with an exposed worm gear

SITE VISIT EVALUATION (CONT'D)

5. Plumbing Connections (swivel joint and flexible hoses, etc.)
Swivel joint and flexible hoses assemble has been a source of leakage.

6. Hazard Avoidance System (defocus, "stow" position, over-temperature, overpressure, alarms, etc.)

A desteer mode is provided to defocus by driving the receiver 5° off of focus, plus a stow mode in one direction only with a positive motor drive lock

7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

Appears generally good

- C. Factory Cooperation during Design, Installation, and System Check-Out
Cooperation fine during installation but problems arose after check-out and factory follow-up was slow

- D. Equipment Warranty

90 day

- E. Overall Installed Cost Per Square Foot of Aperature (purchase price of equipment, labor hours for installation, etc.)

Not available for these installations

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS

SITE VISIT EVALUATION

I. Thermal Performance

A. Efficiency Vs Operating Conditions (on-site data)

No on-site installations of the GE 3x collector have yet been made. On-site performance data will be available from the Tropicana industrial process steam application during the first half of 1979.

B. Efficiency Degradation with Age (from on-site data)

This data will be available after the installation of the 3x collectors at Tropicana.

C. Fill Factor (aperture area per gross field area)

$$\frac{\text{Aperture area}}{\text{Gross field area}} = \frac{1}{2} \quad (\text{For Tropicana installation})$$

D. Tracking Accuracy Requirements to Optimize Performance

Only four (4) seasonal tilt angle adjustments for a latitude of 27.9° are required. This, for example, results in only a 1.2% deviation from the optimum (maximum possible collected energy) that would be realized if continuous tracking were employed.

II. Structural Characteristics

A. Static Weight (dead load)

125 pounds

B. Wind Loads

40 pounds/ ft.² (~100 mph)

C. Support Structure Tie-In Technique

Each collector ties in to a 4 1/2" OD mounting pipe at four places by means of a 'U' bolt. Rotation of the pipe effects seasonal adjustments.

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS

SITE VISIT EVALUATION

(Continued)

D. Collector Support Spacing

Collectors are arranged in rows and mounted in pairs on two pylons spaced 18' apart.

III. Installation Requirements (labor and materials)

A. Plumbing Connections

Connections from one collector module to the next are made by standard hydraulic fittings on each header tube which is integral to the collector. Collectors may be connected in series, approximately 4 to 6 per row, which eliminates external piping. Inlet and outlet connections on each end of the collector are both located in one corner for convenient access.

B. Roof Reinforcement and Support Structure Installation

Collector field for Tropicana is ground installation using 4 1/2" OD pylons with concrete footings 1 foot in diameter and 4 feet into ground. Roof installations are feasible. Roof reinforcement would depend on the building structure.

C. Constraints Caused by Special Fluids

None. Stainless steel fluid tubing is employed throughout the collector field.

D. Tracking Control System

None required. Seasonal adjustments of tilt angle are made manually.

E. Modular Assembly and Site Equipment Requirements (hoists, slings, etc.)

Each collector is delivered as an assembly and can be handled by two men. No hoists or slings are required for a ground installation.

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS

SITE VISIT EVALUATION

(Continued)

IV. Maintenance History

A. Reflective Surface Optical Durability

Tests on Alglas reflector indicates excellent environmental resistance to salt, humidity and washing. Resistance to abrasion is moderate.

B. Absorptive Surface Optical Durability

The absorptive coating on GE collectors are protected by a vacuum shroud and consequently, are not affected by the environment (except for effects of solar radiation) and offer excellent durability.

C. Receiver Tube Cover Sealing Problems

Thousands of GE vacuum shrouds have been fabricated without any sealing problems.

D. Mechanical Durability of Tracking System

There is no automatic tracking system associated with the 3x collector. The simplicity of manual adjustment mechanism ensures high reliability and durability.

E. Mechanical Durability of Movable Plumbing Connections

At the ends of each row of collectors there is a flexible plumbing connection consisting of an insulated 3/4" ID stainless steel corrugated hose, covered with a stainless steel wire braid jacket.

F. Hail Resistance

1" hail stones (with protection cover)

G. Cleaning System

The collectors can be washed down with water to accomplish cleaning

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS

SITE VISIT EVALUATION

(Continued)

H. Drive System Enclosure

None

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

Receiver tubes (vacuum shrouds) can be replaced on site in a simple fashion. The plumbing system is mechanically isolated from the shrouds and consequently, not affected by tube replacement. If reflective surfaces are damaged, a complete collector would be replaced.

J. Self-Aligning Bearings for Reflector Systems

Simple bearings are provided at the ends of the mounting pipe to facilitate the seasonal manual tilt angle adjustments and stowage rotation.

K. Leakage Problems

None anticipated.

L. "Stow" Position Difficulty

Rotation of the collectors to the "stow" position during hurricane conditions is accomplished by manual rotation. Two men are required.

V. Overall Quality of the System

A. Installation

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

2. Receiver (image size, cover, back insulation, etc.)

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS

SITE VISIT EVALUATION

(Continued)

3. Support Pylons (rigidity, tie-in, bearings, etc.)
4. Tracking System (feedback system, drive system, etc.)
5. Plumbing Connections (swivel joint, flexible hoses, etc.)
6. Hazard Avoidance System (defocus, "stow" position, overtemperature, overpressure, alarms, etc.)
 Overtemperature, overpressure and other warning alarms are designed into the Tropicana system.
7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

C. Factory Cooperation during Design, Installation, and System Check-Out

D. Equipment Warranty

Standard Federal Procurement Regulation - Inspection and Correction of Defects for CPFF contracts.

E. Overall Installed Cost Per Square Foot of Aperture (purchase price of equipment, labor hours for installation, etc.)

\$20/Ft² for collectors alone.

Installation costs are currently being evaluated for the Tropicana industrial application.

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATIONI. Thermal Performance

- A. Efficiency Vs Operating Conditions (on-site data)
Project under construction at the time of the site visit.
- B. Efficiency Degradation with Age (from on-site data)
Project under construction at the time of the site visit.
- C. Fill Factor (aperture area per gross field area)
?
- D. Tracking Accuracy Requirements to Optimize Performance
?

II. Structural Characteristics

- A. Static Weight (dead load)
0.75 lbs/ft² (mirror only).
- B. Wind Loads
?
- C. Support Structure Tie-In Technique
Double nut used for four bolts per pylon mounted on a concrete pad.
- D. Collector Support Spacing
20 ft.

III. Installation Requirements (labor and materials)

- A. Plumbing Connections
Left up to the installer; even the flexible hose is installer-supplied. At this installation, the collector field piping was installed underground using Permapipe. Also, Barco ball joints were used in lieu of high-pressure hoses.

SITE VISIT EVALUATION (CONT.)

B. Roof Reinforcement and Support Structure Installation

Ground mount installation with pylons supported on concrete pads. Erection and alignment of pylons required five man-hours of unskilled labor and 2.5 man-hours of transit operator per 80-ft row.

C. Constraints Caused by Special Fluids

None.

D. Tracking Control System

Sun sensor controls by Delavan Electronics. The labor required was 3.5 man-hours of electrician and 3.5 man-hours of electrician helper per 80-ft row.

E. Modular Assembly and Site Equipment Requirements (hoists, slings, etc.)

Modular assembly is an 8-ft x 10-ft reflector.

IV. Maintenance History

A. Reflective Surface Optical Durability

Mirror surface is 3M FEK 244. No experience on this project yet, but other types of installations indicate a 10-year life with some deterioration over this life.

B. Absorptive Surface Optical Durability

Good.

C. Receiver Tube Cover Sealing Problems

Some seal problems have been experienced in the past.

D. Mechanical Durability of Tracking System

Exposed chain and sprocket looks to be a problem.

E. Mechanical Durability of Movable Plumbing Connections

Unknown since all movable plumbing is installer-supplied.

SITE VISIT EVALUATION (CONT.)

F. Hail Resistance

There appears to be a hail damage problem due to the thin sheet metal over the honeycombs.

G. Cleaning System

A pressure water and detergent.

H. Drive System Enclosure

None.

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

These items can be replaced but only if the complete reflector assembly is replaced.

J. Self-Aligning Bearings for Reflector Systems

Self-aligning bearings are included.

K. Leakage Problems

None yet.

L. "Stow" Position Difficulty

None yet.

V. Overall Quality of the System

A. Installation

The installation procedure, witnessed on the site visit, was particularly rapid and simple. The overall quality of the installation was good.

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

Excellent reflector stiffness due to the honeycomb construction.

SITE VISIT EVALUATION (CONT.)

2. Receiver (image size, cover, back insulation, etc.)

The receiver is covered with glass for half the surface, the upper portion being covered with a metal shield. These receivers were coated with black chrome on copper, but the system temperature is only 240°F.

3. Support Pylons (rigidity, tie-in, bearings, etc.)

Adequate.

4. Tracking System (feedback system, drive system, etc.)

Delavan Electronics with focus, defocus, and stow features.

5. Plumbing Connections (swivel joint, flexible hoses, etc.)

Barco ball joints were used.

6. Hazard Avoidance System

The hazard avoidance system includes defocus and "stow" modes for adverse conditions such as low fluid flow, high winds, low insolation, and power failure.

7. Weatherability

Appears to be adequate.

C. Factory Cooperation during Design, Installation, and System Check-Out

Good.

D. Equipment Warranty

?

E. Overall Installed Cost Per Square Foot of Aperture (purchase price of equipment, labor hours for installation, etc.)

Not available for this installation.

Honeywell, Inc.
General Office
Building

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATION

I. Thermal Performance

A. Efficiency Vs Operating Conditions (on-site data)

System not in operation - No efficiency data available from site visit. Primary system operating with Thermanal-44 secondary system operating with Caloria Ht-43 with two (2) 18,000 gallon underground storage tanks with rock-fill.

B. Efficiency Degradation with Age (from on-site data)

5% in 3 months due to dirt and dust from freeway. The above results are from mirror tests conducted at the general office building. To this date no tests have been made to degradation from smog. Reflective surface is manufactured by 3M and provided by Hexall. Manufacturer recommends cleaning the surface weekly with mild detergent, using Joy Soap. 3M Manufacturing Company recommends cleaning surface with 460 Psi and mild detergent soap.

C. Fill Factor (aperture area per gross field area)

Manufacturer recommends 9 to 10 ft. 8 inches spacing. Fill Factor 40-50%. Manufacturers stated at the above spacing, when the sun goes above 22°F., there is no shading factor from the sun on the other rows of collectors.

D. Tracking Accuracy Requirements to Optimize Performance

Plus or Minus $\frac{1}{4}^{\circ}$ accuracy.

SITE VISIT EVALUATION (CONT'D.)

II. Structural Characteristics

A. Static Weight (dead load)

Static weight not available.

B. Wind Loads

Collector suitable for 100MPH windloads when in the stowed position, 30MPH when collectors are in the vertical position. Supporting steel must be calculated by others.

C. Support Structure Tie-In Technique

Purchaser is to provide support legs and tie-in as required on the job site.

D. Collector Support Spacing

Manufacturer recommends 9 - 11 feet collector spacing.

SITE VISIT EVALUATION (CONT'D.)

III. Installation Requirements (labor and materials)

A. Plumbing Connections

All inlet and outlet connections will be provided with swivel joints and stainless steel or steel flexible pipe connections. Connections between collector tubes are welded.

B. Roof Reinforcement and Support Structure Installation

Existing installation at the general offices building had 18 or 20 inch I-beam steel supports.

C. Constraints Caused by Special Fluids

No special constraints due to Therminal, Caloria, or other high temperature oils. All welded pipe and forged steel or steel body valves were used in the installation. No fire protection or spillage dike were installed at this job site. No other special fire protection systems were installed for using Therminal.

D. Tracking Control System

Delevan modified by Honeywell.

E. Modular Assembly and Site Equipment Requirements (hoists, slings, etc.)

The collectors will come with the receiver tubes disassembled. The reflective surface shall be completely assembled. The installer must build the support steel structure, mount the tracking motor-drive system, the wood pillow block bearings between collectors, mount the receiver tube to the reflective surface and align in the field. A crane will be required to lift the panels to the roof, the panels are light-weight and can be carried by hand to the installation area.

SITE VISIT EVALUATION (CONT'D.)

IV. Maintenance History

A. Reflective Surface Optical Durability

Same as Hexcel 5% degradation after 5 years.

B. Absorptive Surface Optical Durability

The manufacturer has seen no degradation of black chrome under normal use. Neither of his systems has ever been over-temperatured. Does not recommend temperatures of over 500°F. in the absorber tube.

C. Receiver Tube Cover Sealing Problems

The Receiver Tube is not sealed, it is open to the atmosphere. The glass cover is gasketed and field removable.

D. Mechanical Durability of Tracking System

The tracking system consists of a windsmith gear box having an oil encased geartrain, complete with brake and anti-backlash system to reduce gear wear. The motor is a fractional horsepower totally enclosed, fan cool suitable for outdoor use.

E. Mechanical Durability of Movable Plumbing Connections

Installation seemed very good unless under operating conditions swivel joint develops leak.

F. Hail Resistance

Not good when reflective surface is exposed to direct hail. Very good hail resistance in the stowed position.

SITE VISIT EVALUATION (CONT'D.)

G. Cleaning System

No cleaning system was installed at the general offices job site nor at the West Point Pepperell job site. It will be very difficult for the manufacturer to clean the reflective surface at the general office facility. West Point Pepperell has a car wash cleaning service clean the reflective surface on their collectors under a monthly contract. The manufacturer recommends a mild detergent Joy Soap solution to clean the reflective surface.

H. Drive System Enclosure

Oil encased gears TEFC motordrive, drive system is extra heavy duty. The Drive System cannot be controled by hand and is provided with 110, to 20, or 460 volt only. No low voltage motors will be provided.

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

Modual ability in 10 foot lengths. According to 3M a good technician can replace the reflective surface on the job site if the sub-surface is not dented or pitted. Honeywell has yet to replace a reflective surface in the field.

J. Self-Aligning Bearings for Reflector Systems

Bearing between reflectors are oil soaked maple wood bolted down between collectors.

K. Leakage Problems

No leakage present, system not operational to date.

L. "Stow" Position Difficulty

No stow position difficulty, can go from tracking the sun to the stow position in 2 and $\frac{1}{2}$ minutes.

SITE VISIT EVALUATION (CONT'D.)

V. Overall Quality of the System

A. Installation

Good except for possible problem with swivel joint leakage. Dirt or dust collecting on open receiver tube glass is a good possibility, if receiver tube requires replacement in the field it must be removed with a cutting torch and rewelded in the field.

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

Has leveling plate screws and receiver tube has alignment screws with adjustability built-in.

2. Receiver (image size, cover, back insulation, etc.)

Image size 1" or less cover is glass low iron, back insulation is calcium silicate in aluminum extrusion box.

3. Support Pylons (rigidity, tie-in, bearings, etc.)

By owner or purchaser.

4. Tracking System (feedback system, drive system, etc.)

Closed loop shadow bar Delevan Honeywell modified. Drive system heavy duty as manufactured by Windsmith Gearbox Corporation.

5. Plumbing Connections (swivel joint, flexible hoses, etc.)

Swivel joint and flexible hose connections on inlet and outlet of each collector row.

SITE VISIT EVALUATION (CONT'D.)

6. Hazard Avoidance System (defocus, "stow" position, overtemperature, overpressure, alarms, etc.)

Thermister device to control over-temperature which stows collectors at 350°F. and rings alarm bell. Collectors return to tracking on 50°F. drop in temperature.

7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

Looks adequate for weather ability.

- C. Factory Cooperation during Design, Installation, and System Check-Out

The manufacturer says he is willing to provide all the factory cooperation you are willing to pay for.

- D. Equipment Warranty

Manufacturer has not established equipment warranty at this time and will advise at a later date. Manufacturer indicates standard warranty of one year parts covering material and workmanship may be provided.

- E. Overall Installed Cost Per Square Foot of Aperature (purchase price of equipment, labor hours for installation, etc.)

Not available at this time. The manufacturer indicated the cost per square foot to purchase the equipment which includes the collector only with no tracking devices will probably be around \$35.00 per square foot.

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATION

I. Thermal Performance

- A. Efficiency Vs Operating Conditions (on-site data)
Not available.
- B. Efficiency Degradation with Age (from on-site data)
Not available.
- C. Fill Factor (aperture area per gross field area)
0.37
- D. Tracking Accuracy Requirements to Optimize Performance
 $\pm 1^\circ$ during tracking operation.

II. Structural Characteristics

- A. Static Weight (dead load)
7 lb/ft²
- B. Wind Loads
34 lb/ft²
- C. Support Structure Tie-In Technique
4 J-bolts with double nuts
- D. Collector Support Spacing
54 in. row-to-row and 96 in. pylon-to-eylon

III. Installation Requirements (labor and materials)

- A. Plumbing Connections
Fixed, hard-mounted steel receiver tube with 1/2 in. O.D.

SITE VISIT EVALUATION (CONT.)

B. Roof Reinforcement and Support Structure Installation

The total weight due to wind loading is small, but a large number of roof penetrations would be required because of the small collector unit.

C. Constraints Caused by Special Fluids

High-pressure plumbing due to a working fluid of high-pressure water.

D. Tracking Control System

A Delavan photoelectric sensor unit.

E. Modular Assembly and Site Equipment Requirements

No hoists or slings are required except to transfer units to the rooftop. The total estimate to install a collector field is 100 ft²/man/day.

IV. Maintenance History

A. Reflective Surface Optical Durability

Glass mirror segments have excellent durability as long as the back coating for the silvering is protected.

B. Absorptive Surface Optical Durability

Black chrome optical coating has good durability as long as tube cover remains sealed and no overtemperature problems occur.

C. Receiver Tube Cover Sealing Problems

Since the receiver tube and cover are stationary, all moving seals are eliminated, thereby providing excellent durability.

D. Mechanical Durability of Tracking System

The durability of the mechanical tracking system is good since the worm gear assembly is enclosed.

E. Mechanical Durability of Movable Plumbing Connections

No movable plumbing.

SITE VISIT EVALUATION (CONT.)

F. Hail Resistance

Good hail resistance below a hail size of 1 in.

G. Cleaning System

High-pressure water cleaning.

H. Drive System Enclosure

Drive system is enclosed to provide a dustproof seal at the input shafts to protect the worm gear and worm mounted on a steel tube.

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

Excellent.

J. Self-Aligning Bearings for Reflector Systems

Teflon bearings encased in an aluminum casting.

K. Leakage Problems

None since all plumbing is stationary.

L. "Stow" Position Difficulty

None.

V. Overall Quality of the System

A. Installation

Excellent overall quality.

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

Excellent quality with a pointing or aiming slope error of $\pm 0.5^\circ$ or less, figure slope error of 0.15° or less, and a mirror reflectivity of 0.9.

SITE VISIT EVALUATION (CONT.)

2. Receiver (image size, cover, back insulation, etc.)

The receiver is a steel tube with 0.50 in. O.D. and wall thickness of 0.028 in. The absorptance is 0.95 and emittance is 0.2. The quality is very good.

3. Support Pylons (rigidity, tie-in. bearings, etc.)

Very good.

4. Tracking System (feedback system, drive system, etc.)

Adequate Delavan tracking system.

5. Plumbing Connections (swivel joint, flexible hoses, etc.)

Excellent. All plumbing is stationary.

6. Hazard Avoidance System (defocus, "stow" position, overtemperature, overpressure, alarms, etc.)

These hazard avoidance systems are available on the Delavan unit.

7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

Excellent.

- C. Factory Cooperation during Design, Installation, and System Check-Out

Test System.

- D. Equipment Warranty

?

- E. Overall Installed Cost Per Square Foot of Aperture (purchase price of equipment, labor hours for installation, etc.)

Test System.

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATION

I. Thermal Performance

A. Efficiency Vs Operating Conditions (on-site data)

Not available at this time.

B. Efficiency Degradation with Age (from on-site data)

Not available at this time.

C. Fill Factor (aperture area per gross field area)

0.31

D. Tracking Accuracy Requirements to Optimize Performance

0.29° on 5 milliradians

SITE VISIT EVALUATION (CONT'D.)

II. Structural Characteristics

A. Static Weight (dead load)

3.7 lbs/ft²

End Pylon Load = 260 lbs

Center Pylon Load = 520 lbs

B. Wind Loads

For Stand-Alone Collector:

Stow PositionDrive unit: $D_F = 4312$ lbs, $L_F = 3080$ lbs, $T_m = 6468$ ft-lbs,
 $F_B = 13,490$ lbsAll other pylons: $D_F = 4312$ lbs, $L_F = 3080$ lbs, $T_m = 0$,
 $F_B = 10,256$ lbsAt 120° PositionDrive unit: $D_F = 2400$ lbs, $L_F = 0$, $T_m = 35,574$ ft-lbs,
 $F_B = 23,072$ lbs

Field Installation Assume 67% of Stand-Alone.

Maximum $D_F = 2900$ lbs, Maximum $L_F = 2000$ lbs
Maximum $T_m = 24,000$ ft-lbs Maximum $F_B = 17,300$ lbs

C. Support Structure Tie-In Technique

The double nut technique is used to fasten the bottom of the support pylons and allow for adjustment and alignment.

D. Collector Support Spacing

Pylon spacing center-to-center = 246 in. (20.5 ft)

Row spacing center-to-center = 24 ft

SITE VISIT EVALUATION (CONT'D.)

III. Installation Requirements (labor and materials)

A. Plumbing Connections

The receiver tube is fully floating with linear as well as rotational freedom. Each end is terminated with an expansion bellows cover which connects to a very flexible insulated hose. The hose assembly is connected to the pylon support at each end of the row where it connects to either a crossover pipe or the manifold plumbing.

Labor = 6 hrs per row to install receiver and hose connection.

B. Roof Reinforcement and Support Structure Installation

The solar field foundation should be completed to accommodate the given pylon bolt pattern and pylon spacing. The double nut technique is used to fasten the bottom of the support pylons and allow for adjustment and alignment. The pylons should be installed and aligned with a standard transit or other suitable optical instrument. When the pylons are aligned and tightened to the foundations, the mirror modules are ready for installation.

Labor = 8 hrs per row to align and install pylons.

C. Constraints Caused by Special Fluids

The suggested heat transfer fluid is Caloria HT-43 which is a petroleum-base heat transfer fluid formulated from a highly stable paraffinic-base stock fortified with a high-temperature oxidation inhibitor. There does not seem to be any special constraints needed for handling this fluid except an overtemperature control.

D. Tracking Control System

The shadow bar tracker bracket is bolted onto the collector next to the drive pylon. The shadow bar sensor is bolted to the bracket and aligned lengthwise with the collector. The hydraulic power supply is then piped in parallel to each drive pylon and connected to the hydraulic fittings at the bottom of each control box.

Labor = 4 hrs per row to assemble tracking control components.

E. Modular Assembly and Site Equipment Requirements (hoists, slings, etc.)

The system is a modular assembly which does require a motor crane and specially-improvised slings.

SITE VISIT EVALUATION (CONT'D.)

IV. Maintenance History

A. Reflective Surface Optical Durability

Not enough in-field experience has been gained to date for actual solar collectors, but tests have been conducted on the 3-M film used. These tests showed a decrease in reflectance from 84% to 78% after 7 yrs.

B. Absorptive Surface Optical Durability

For sepearate tests for black chrome without any overtemperature problems, this coating is estimated to drop from 96% to 90% in 10 yrs.

C. Receiver Tube Cover Sealing Problems

No receiver tube cover sealing problems are foreseen. Each receiver tube is 20 ft long and connects to the next with a union that tightens with two wrenches. The glass jacket "O" ring retainer slips over the receiver to provide a dust-tight seal.

D. Mechanical Durability of Tracking System

The durability of the hydraulic tracking system seems to be far superior to the systems that use a small stepping motor and worm gear drive. Hydraulics eliminate any backlash problems as well as provide a slight cushioning effect to sudden loads due to wind buffeting.

E. Mechanical Durability of Movable Plumbing Connections

The mechanical durability of the movable plumbing connections is excellent. In the opinion of the project manager of this project, the hoses used for this collector are far superior to any that he has seen.

F. Hail Resistance

With the 0.040-in. sheet metal backing, the reflector is not only resistant to breakage but also any dimpling due to hailstorms. This system also has a fast tracking mode for stowing this unit in the event of a thunderstorm.

SITE VISIT EVALUATION (CONT'D.)

G. Cleaning System

The cleaning system is a pressure washer with a nozzle pressure of 400 to 800 psi. A Malsbary C-310 detergent is used.

H. Drive System Enclosure

The hydraulic actuators and power supply are completely enclosed.

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

The receiver tube is easily replaced on-site. While the manufacturer indicates that the reflective surface can be field replaced, extreme care for dust contamination must be used.

J. Self-Aligning Bearings for Reflector Systems

This system does have self-aligning spherical bearings to accommodate up to a 5° misalignment.

K. Leakage Problems

No leakage problems have been experienced to date.

L. "Stow" Position Difficulty

No "stow" position difficulties have been experienced. On the contrary, the fast "stow" feature on this collector system is a definite plus.

SITE VISIT EVALUATION (CONT'D.)

V. Overall Quality of the System

A. Installation

This collector system has an excellent overall quality.

B. Collector Module

1. Reflector (deflection, misalignment, smoothness, etc.)

The reflective surface is an aluminized second surface acrylic sandwich bonded to the mirror sheet metal surface. This film has demonstrated up to 84% specular reflectivity and excellent weather resistance for 7 years (a drop to only 78%). This material is 3-M's FEK-244.

2. Receiver (image size, cover, back insulation, etc.)

The 1-5/8-in. carbon steel receiver tube is plated with black chrome and covered by a Pyrex (7740) glass tube. The entire assembly is mounted to the receiver tube stand through a unique, fully adjustable clamp.

3. Support Pylons (rigidity, tie-in, bearings, etc.)

The support structure is a spherical self-aligning bearing mounted on a 53-in. high pylon, mounted to the roof structure by four J-bolts per pylon.

4. Tracking System (feedback system, drive system, etc.)

Solar tracking is effected through the use of a solid state electronic differential shadow bar device. Accurate tracking has been accomplished with this device. The tracking actuator is a hydraulic system that eliminates backlash due to wind buffeting.

5. Plumbing Connections (swivel joint, flexible hoses, etc.)

The fluid is transferred from the receiver by an insulated stainless steel flex hose which allows rotation of the collector with unrestricted flow.

SITE VISIT EVALUATION (CONT'D.)

6. Hazard Avoidance System (defocus, "stow" position, overtemperature, overpressure, alarms, etc.)

This system is a simple relay contact such that any type of hazard signal can be included very simply. The following are manufacturer-supplied signal devices: Rain, light switch, night, overtemperature, loss of power, loss of hydraulic fluid. The following can easily be added: Overpressure, high wind, loss of flow, and loss of heat transfer fluid.

7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

All aluminum construction with completely enclosed drive mechanism, sealed bearings, and sealed receiver tubes proved an extremely weatherable system. The only question is the weatherability of the 3-M reflective film pass the 7-year life of current testing.

- C. Factory Cooperation during Design, Installation, and System Check-Out

The cooperation of the factory representative is excellent.

- D. Equipment Warranty

1 Year

- E. Overall Installed Cost Per Square Foot of Aperature (purchase price of equipment, labor hours for installation, etc.)

Purchase price is \$19/ft² with an estimated installation cost of \$1 to \$2/ft².

CONCENTRATING SOLAR COLLECTOR INSTALLATIONS
SITE VISIT EVALUATIONI. Thermal Performance

A. Efficiency Vs Operating Conditions (on-site data)

Not available.

B. Efficiency Degradation with Age (from on-site data)

Not available.

C. Fill Factor (aperture area per gross field area)

0.45.

D. Tracking Accuracy Requirements to Optimize Performance

The image at all times should be within 1/4 in. of the center of the receiver.

II. Structural Characteristics

A. Static Weight (dead load)

?

B. Wind Loads

7900 lb vertical load and 7400 lb horizontal load on support pier in a 100 mph wind.

C. Support Structure Tie-In Technique

Four J-bolts per pier with double nuts used for adjustment.

D. Collector Support Spacing

20 ft between rows.

III. Installation Requirements

The entire assembly is estimated to be approximately 28 hrs per 200 ft² of collector module with 24 hrs being pipe fitters and 4 hrs being an electrician.

SITE VISIT EVALUATION (CONT.)

IV. Maintenance History

A. Reflective Surface Optical Durability

Cracking problems have been observed due to the mechanical forming of the mirror curvature.

B. Absorptive Surface Optical Durability

Good durability.

C. Receiver Tube Cover Sealing Problems

Since the cover is a flat piece of glass, a seal must be maintained along the total length of the receiver.

D. Mechanical Durability of Tracking System

Adjustment problem may occur due to the chain and linkage assembly.

E. Mechanical Durability of Movable Plumbing Connections

All plumbing is stationary, so there is no movable plumbing connections.

F. Hail Resistance

Potential problem due to the mechanical curving of the mirrors.

G. Cleaning System

Receiver glass should be washed with ammonia and water and allowed to air dry. Mirrors should be washed with deionized water and a weak solution of liquid dish detergent.

H. Drive System Enclosure

None.

I. Ability to Replace On-Site the Reflective Surface and Receiver Tube Cover if Damaged

Adequate.

SITE VISIT EVALUATION (CONT.)

J. Self-Aligning Bearings for Reflector Systems

None.

K. Leakage Problems

Stationary piping is used so no leak problem should be experienced.

L. "Stow" Position Difficulty

None.

V. Overall Quality of the System

A. Installation

Overall quality of the system is fair.

B. Collector Module

1. Reflector

The reflector surface is a second surface glass reflector. Each module is a linear Fresnel concentration system consisting of two bays of ten reflectors each.

2. Receiver

The receiver is two 1-1/4-in. diameter Schedule 160 ASTM A-106B absorber tubes enclosed in a metal container on three sides with Johns Manville Series 1000 glass fiber insulation and a flat glass window on the fourth side.

3. Support Pylons (rigidity, tie-in, bearings, etc.)

Good overall rigidity is provided by the support structure.

4. Tracking System (feedback system, drive system, etc.)

The tracking system includes a sun tracking sensor, a reflector drive mechanism, and a system controller.

SITE VISIT EVALUATION (CONT.)

5. Plumbing Connections (swivel joint, flexible hoses, etc.)

All plumbing is stationary.

6. Hazard Avoidance System (defocus, "stow" position, overtemperature, overpressure, alarms, etc.)

?

7. Weatherability (wind buffeting, materials, misalignment due to support pylon shifting, etc.)

Good

- C. Factory Cooperation during Design, Installation, and System Check-Out

?

- D. Equipment Warranty

1 year

- E. Overall Installed Cost Per Square Foot of Aperature (purchase price of equipment, labor hours for installation, etc.)

Test System.

APPENDIX B

SOCOSIM COMPUTER PROGRAM

B.1 INTRODUCTION

SOCOSIM is a solar collector simulation program which predicts the performance of not only flatplate, but also a variety of other collectors. SOCOSIM has the capability of simulating the performance of:

1. A flatplate collector.
2. A NS axis tracking concentrator of any tilt.
3. An EW horizontal axis tracking concentrator.
4. A two-axis tracking concentrator.
5. A stationary south-facing evacuated tube collector with NS absorber axis.
6. A stationary south-facing compound parabolic concentrator with EW absorber axis.

Salient features of SOCOSIM include:

1. Designed to be called and implemented by TRNSYS main program; or can easily be adapted to "stand alone" with user-written calling program.
2. Designed to read weather data from a SOLMET-format weather tape.
3. Collector performance determined from 1st or 2nd order coefficients to efficiency curve.
4. Uses $\Delta T/I$ information from collector efficiency curve where ΔT can be in terms of inlet fluid or average fluid temperature.
5. Makes hourly corrections for incident angle effects with a simple $K_{T\alpha}$ factor.
6. For tracking trough concentrators, makes hourly correction for rays focused past collector ends; and for rotational neighbor shading.

B.2 TRNSYS

TRNSYS is a well known computer program developed by the University of Wisconsin with subroutines for modelling the various components of a solar energy system (e.g., flatplate collectors, pumps, controls, storage, load). TRNSYS allows the user to derive collector efficiency from a performance curve or by analytical calculations, but it is limited to stimulating flatplate collectors.

B.3 SOLMET WEATHER DATA

The scarcity of reliable hourly insolation data has been a problem for solar simulators in the past. But recently, the National Climatic Center has recently modernized its weather tapes into a standardized FORTRAN-compatible format to include quality controlled hourly insolation data.

B.4 SOCOSIM

Recognizing TRNSYS and the SOLMET tapes as already powerful simulating tools, SOCOSIM was developed at Trinity University in a manner that builds upon these in extending their application to non-flatplate collectors. SOCOSIM consists of three subroutines which can be called upon by TRNSYS:

- SOLMET READER--Reads hourly weather data from the new SOLMET tapes; performs appropriate calculations to deliver direct and diffuse insolation values.
- SOCOSIM INSOLATION--Projects direct and diffuse insolation onto the surface of various tracking or nontracking collectors; calculates geometric correction factors for transmittance and absorptance, end losses, and neighbor shading.
- SOCOSIM COLLECTOR--Calculates the collector performance from a 1st or 2nd order efficiency curve.

B.4.1 SOLMET READER

The SOLMET READER can be used to read a variety of parameters from a SOLMET-format tape, depending on which ones are available and desired. Conventional methods are used when necessary to convert the available insolation data to horizontal direct and diffuse or direct normal insolation. For a typical weather tape, the hourly parameters read are:

1. Horizontal extraterrestrial radiation
2. Direct normal insolation
3. Total horizontal insolation
4. Ambient temperature

giving outputs of:

1. Direct normal insolation
2. Fraction of radiation transmitted through the atmosphere (K_T)
3. Ambient temperature.

B.4.2 SOCOSIM INSOLATION

This subroutine calculates the insolation projected on tracking collector systems. The direct insolation available at the collector's aperture is found from conventional geometry knowing the available direct normal insolation and the axial incident angle.

$$\cos \theta_{ax} = (\sin^2 \delta + \cos^2 \delta \cos^2 H)^{.5}$$

The incident angle upon the horizontal collector array is

$$\cos \theta_a = \cos (L-S) \cos \delta \cos H + \sin(L-S) \sin \delta$$

Incident angle effects on transmittance and absorptance are handled with the correction factor

$$K_{\tau\alpha} = 1 + b_o [(1/\cos \theta) - 1]$$

where b_o is experimentally determined. This approach can be applied to axial trough concentrators if θ is the incident angle in the axial direction, and if one considers the fact that the effect of axial incident angle on transmittance and absorptance for a linear collector is approximately the same as the angular effect on a comparable planar collector.

End loss effects come about when axial incident angles cause some sun rays to be focused at a point beyond the end of the absorber tube. This effect is compensated for with the correction factor

$$K_E = (L_c - (ENDS) (F) \tan \theta_{ax}) / L_c$$

where ENDS, the parameter shown in Table B.1, is 0, 1, or 2 depending on whether the concentrator is a parabolic reflector or a fresnel lens; and also whether the ends of the trough are open, closed and reflective, or closed and nonreflective.

Neighbor shading can be an important factor in the performance of a tracking system of collectors and is a function of collector width (W) and spacing (X). This effect is addressed as follows

$$\cos \beta = \cos \theta_a / \cos \theta_{ax}$$

$$\cos \beta_c = W/X$$

$$K_S = \cos \beta / \cos \beta_c \quad \text{for } \beta > \beta_c$$

$$1.0 \quad \text{for } \beta < \beta_c$$

where β is the instantaneous angle of rotation and β_c is the critical rotational angle at which shading begins to occur.

TABLE B.1

End Configuration	ENDS	
	Parabolic Reflector	Fresnel Lens
Closed, reflective	0	0
Open	1	1
Closed, nonreflective	2	1

B.4.3 SOCOSIM COLLECTOR

This subroutine uses the available insolation at the collector aperture and geometric correction factors from SOCOSIM INSOLATION, along with values for ambient and fluid inlet temperatures, and 1st or 2nd order coefficients to the collector efficiency curve, to determine collector performance. The efficiency curve must be given in terms of efficiency vs. $\Delta T/I$ where ΔT is the difference between ambient and either fluid inlet or average fluid temperatures. In the former case the collector performance is determined in typical fashion. However, when $\Delta T/I$ is in terms of average fluid temperature, SOCOSIM uses the following approach

$$K = K_E K_S (K_{\tau\alpha} I_B + K_{\tau\alpha 60} I_D) / (I_B + I_D)$$

For linear efficiency curves ($a_2 = 0$):

$$T_{out} = \frac{2GC_p T_{in} + 2IKa_o + a_1 T_{in} - 2a_1 T_{amb}}{2GC_p - a_1}$$

For nonlinear efficiency curves ($a_2 \neq 0$):

$$A = -a_2$$

$$B = 4IGC_p - 2Ia_1 - 2a_2 T_{in} + 4a_2 T_{amb}$$

$$C = 4Ia_1 T_{amb} - 4IGC_p T_{in} - 4Ka_o I^2 - 2Ia_1 T_{in} \\ - a_2 T_{in}^2 + 4a_2 T_{in} T_{amb} - 4a_2 T_{amb}^2$$

$$T_{out} = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

After solving the above quadratic equation explicitly for T_{out} , the collector performance can be found in the conventional manner.

APPENDIX C

COST-EFFECTIVE SELECTION INDICATOR

COST-EFFECTIVE SELECTION OF FLAT-PLATE SOLAR COLLECTORS

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ABSTRACT

An experimental program was conducted to determine the instantaneous thermal efficiencies of 16 different flat-plate solar collector designs. These collectors featured selective and nonselective absorber plate coatings, and single and double covers of water-white crystal glass, float glass, and fiberglass-reinforced plastic. An indicator based on initial collector cost and instantaneous thermal efficiency was devised to allow selection of the most cost-effective collector. It is shown that the cost effectiveness varies with operating conditions, and that a single collector design is not necessarily the most cost effective for all operating conditions. All-day efficiency tests were conducted for several collector designs, and the results were used to predict the long-term thermal performance for all 16 collector designs. Two design examples are presented in which the initial cost of the collector bank for each of the 16 collector designs is calculated. It is shown that the savings realized by selecting the most cost-effective collector in comparison with the least cost-effective collector can be as high as 60 percent.

INTRODUCTION

For a given application and geographic location, the cost of the energy obtained from a solar collector is a function of its initial cost, long-term thermal performance, life, and maintenance requirements. Unfortunately, due to the fact that most of the solar collectors available today are relatively recent designs, data on long-term thermal performance, life, and maintenance requirements are generally not available. Thus, at the present time the selection of a collector must be based largely upon considerations of initial cost and short-term thermal performance.

According to a recent survey⁽¹⁾, there are presently about 130 medium-temperature, flat-plate collectors on the market today. Depending upon the design features employed, the cost and thermal efficiency of these various collectors can vary rather widely. The collectors which employ certain design features to increase thermal efficiency, such as multiple covers, covers

with superior optical properties, and selective coatings on absorber plates, usually have a higher initial cost. The question that arises is whether or not the additional cost of a more efficient collector is justified in terms of the additional energy it will collect.

The purpose of this paper is to present a simple method, based only upon initial collector cost and short-term thermal performance, that can assist system designers in making a rational selection of the most cost-effective flat-plate solar collector for a given application.

DISCUSSION

Experimental Program. An experimental program was undertaken to determine the thermal performance characteristics of 16 different flat-plate solar collector designs. These collectors were designed, fabricated, and tested at the authors' laboratory. The test facility was designed and instrumented in accordance with the recommendation of Reference 2.

The collectors employed tube-in-sheet absorber plates made of aluminum. Two absorber plate coatings were employed, a nonselective flat black paint and a selective black chrome coating. The cover materials used were water-white crystal glass, float glass, and a fiberglass-reinforced plastic. Various combinations of the number and type of covers used with each of the two absorber plate coatings were employed to give the 16 different designs, which are similar to many of the flat-plate solar collectors currently available. A summary of these designs is shown in Table 1.

Instantaneous efficiency data were obtained for all 16 designs over a wide range of test conditions, including an absorber plate temperature range of $110\text{F} \leq t_p \leq 190\text{F}$, ambient temperature range of $55\text{F} \leq t_a \leq 75\text{F}$, and insolation range of $245 \text{ Btu/hr-ft}^2 \leq I_i \leq 308 \text{ Btu/hr-ft}^2$.

In addition to these instantaneous efficiency tests, two of the collectors were subjected to all-day tests to determine the thermal performance under long-term operation. These all-day tests were conducted on various days during the period from March to June, 1976. Test conditions included clear as well as partly cloudy skies, an absorber plate temperature range of $140\text{F} \leq t_p \leq 190\text{F}$, ambient temperature range of $65\text{F} \leq t_a \leq 90\text{F}$, and total solar radiation range of $1000 \text{ Btu/Day-ft}^2 \leq H_{pc} \leq 2600 \text{ Btu/Day-ft}^2$.

As has been found by investigators in the past, (3-6) the instantaneous collector efficiency data for all the collectors tested in this study were correlated reasonably well by the expression:

$$\eta_i = (\overline{\tau\alpha})_e - U_L \zeta_i \quad (1)$$

where

η_i = instantaneous collector efficiency determined over a 15-min. test period

$(\overline{\tau\alpha})_e$ = effective transmittance-absorptance product

U_ℓ = thermal loss coefficient

$\zeta_i = (t_p - t_a)/I_i$

t_p = average plate temperature during test period

t_a = average ambient temperature during test period

I_i = average insolation measured in the plane of the collector during a 15-min. test period

The experimental values of $(\overline{\tau\alpha})_e$ and U_ℓ , which are the intercept and slope respectively of the linear curve of η_i vs ζ_i , are also shown in Table 1 for all 16 collector designs.

Space does not permit a discussion and comparison of the instantaneous efficiency data for all of the designs, however, as an illustration of the effect of some of the important variables in collector design, Figures 1 and 2 are included to show the effect of the number of cover plates on the instantaneous collector performance. Figure 1 is a plot of instantaneous collector efficiency, η_i , versus the operating parameter, ζ_i , for a crystal-glass cover material and a black chrome absorber plate coating. At low ζ_i values the single-cover design (design no. 10) is more efficient, while at high ζ_i values the double-cover design (design no. 16) is more efficient. Figure 2 shows the instantaneous performance for float-glass cover material and a black paint absorber plate coating. Under all conditions tested, the double-cover design (design no. 7) is more efficient than the single-cover design (design no. 2).

An instantaneous efficiency performance summary for all 16 collector designs is shown in Figure 3, where the range of the efficiency variation for all 16 collector designs is indicated by the shaded envelope. At low ζ_i , the upper boundary of the envelope is formed by the efficiency curve for the single crystal-glass cover with a black chrome absorber plate coating (design no. 10), while at high ζ_i , the upper boundary is formed by the efficiency curve for the double crystal-glass cover with a black chrome absorber plate coating (design no. 16). The lower boundary is the design with a single plastic cover with a black paint absorber plate coating (design no. 1). The curves for all the other designs fall within the shaded envelope.

As can be seen in Figure 3, the variation between the most efficient and least efficient collector design is rather large.

For evaluating daily performance of a collector, it is convenient to define two other types of efficiencies. One is the collection period efficiency, η_{cp} , defined as the energy collected during the daily collection period divided by the total solar energy available during that period. The second is the all-day efficiency, η_{ad} , defined as the energy collected during the daily collection period divided by the total solar energy available during the entire day.

Collector design no. 's 6 and 10 were subjected to all-day efficiency tests, and it was found that the experimentally-determined collection period efficiency, η_{cp} , could be correlated by the expression

$$\eta_{cp} = (\overline{\tau\alpha})_e - U_L \zeta_{cp} \quad (2)$$

where

$$\zeta_{cp} = \frac{(t_{p_{cp}}) - (t_{a_{cp}})}{I_{cp}}$$

$(t_{p_{cp}})$ = average absorber plate temperature during collection period

$(t_{a_{cp}})$ = average ambient temperature during collection period

I_{cp} = average insolation measured in the plane of the collector during collection period

and where $(\overline{\tau\alpha})_e$ and U_L are the same constants as determined for the collector in question in the instantaneous efficiency tests.

An example of the correlation is shown for design no. 10 in Figure 4, where the data points plotted are the experimentally-determined collection period efficiencies, and the solid line is Eq. (2) where $(\overline{\tau\alpha})_e$ and U_L are the values determined from the instantaneous efficiency tests for design no. 10 as presented in Table 1.

The all-day efficiency is related to the collection period efficiency by

$$\eta_{ad} = R_I \eta_{cp} \quad (3)$$

where R_I is the ratio of solar radiation available during the collection period to the solar radiation available from sunrise to sunset. With Eq. (2), Eq. (3) becomes

$$\eta_{ad} = R_I (\overline{\tau\alpha})_e - R_I U_\ell \zeta_{cp} \quad (4)$$

We now define an all-day operating parameter as

$$\zeta_{ad} = \frac{(t_p)_{cp} - (t_a)_{cp}}{I_{ad}} \quad (5)$$

where $(t_p)_{cp}$ and $(t_a)_{cp}$ are as previously defined, and I_{ad} is the daily average insolation. Then

$$R_I \zeta_{cp} = R_T \zeta_{ad} \quad (6)$$

where R_T is the ratio of the length of the collection period to the length of the solar day. With Eq. (6), Eq. (3) becomes

$$\eta_{ad} = R_I (\overline{\tau\alpha})_e - R_T U_\ell \zeta_{ad} \quad (7)$$

For the two collector designs which were subjected to all-day tests, it was found that Eq. (7) correlates the experimentally-determined values of η_{ad} quite well, where for the conditions of the tests R_I and R_T were determined experimentally to be approximately constant. Figure 5 illustrates this correlation of the all-day efficiency data for design no. 10, where the solid line in the figure is Eq. (7), and where $(\overline{\tau\alpha})_e$ and U_ℓ are again the values determined from the instantaneous efficiency tests for design no. 10.

It is not suggested here that R_I and R_T will be constants and the same for all collectors. Indeed, they may be expected to vary with wide variations in operating temperature of the absorber plate, and to some extent with the thermal capacitance of the collector. However, since the collectors employed in this study were all of very similar thermal capacitance, it is assumed that for approximately equal operating temperatures R_I and R_T are the same for all 16 collectors and are constants. Equation (7) will then be used later in the cost-effectiveness analysis for the purpose of estimating the long-term thermal performance of those collector designs for which all-day tests were not conducted.

Cost Effectiveness Analysis. The economic analysis of a solar energy system is very complex due to the many variables involved. In determining whether or not a solar energy system can be cost effective, such factors as the initial cost of the system, system life, maintenance costs, local climatic

conditions, local conventional energy costs, and other items must be considered. Such an economic analysis involving a complete solar energy system is beyond the scope of this paper. The principal thrust of this paper with respect to the economics of solar energy utilization involves consideration of the performance and initial cost of the collectors, which are a major cost element in any solar energy system, and have a significant influence on the cost of the solar energy collected over the lifetime of the system.

As has been mentioned previously, numerous collector designs are available, and costs and efficiencies vary widely. In this study, we have sought to devise a means for comparing one collector with another, in order to provide a rational procedure for selecting the collector design which is most cost effective. Once the most cost effective collector has been selected for a system, then a system analysis must be conducted to determine the actual cost of the collected solar energy.

Selecting the most cost-effective collector involves considerations of both thermal performance and cost. A more efficient collector will collect more energy than a less efficient one, but will usually cost more. The additional cost of the more efficient collector may well be justified in terms of the additional energy that it will collect, but to make such a determination requires some kind of indicator that includes the effects of both thermal performance and cost.

To derive such an indicator, let us consider a collector system, the instantaneous energy collection rate of which will be given by

$$Q_c = \eta_i I_i A \quad (8)$$

If the cost of the collector bank is C , then we may compute the cost of the thermal power attributable to the collector as

$$\text{Power cost} = \frac{C}{\eta_i I_i A} \quad (9)$$

or

$$\text{Power cost} = \frac{C_u}{\eta_i I_i} \quad (10)$$

where the thermal power cost is in units of, say, dollars per watt, and C_u is the collector cost in dollars per unit area. An analogy may be drawn between this power cost and the cost of an electrical power plant, which is commonly given in terms of an installed cost per kw of generating capacity. There is a difference, of course, in that the input to an electrical power plant can be controlled, while the input, I_i , to the solar energy system

cannot be controlled and varies with time. While one has no control over I_i in Eq. (10), it is possible to select a collector which has a minimum value of C_u/η_i , the ratio of collector cost per unit area to instantaneous efficiency.

It must be realized that while C_u is a fixed initial cost per unit area of the collector bank, η_i varies with the solar input, I_i , the ambient temperature t_a , and the plate temperature t_p , as shown previously. Thus, in order to select the collector with the optimum C_u/η_i ratio, it is necessary to relate this ratio to the operating variables, I_i , t_p , and t_a . This is done by plotting the C_u/η_i ratio versus the operating parameter ζ_i . For the collector cost per unit area, C_u , we use the costs of the materials only, shown for each collector in Table 1. Since the collectors tested in this study were constructed at our research laboratories, and were not manufactured in mass production, it would not be realistic to include our labor cost. By using materials costs only, all collectors are compared on an equal basis. However, the method can be applied to any commercial collector, using the purchase price for the cost of the collector.

Figure 6 is a plot of C_u/η_i versus ζ_i for the same two designs (design no.'s 10 and 16) that were illustrated in Figure 1. In Figure 6 it is seen that the single cover is the more cost effective at low ζ_i values and the double cover is the more cost effective at the high ζ_i values.

Figure 7 is a plot of C_u/η_i versus ζ_i for the same two designs (design no.'s 2 and 7) that were illustrated in Figure 2. Under all but the very low ζ_i values the double cover is more cost effective.

A summary of the cost-effectiveness results for all 16 designs is shown in Figure 8, where the range of the cost-effective indicator variation is indicated by the shaded envelope. The lower boundary indicates the most cost-effective design. If the lower boundary was formed by a single design, then under all instantaneous operating conditions that design would be optimum. Obviously if one design is optimum for all instantaneous conditions then it is also optimum for all long-term operation. Since the lower boundary in Figure 8, is not formed by the curve for one design but by two different designs, then there is a cross-over point between the two different designs.

For a given application, if the collector system always operates at a ζ_i less than the cross-over value of 0.368, then without a doubt design no. 10 is the more cost-effective selection. If the collector system always operates at a ζ_i greater than 0.368, then design no. 16 is always the more cost-effective selection. If the collector system operates over a ζ_i range that includes the cross-over point, then some estimate must be to determine whether the long-term average ζ_i is above or below the cross-over.

To illustrate the cost impact involved in selecting the most cost-effective collector versus other possible candidates, two simple examples will be

presented below. In these examples the cost of a collector bank will be calculated for all 16 designs, and the total costs will be compared to determine which design would yield the smallest initial investment. It is again emphasized that the costs shown are for collector materials only.

The first example assumes a domestic solar hot water heater operating in San Antonio, Texas, with a capacity adequate for a family of four. From the 20-year weather records summarized in Table 2, the average daily insolation in the plane of a collector tilted at 30° from the horizontal for an average year is $146.8 \text{ Btu/hr-ft}^2$, the average daytime ambient temperature is 72°F , and the average collector plate temperature was assumed to be 135°F . The average daily operating parameter, ζ_{ad} , is therefore 0.429. This value was used in Eq. (7) with the appropriate constants from Table 1, and R_I equal to 0.823, and R_T equal to 0.529 to determine the average daily efficiency for all 16 designs. This efficiency, along with the calculated required collector area and total collector bank cost, are shown in Table 3. Also included in this table is the cost penalty, $\Delta \$$, incurred for selecting a collector other than the optimum.

As seen in Table 3, the most cost-effective design is design no. 10, which features a single crystal-glass cover and a selective absorber plate coating. From the results shown in Figure 8, it would be expected that the most cost-effective collector would be either design no. 10 or 16. Since a collector for water heating is a medium-temperature collector, the ζ_i range tends to be low, thus indicating that design no. 10 would be the more cost effective. Also seen in Table 3 is the fact that a savings of about 35 percent can be realized if the most cost-effective design is selected over the least cost-effective design.

The second example assumes a space heating system operating in San Antonio, Texas, for a 2500 ft_h^2 living area and a heating load of $10 \text{ Btu/deg. -day-ft}_h^2$. To supply 80 percent of the load, the design is based on the February weather records. The average collector plate temperature is assumed to be 140°F , the average daytime ambient temperature is 58°F , the average daily insolation is $150.4 \text{ Btu/hr-ft}^2$, and the degree-days is 286. Therefore, the average daily operating parameter ζ_{ad} is 0.545. This value was used in Eq. (7) with the appropriate constants from Table 1, along with R_I and R_T , to determine the average daily efficiency for all 16 designs. The efficiency, required area, total cost of the collector bank, and cost penalty are shown in Table 4.

As seen in Table 4, the most cost-effective design is again design no. 10. This result also agrees with what one would infer from Figure 8. It will also be noted in Table 4 that the difference in collector bank cost for design no. 10 and 16 is relatively small, which again agrees with Figure 8 in that when the average ζ_i is near the cross-over point of the curves, both collectors should exhibit about the same cost effectiveness. Finally, it is seen in

Table 4 that the savings realized by selecting the most cost-effective design over the least cost-effective design for this example is about 60 percent.

CONCLUSIONS

This paper presents a method that can be extremely useful for selecting the most cost-effective flat-plate collector for a particular application. The simplicity of the method lies in the fact that all that is required for applying the method is the initial cost of the candidate collectors and the results from instantaneous efficiency tests. Because the method does not include the cost factors due to collector life, possible deterioration is thermal performance with time, or maintenance requirements, it is to be applied with careful judgement. It may be expected that data will become available on these factors in the future as experience is gained with solar energy system operation. For the interim period, however, the method presented in this paper can be applied by system designers with data that are presently available, or can be easily obtained.

NOMENCLATURE

- A = area of the collector bank, ft^2
- C = cost of the collector bank, \$
- C_u = collector cost per unit area, $\$/\text{ft}^2$
- H = total solar radiation on a horizontal surface of unit area per day, Btu/day-ft^2
- H_{pc} = total daily solar radiation measured in the plane of the collector, Btu/day-ft^2
- I_{ad} = daily average insolation measured in the plane of the collector, Btu/hr-ft^2
- $(I_{ad})_{30^\circ}$ = daily average insolation on a surface of unit area tilted 30° from horizontal, Btu/hr-ft^2
- I_{cp} = average insolation measured in the plane of the collector during the daily collection period, Btu/hr-ft^2
- $(I_{cp})_{30^\circ}$ = average insolation during the daily collection period on a surface of unit area tilted 30° from horizontal, Btu/hr-ft^2

- I_i = average insolation measured in the plane of the collector during a 15-min. test period, Btu/hr-ft²
- Q_c = instantaneous energy collection rate, Btu/hr
- R_I = ratio of solar radiation available during the collection period to the solar radiation available from sunrise to sunset
- R_T = ratio of the length of the collection period to the length of the solar day
- t_a = average ambient temperature during a 15-min. test period, F
- $(t_a)_{cp}$ = average ambient temperature during the daily collection period, F
- t_p = average plate temperature during a 15-min. test period, F
- $(t_p)_{cp}$ = average plate temperature during the daily collection period, F
- Δt_w = temperature rise of the heat transfer fluid due to flow through the collector, F
- U_ℓ = thermal loss coefficient, Btu/hr-ft²-F
- V = wind velocity, mph
- ζ_{ad} = $\left[(t_p)_{cp} - (t_a)_{cp} \right] / I_{ad}$
- ζ_{cp} = $\left[(t_p)_{cp} - (t_a)_{cp} \right] / I_{cp}$
- ζ_i = $(t_p - t_a) / I_i$
- η_{ad} = all-day thermal efficiency
- η_{cp} = collection period thermal efficiency
- η_i = instantaneous thermal efficiency
- $(\overline{\tau\alpha})_e$ = effective transmittance-absorptance product

REFERENCES

- (1) Stoll, R. D., "Solar Collector Manufacturing Activity," FEA/B-76/403, 1976.
- (2) Hill, J. E., and Kusuda, T., "Method of Testing for Rating Solar Collectors Based on Thermal Performance," NBSIR 74-635, 1974.
- (3) Hottel, H. C. and Woertz, B. B., "The Performance of Flat-Plate Solar-Heat Collectors," ASME Transactions, Vol. 64, 1942, pp 91-104.
- (4) Hottel, H. C. and Whillier, A., "Evaluation of Flat-Plate Solar-Collector Performance," Transactions of the Conference on the Use of Solar Energy, Vol. 2, Part I, University of Arizona Press, 1955, pp 74-104.
- (5) Whillier, A., "Design Factors Influencing Solar Collector Performance," Low Temperature Engineering Applications of Solar Energy, ASHRAE, 1967, pp 27-40.
- (6) Simon, F. F., "Status of the NASA-Lewis Flat-Plate Collector Tests with a Solar Simulator," NASA-TM-X-71658, 1974.

TABLE 1
COLLECTOR DESIGNS INCLUDED IN TEST PROGRAM

DESIGN NO.	NO. OF COVERS	COVER MATERIAL	ABSORBER PLATE COATING	$(\tau\alpha)_e$	U_L	$\$/\text{FT}^2$
1	1	PLASTIC	BLACK PAINT	0.552	0.994	5.97
2	1	FLOAT GLASS	BLACK PAINT	0.579	1.068	6.17
3	1	CRYSTAL GLASS	BLACK PAINT	0.660	1.106	6.45
4	2	PLASTIC	BLACK PAINT	0.580	0.784	6.51
5	2	PLASTIC/FLOAT GLASS	BLACK PAINT	0.591	0.938	6.71
6	1	PLASTIC	BLACK CHROME	0.660	0.920	6.77
7	2	FLOAT GLASS	BLACK PAINT	0.532	0.640	6.91
8	1	FLOAT GLASS	BLACK CHROME	0.631	0.886	6.97
9	2	PLASTIC/CRYSTAL GLASS	BLACK PAINT	0.577	0.754	6.99
10	1	CRYSTAL GLASS	BLACK CHROME	0.733	0.988	7.25
11	2	PLASTIC	BLACK CHROME	0.550	0.564	7.31
12	2	CRYSTAL GLASS	BLACK PAINT	0.631	0.744	7.47
13	2	PLASTIC/FLOAT GLASS	BLACK CHROME	0.598	0.780	7.51
14	2	FLOAT GLASS	BLACK CHROME	0.550	0.612	7.71
15	2	PLASTIC/CRYSTAL GLASS	BLACK CHROME	0.598	0.780	7.79
16	2	CRYSTAL GLASS	BLACK CHROME	0.621	0.542	8.27

TABLE 2
CLIMATOLOGICAL SUMMARY*
SAN ANTONIO, TEXAS
LAT 29° 32' N
LON 98° 28' W
EL 794 FT

MON	H , BTU/DAY FT^2	$(I_{ad})_{30^\circ}$, BTU/HR FT^2	$(I_{cp})_{30^\circ}$, BTU/HR FT^2	t_a , F	V , MPH
JAN	980	141.7	220.5	54	9.0
FEB	1234	150.4	234.0	58	9.8
MAR	1528	154.0	239.0	66	10.4
APR	1636	135.5	210.8	74	10.7
MAY	1895	135.7	211.1	79	10.2
JUNE	2192	146.0	227.1	85	10.1
JULY	2288	156.9	244.1	88	9.3
AUG	2045	158.2	246.1	87	8.5
SEPT	1724	141.7	220.5	82	8.5
OCT	1414	160.5	249.7	74	8.4
NOV	1076	148.1	230.4	63	8.9
DEC	871	132.4	206.0	56	8.6
AVG	1574	146.8	228.3	72	9.4

* DERIVED FROM U. S. DEPARTMENT OF COMMERCE WEATHER BUREAU, "CLIMATOLOGICAL DATA: NATIONAL SUMMARY" FOR THE PERIOD 1953-1974.

TABLE 3
DOMESTIC HOT WATER HEATER
FOR SAN ANTONIO, TEXAS*

DESIGN NO.	η_{ad}	A, ft^2	$\$/\text{ft}^2$	\$	$\Delta\$$
1	22.9	75	5.97	446	119
2	23.4	73	6.17	450	123
3	29.2	58	6.45	377	50
4	29.9	57	6.51	371	45
5	27.3	62	6.71	419	92
6	33.4	51	6.77	346	19
7	29.3	58	6.91	403	76
8	31.8	54	6.97	374	47
9	30.4	56	6.99	393	66
10	37.9	45	7.25	326	0
11	32.5	53	7.31	384	58
12	35.0	49	7.47	364	37
13	31.5	54	7.51	407	80
14	31.4	54	7.71	419	93
15	31.5	54	7.79	422	95
16	38.8	44	8.27	364	37

*ASSUMPTIONS: 12 GAL/DAY-PERSON, 4 PERSON/FAMILY, $t_p = 135^\circ\text{F}$,
 $t_a = 72^\circ\text{F}$, $\Delta t_w = 68^\circ\text{F}$.

TABLE 4
RESIDENTIAL SPACE HEATER
FOR SAN ANTONIO, TEXAS*

DESIGN NO.	η_{ad}	A, ft^2	$\$/\text{ft}^2$	\$	$\Delta\$$
1	16.7	925	5.97	5522	1993
2	16.9	915	6.17	5648	2119
3	22.4	690	6.45	4453	924
4	25.1	617	6.51	4017	488
5	21.6	718	6.71	4815	1286
6	27.8	558	6.78	3775	246
7	25.3	611	6.91	4223	694
8	26.3	588	6.97	4096	567
9	25.8	601	6.99	4201	672
10	31.8	487	7.25	3529	0
11	29.1	533	7.31	3893	364
12	30.4	509	7.47	3800	271
13	26.7	580	7.51	4355	826
14	27.6	560	7.71	4317	788
15	26.7	580	7.79	4517	988
16	35.5	436	8.27	3610	80

*ASSUMPTIONS: HEAT LOAD = $10 \text{ BTU/DEG-DAY-FT}_H^2$, LIVING SPACE =
 2500 FT_H^2 , % SOLAR HEAT = 80%, $t_p = 140^\circ\text{F}$, $t_a = 58^\circ\text{F}$, 287 DEG-
DAYS.

FIGURE 1

EFFECT OF NUMBER OF CRYSTAL GLASS COVERS
ON THE PERFORMANCE OF A COLLECTOR WITH
A SELECTIVE COATING

FIGURE 2

EFFECT OF NUMBER OF FLOAT GLASS COVERS
ON THE PERFORMANCE OF A COLLECTOR WITH
A NONSELECTIVE COATING

FIGURE 3

EFFICIENCY RANGE FOR 16 COLLECTOR DESIGNS

FIGURE 4

COLLECTION-PERIOD EFFICIENCY FOR A SINGLE-
COVER COLLECTOR WITH A SELECTIVE COATING

ALL-DAY EFFICIENCY FOR A SINGLE-COVER COLLECTOR WITH A SELECTIVE COATING

EFFECT OF NUMBER OF CRYSTAL GLASS COVERS ON THE COST-EFFICIENCY RATIO FOR A COLLECTOR WITH A SELECTIVE COATING

EFFECT OF NUMBER OF FLOAT GLASS COVERS ON THE COST-EFFICIENCY RATIO FOR A COLLECTOR WITH A NONSELECTIVE COATING

COST-EFFICIENCY RATIO RANGE FOR 16 COLLECTOR DESIGNS